# GENERATION OF COLD ATOMS USING DUAL STAGE LASER ABLATION

by

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# ABSTRACT

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A recent publication claimed the generation of a sub-thermal atomic beam using laser induced back ablation (LIBA). In this paper, we suspect the measurement of the velocity distribution in an atomic beam created using (LIBA). Our work produced a direct and accurate measurement of the velocity distribution of an ablated calcium beam. With our probe laser tuned into the calcium resonance, the ablated calcium atoms detected were moving at 4 000 meter/second, way above the thermal temperature. We find no evidence for cold atoms generated using LIBA.

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# Chapter 1

# Introduction

A publication in 2005 reported the generation of a sub-thermal indium beam laser induced back ablation (LIBA) [1]. Created using LIBA, indium atoms moved at an unusually slow speed, 40-100 m/s (3-16 Kelvin). This group claimed that low velocities atomic beams were achieved by using an unfocused low intensity YAG laser. To test this surprising result, we designed a similar and yet more accurate experiment in which our probe laser beam was tuned to the atomic resonance so that the ablated atoms can be directly detected.

## 1.1 What is laser ablation?

Laser ablation employs high intensity, short, pulsed lasers to remove atoms from the surface of materials. Lasers can locally heat up a material and evaporate atoms from the target surface without affecting the neighboring area. The ablation method can be used to clean undesired material from a surface, known as laser cleaning. It can also be used in laser surgery and other applications. In addition to the medical uses, the method has a wide application in industry, such as laser machining, drilling, marking, and welding.

## 1.2 The virtue of a back ablated film

Laser back ablation involves sending a laser beam through the back side of a substrate disc, and the laser strikes a thin film deposited on the front of the substrate. Using this technique, a collimated beam can then be generated [2]. However, the mechanism for generating a collimated beam using back ablated method is unknown.

## 1.3 What is a sub-thermal atomic beam?

Sub-thermal means below room temperature. Temperature is defined in terms of particles' thermal velocity by $v_{th} = \sqrt{kT/m}$. The melting temperature for indium is about 1 000 Kelvin, corresponding to around 4 000 m/s, way above thermal velocity for room temperature. As such, the ablated indium atoms reported in Ref. [1] had no reason to move at 100 m/s, forty times slower than the expected value.

## 1.4 The direct velocity measurement

The direct measurement is called the velocity selective time of flight measurement. Given a known distance between the atomic beam source and the laser beam, we measure the amount of time required for atoms to travel. Dividing the distance with the time measured, the velocity can be determined. Velocity sensitivity comes from measuring the atomic fluorescence as a function of the laser frequency. These parameters are related through the Doppler effect.

## 1.5 The need for new measurements

In a 2005 publication [1], a helium-neon (HeNe) laser was placed across from a position-sensitive photodiode. The atomic beam crossed the HeNe laser beam path. The laser was deflected as a result of the production of a pulsed atomic beam via rear side laser illumination. The velocity of the atomic beam was determined by measuring the peak position of the deflected signal for known distance between the thin film target and the He Ne beam. In the Lorenz atom, the density and the index of refraction are approximately proportional to each other. As density changes, index of refraction changes and the atomic beam would act like a lens. From this indirect method they deduce the velocity.

The method they used to measure the velocity of the beam was indirect and problematic. First, did they observe low velocities because large clumps of material were ablated off and not individual atoms? If we examine their results from a practical point of view, there is no known physical mechanism by which a sub-thermal beam could be created using their setup. A YAG laser knocks off atoms from an indium target, and then the atoms suddenly slow down to 100 m/s (16Kelvin) for no reason. It breaks the law of conservation of energy. Also via their method, they have no way of showing the atoms they detected all come from the same direction, or whether they were measuring atoms, ions, or clusters.

As discussed, the physical mechanism for generating these cold atoms is unknown. In addition, previous velocity measurements on a back ablated beam all used indirect methods such as interferograms and shadowgraphs [3]. Furthermore, no research has reported the velocity distribution measurement of a back ablated beam for neutral atoms. As such, an investigation on a back ablated beam with a direct method was initiated by us. We obtain the velocity distribution of a back ablated beam using the velocity selective Doppler time of flight method.

# Chapter 2

# Experimental set up

Our laser-induced Doppler selective fluorescence experiment allowed a direct velocity measurement on the particle beam. Our design uses a number of optics and motors as well as two YAG laser beams and a blue probe laser. We split the 532 nm YAG laser beam into two laser beams, called YAG1 and YAG2 with 33% and 67% of the total power. We tightly focus YAG1 onto the calcium target. This ablates the target and deposits atoms onto a nearby transparent disc creating a thin film. We then use YAG2 to back ablate the film, forming an atomic beam. The YAG1 beam was lined up so it hits right on the left edge of the calcium target. Then we listen to the hitting sound and adjust the YAG1 laser beam so it hits the target with the maximum amount of power. We also ensure the thin film deposited on the sapphire disc are being completely ablated by YAG2. If not, the thin film would become thicker and each laser shot will not produce the same amount of atoms.

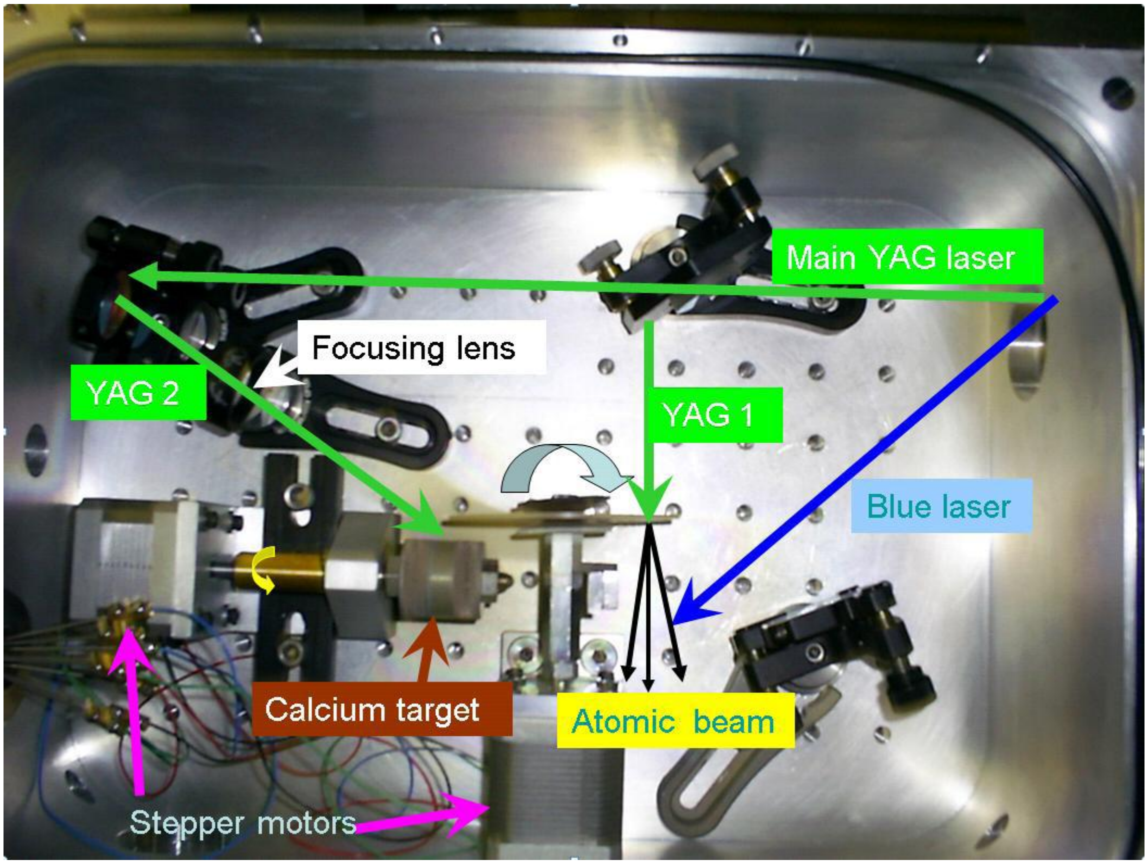

**Figure 2.1** Experimental Setup. Our main YAG laser beam is split to two beams of YAG1 and YAG2. YAG2 ablates the calcium target, and the ablated calcium atoms are deposited on the nearby disc that rotates. YAG1 is used to back ablate the calcium thin film, creating a collimated atomic beams. The collimated atomic beams is intercepted by the blue probe laser beam tuned into the atomic resonance, and florescence signals are produced.

## 2.1 Vacuum Chamber

To be able to take long runs of data, the entire two-stage ablation process is placed in a vacuum chamber to increase the mean free path for atoms in the beam and to prevent the calcium target from oxidation.

Inside the vacuum chamber, the stepper motor wires were protected from touching and causing a short circuit with Teflon tubing. Outside the chamber the wires were protected with heat shrink tubing.

Directly above the intersection point of the blue laser and the ablated calcium beam, a window was made on the vacuum lid. Through this window, scattered fluorescence light can pass to the Photomultiplier Tube detector.

## 2.2 Two calcium targets and stepper motors

The longevity of the experiment is also achieved, in part, by using stepper motors. The calcium target and the sapphire disc were attached to the stepper motors. Our stepper motors have a rotation period of 10 seconds to rotate and advance. Through this setup, each YAG laser pulse was able to strike a fresh region on the calcium target and the sapphire disc. Instead of using a silicon glass as our substrate, a sapphire disc was used to prevent calcium atoms and silicon substrate from interacting. The calcium target's position relative to its motion is important. To be able to know precisely the precision of the target, we control the target using a LabView program designed by Michael Amonson.

## 2.3 Blue laser beam of 423 nm

To directly detect the back ablated calcium atoms, we employed one of the fundamental ideas in atomic physics: the idea of resonance. Each atom has a number of resonances determined by atomic wave function. For calcium atoms, the first resonance is at 423 nm. Our 423 nm probe laser beam was generated via a 1 Walt injection locked ti:sapphire laser. Starting with a simple diode laser of 846 nm, it passed through a set of optical isolators that rotate the direction of its polarization, so the infrared light could not go back to the path it came. The infrared light was then amplified by a tapered amplifier to 150 mW. The amplified beam passes another set of optical isolator and was amplified again by Ti:sapphire laser to reach 1 W. Then we frequency doubled it to 423 nm using bowtie cavity. Once the blue laser beam of 423 nm was successfully generated, we locked the system using the designed lock circuits. This blue laser system is designed by Dr. Bergeson, and more detailed description can be found in [4]

Our probe laser beam passed a set of four mirrors aimed that changed the polarization state of the blue laser. The blue laser beam has to be horizontally polarized so the photons scattered by the calcium atoms can be detected using our optical geometry. The intensity of the probe laser changed over the day. So we measured the laser power periodically. At the end, we found the power drifting issue was not a significant problem.

We use a separate reference cell to find the exact 423 nm resonance. A calcium vapor was generated by heating a calcium solid in a small vacuum chamber. A blue laser beam goes through the chamber interacting with the calcium vapor. By observing the intensity of the scattered fluorescent light in the cell, we can determine where maximum fluorescent signal occurs and therefore the resonance frequency of calcium atoms with zero velocity.

## 2.4 Digital Oscilloscope and Photo Multiplier Tube (PMT) Set up

Our digital oscilloscope triggered along with the pulses of the YAG laser. To do so, a photodiode was used to detect the scattered light from the YAG. Under normal triggering, which requires a triggering condition, our oscilloscope was set to trigger at a negative slope with a certain amplitude.

The voltage applied to a PMT controls its sensitivity. As a PMT's control voltage goes up, its current and sensitivity will also go up. If our PMT's anode current is above 0.1 mA, it will permanently damage the PMT. The linear region of the PMT is also tested by varying the intensity of laser pulse by a known fraction, measuring the output of the PMT, and comparing the input and output ratio is for a thirty nanosecond pulse. We found that if the signal goes above 40 millivolts in a thirty nanosecond pulse, the PMT signal is saturated and is no longer linearly proportional to the input optical signal.

## 2.5 Noise reduction

We used an optical filter and an imaging technique to reduce background signal. Before the scattered fluorescence signal is passed to the PMT, it went through a 420 nm filter with full width half max (FWHM) of 10 nm that only passed the signal scattered by calcium atoms. The signal then went through a 75mm focusing lens that took the signal located 150 mm on one side and focused it to 150 mm on the other side right on the entrance of the PMT. The point where the laser beam and atomic beam intersect is imaged onto an aperture. The aperture passes the fluorescence and block unwanted scattered laser light.

The digital oscilloscope was terminated with 50 ohms input impedance to minimize cable reflections.

## 2.6 Data Taking

With all the instruments running under the optimized condition, we maximize the measured fluorescence by adjusting the optical alignment. We also make sure the thin films deposited on the sapphire disc are being completely ablated as we are taking the data; otherwise, each YAG1 laser shot may ablate a different amount of particles as the thin film gets thicker.

For the Doppler shift measurement method to work, the atomic line width has to be greater than the probe laser's line width. The line width for the probe laser is about one MHz, and 35 MHz for calcium atoms. The Doppler shift is several GHz, many times greater than the laser line width. The probe laser's frequency can be slightly changed by adjusting the piezo voltage in the frequency doubling cavity. We recorded the initial, center, and ending voltage for each set of data we took. The room temperature in the lab varied and thus caused the blue laser to drift by a few volts. So at the end of each data taking process, we check the laser system as well as the signal shown on the oscilloscope to see how much the probe laser drifted. The fluorescence signal a much better indication of the laser frequency than the number obtained from the piezo voltage.

To limit the amount of atomic beams that intersect with the probe laser beam, a collimating device consisted of two washers was placed right behind the sapphire disc. With that device, we observed the slow beam phenomena previously reported in the publication [1], a slow atomic beam moving at 100 m/s. However, as the probe laser beam was raised above the atomic beam path, the fluorescence signal remained. We concluded, from this small adjustment on probe laser beam, that the detected fluorescence signal did not come from the spot where the atomic beam and the blue laser intercept. As such, the detected signals did not come from the desired source. We suspected that some ablated atoms stick to the washer facing the sapphire, and then YAG2 laser strike them and created a third ablation beam detected up by the PMT. After the collimating device was removed, the signal resumed to the normal Maxwell Boltzmann distribution.

The group claimed cold atoms were achieved by lowering the intensity of the back ablated laser. To achieve the same intensity region of the ablated laser beam reported in the publication, we lowered the intensity of our YAG1 laser beam by adding neutral density filters. However, no atoms were able to leave the thin film because the intensity of the laser was not strong enough to ablate any atoms. The early signal and late signal each respectively correspond to the fast atoms and the slow atoms. From all the data we took, fast atoms were moving well above 1 000 m/s, approximately 4 000 degree Kelvin, well above the temperature measured in that recent publication (16 degree Kelvin).

# Chapter 3

# Post Data Processing

## 3.1 Noise Reduction

For post data processing, removing the background signal from the data set is the initial step. We subtract the background signal taken with the probe laser blocked from the original signal at each detuning. This removes the signal from the scattered YAG laser.

The second step is averaging out the noise. Averaging every ten data points and making a new plot can get ride of the noise because how signals look like every two nano-second is not as important as the overall shape of the signal.

## 3.2 Modeling and Simulation

The modeling and the simulation work is to show that our method of analyzing the data is valid. By setting the probe laser frequency at a specific detuning, we determine the atom's velocity and also the relative number of atoms. The velocity of the ablated calcium atoms in the beam can be determined just from the distance between the disc and the probe laser beam divided by the time from t = 0 to the peak of the fluorescence signal. The relative number of atoms moving at that velocity can be determined by measuring the maximum height of the fluorescence signal.

Our goal is to derive the simplest model that includes relevant physics and accurately reproduces the data. We model the number of ablated atoms flying out of the ablated thin film. As reported in [2], a back ablated beam is highly collimated. Therefore we model this collimated beam as a flux of atoms coming out of a small hole on one side of a square box full of atoms at a temperature $T$. The flux is proportional to $A$, the size of the hole; $v$, the atom's velocity; and $n$, the density of the atoms in the box,

$$\text{Flux} = nAv. \tag{3.1}$$

The number of atoms at a particular velocity $v$ is given by a Boltzmann factor. In a one dimensional beam of atoms, we write the atomic velocity distribution $f(v)$ as,

$$f(v) \propto nAv \exp\left(-\frac{v^2}{v_{\text{th}}^2}\right). \tag{3.2}$$

Atoms in the beam pass through a laser beam located a distance $d$ from the disk. As they pass through, they can fluoresce. The probability of atoms fluorescing at a particular laser frequency is given by the two level Lorentzian model

$$L(\nu - \nu_0) = \frac{1}{(\nu - \nu_0)^2 + \gamma^2/4} \tag{3.3}$$

where $\nu$ is the laser frequency, $\nu_0$ is the resonance frequency in the rest frame of the atom, and $\gamma$ is the full width at half-maximum (FWHM) of the resonance transition.

In the reference frame of the moving atoms, the probe laser beam frequency is obtained according to $\Delta\nu = \nu_0(v/c)$ where $v$ is the velocity of the atoms in the lab frame. This effect can be incorporated into the Lorentzian Lineshape from Eq.(3.3)

$$L(v) = \frac{1}{\left[(\nu - \nu_0) - \nu_0 \frac{v}{c}\right]^2 + \gamma^2/4}. \tag{3.4}$$

The relative probability of measuring a fluorescence photon at a particular detuning at a particular velocity is given by

$$P(v,\nu) = f(v)L(v) = v\exp\left(-\frac{v^2}{v_{\text{th}}^2}\right)\frac{1}{\left[(\nu-\nu_0)-\nu_0\frac{v}{c}\right]^2+\gamma^2/4}. \tag{3.5}$$

In our model, all the ablated calcium atoms leave the surface of the sapphire disc at the same time and form a collimated beam. This idea means that the ablation time is very small compared to the flight time from the disc to the probe laser beam. The atoms only scatter light from the probe laser when they are crossing the probe laser beam. Atoms of different velocities will cross the probe laser beam at different times. We simulate this by multiplying the fluorescence probability by an appropriate step function. The time the atoms spend in the probe laser beam depends on their velocity and on the spatial width of the probe laser beam. This relationship allows us to convert the probability function in Eq.(3.5) into fluorescence signal as a function of time

$$s(t,\nu,d) = \int_0^\infty P(v,\nu)\,\mathcal{S}(t,v,d)\,\mathrm{d}v, \tag{3.6}$$

where $\mathcal{S}(t,v,d) = 1$ when $d-\frac{w}{2} < vt < d-\frac{w}{2}$ and zero otherwise, and the spatial width of the probe laser beam is $w$. The fluorescence signal is recorded immediately by our PMT and oscilloscope.

The simulation is a computer calculation that used the model described above to predict the fluorescence signal. It is a numerical integration of Eq.(3.6). We create a velocity array, and calculate for each velocity the fluorescence signal. Then we integrate over velocity to generate a fluorescence signal at a particular laser frequency detuning.

This simulated signals and the experimental signals agree well with each other as shown in Fig. 3.1. The velocity distribution from the experiment matches the velocity distribution in the model as shown in the Fig. 3.1

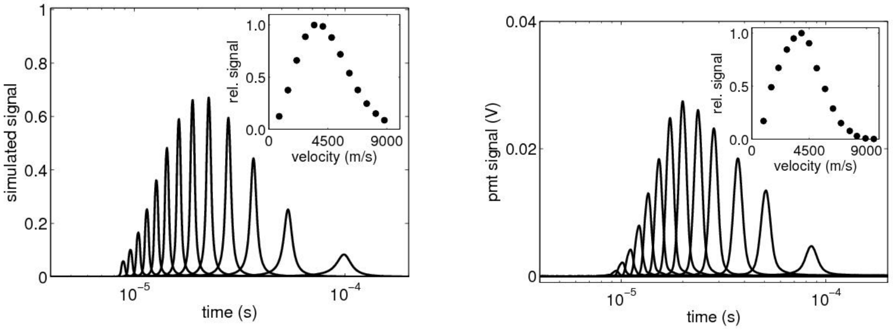

**Figure 3.1** The velocity distribution of a back ablated beam. Simulated fluorescence signal (left panel) and experimental data (right panel). Their overall shape match well.

For Fig. 3.1, we analyze the simulated florescence signals the same way we analyze our experimental data. We find the same distribution using this analysis as we started with in the simulation. This procedure shows that our method of analyzing the data successfully reproducing the velocity distribution.

Atoms at a particular velocity are Doppler shifted into resonance with the detuned probe laser beam. This velocity is equal to the distance from the disk to the probe laser beam divided by the time interval between the ablation and the peak of the fluorescence signal. The number of atoms at this velocity is proportional to the peak height of the fluorescence signal. The velocity distribution is plotted as the peak height vs flight distance in Fig. 3.1. More details can be found in [5]

## 3.3 The mysterious second peak

With the probe laser set to a specific detuning, a typical florescence signal obtained would consist of an early peak and a late peak and each of which respectively corresponds to fast atoms and slow atoms. The presence of these slow atoms, however, is undesired. We performed several measurements to determine the origin of the late atoms as discussed in Sec. 2.6.

Another possible source of this late signal was atomic beam reflection. Our first attempt was to remove the collimating device. The collimating device originally was used to limit the atomic beam as performed in the previous publication [1]. However, the ablated atoms stick on the back side of this device and was ablated again by YAG2 laser beam, forming a third ablated atomic beam. As such, this collimating device was removed.

We then employed a copper pipe in the hope of blocking the multi scattered beams; we drew a line with an angle 53 degree with respect to the disc across the pipe and drilled holes at each end of the line so that the blue laser can goes through. And at the top of the pipe, a hole was also made so the florescence light can come up and be detected by the PMT. With the pipe in that place, the shape of the fluorescence signal, however, became larger and shifted to the left. This probably happened because calcium atoms interacted with the copper wall.

We considered two possibilities that calcium atoms in the wall of the chamber are being ablated, forming a beam going backward that intercepted with the forward traveling atomic beam. A stack of razors was placed against the wall at the end of the beam's propagating path to absorb reflected beams and to reduce the chance of them being second ablated. Under this new set up, several slow signals appeared. We suppose atoms stick to the razors and the YAG2 laser beam came in, striking the blades, and went backward. We closed the shutter of the YAG laser and moved razor blades to a fresh spot, however, the signal remained the same.

We also suspected the slow atoms came from the first stage ablation, so we blocked the path in between the calcium target and the intercepting point of the blue laser and the back ablated beam; but the slow signal remained.

To test if the second peak came from a second ablated source, we moved the probe

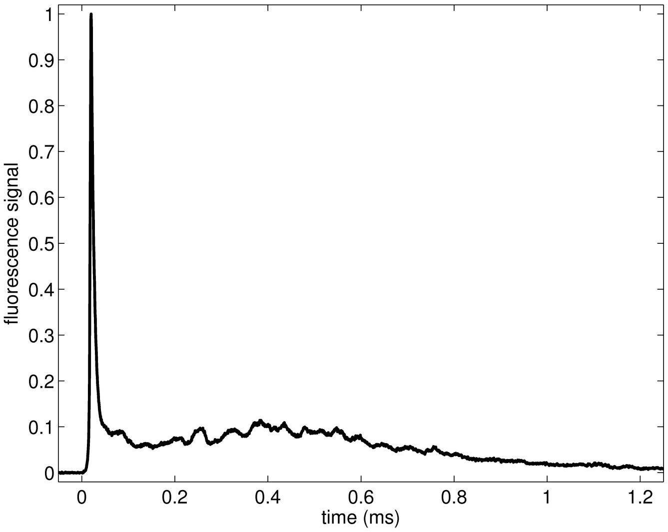

**Figure 3.2** A sample fluoresce signal showing both the early peak ($\sim 10\ \mu$s) and the late peak ($\sim 400\ \mu$s). The late peak appears to come from atoms that are scattered by different surfaces inside the vacuum chamber. Other possibilities are discussed in the text.

laser forward closer to the disc to see how the slow signals would behave under the new configuration. If the slow signals were from a second ablated source, then under this new set up, it would take the slow atoms longer to be detected. But with this new setting, the slow signal shifted forward as well; furthermore, the signal became larger. As we added more neutral density filters to the YAG 2 laser, the signal became bigger and shifted to the right, meaning that the ablated atoms moved much faster than in this set up. We still didn't fully understand what was exactly happening that day.

Our last attempt was rearranging both the stepper motors and the lenses such that reflected atomic beam would have no chance of running into blue laser. Under this new configuration, the slow signal went away. However, the factors leading to the generation of the slow beam are not fully understood. We supposed slow atoms came from multi-scattering sources since the vacuum chamber is a compact geometry.

# Chapter 4

# Discussion

The method used in [1] for measuring the atom's velocity is indirect. It's a density measurement, not a velocity measurement. They measured the deflection of their non-resonant probe laser beam as the atomic beam passed through it. This method does not distinguish between atoms, ions, and clusters. With their probe laser not tuned to the atomic resonance of Indium atoms, they could have detected a cluster of Indium ions. Our experiment, on the other hand, was carefully designed using spectral detuning and time of flight method to precisely detect the ablated neutral calcium atoms and their velocity distribution. We used a velocity-selective Doppler time of flight methods that not only provided information about both the direction and the speed of the ablated beams.

# Chapter 5

# Conclusion

We present the first measurement on the velocity distribution of a back ablated beam. In addition, our results rule out the possibility of creating sub-thermal atomic beam by LIBA. With the probe laser tuned into the calcium resonance, the ablated calcium atoms detected were moving at 4 000 meter/second, way above the thermal temperature. We find no evidence for cold atoms generated using LIBA.

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