Abstract

The ATTA project has been created in order to laser cool and count single atoms of low level krypton contamination in xenon, motivated by the XENON Dark Matter program. An important component of the ATTA system is the laser, and its linewidth must be smaller than that of the atomic transition of the krypton atom to be trapped. An experiment was developed in order to measure this linewidth. A driver was tested and calibrated for use with a pre-made Fabry-Perot interferometer. The driver was successfully used in order to measure key characteristics of the Fabry-Perot, along with the linewidth of the laser. A photodiode circuit was tested and improved upon so that the light from the Fabry-Perot could be analyzed. The noise from this circuit was reduced significantly, though at the end of the experiment, ambient noise was still affecting the signal from the Fabry-Perot and photodiode system.

1 Introduction

1.1 The XENON Dark Matter Program

It has been observed from large-scale cosmological measurements that a large majority of the matter in the universe is of an unknown nature[7]. This "dark matter" has been theorized to cluster around normal matter and is thought to be comprised of Weakly Interacting Massive Particles (WIMPS)[7]. The XENON Dark Matter program is an international collaboration dedicated to the search for dark matter. In order to detect WIMPs, the XENON collaboration has built the XENON100 detector, which is operated at the Gran Sasso National Laboratory below the Gran Sasso Mountain in Italy[1]. The detector is a Time Projection Chamber that uses 170 kg (100 kg target mass) of liquid xenon (Xe) to measure the energy deposited by WIMP collisions with the target nuclei[1, 7].

The collisions are expected to have a low rate of less than 1 event/ton/year and occur at low energies, i.e. below 100 keV[7]. Therefore, a sufficiently sensitive detector with a low background rate is required[7]. Ideally, the detector should be massive and deep underground, for shielding purposes, and contain an efficient detection medium[7]. As a self-shielding noble element, liquid Xe is a such a medium, with a high density that lends itself to use in a compact detector[7]. However, the sensitivity of the experiment is limited by the nuclear and electronic recoil background due to radioactive isotopes in Xe, notably $^{85}$Kr, which is a beta emitter with a half life of 11 years and a 687 keV end point. $^{85}$Kr naturally occurs in atmospheric Xe in the ppm (part per million) level, and is successfully commercially reduced to a ppb (part per billion) contamination level[7]. However, for the XENON100 experiment, the contamination level must be reduced to the ppt (part per trillion) level in order to sufficiently reduce the background level[7]. Although, as a noble gas, krypton (Kr) is hard to separate from Xe, a cryogenic distillation tower has been successfully used to reduce the Kr contamination in Xe to the desired level[7]. In order to verify the low level of contamination, the Atom Trap Trace Analysis (ATTA) system is to be used[7].

![Figure 1: Schematic of ATTA system][1]

1.2 Atom Trap Trace Analysis

The ATTA system (Fig. 1) will utilize a method of laser cooling and single atom counting in order to measure the low level contamination of Kr in Xe. Specifically, the $^{85}$Kr contamination will be determined by measuring the atom trap loading rate of $^{84}$Kr, the most abundant isotope of Kr (57%), in a Xe sample, and
comparing it to a prepared sample with a known fraction of $^{84}$Kr contamination[7]. Then, the $^{85}$Kr contamination will be calculated from the known ratio of $^{85}$Kr/$^{84}$Kr, $2.6 \times 10^{-11}$.

The measurement system, as seen in Fig. 1, will start with a purified Xe sample that is loaded into a reservoir, the amount of gas measured by a high-precision pressure gauge. The gas will then be injected from the reservoir into the source chamber of the vacuum system via a leak valve. Next, in the discharge region, a beam of metastable Kr will be produced. A coaxial radio frequency (rf) resonator coil (Fig. 3) will surround the discharge region to generate the metastable $^{85}$Kr in the $^3P_2$ state ($Kr^*$) (Fig. 2). The metastable state is ideal for trapping due to its relatively long lifetime of $\sim 30$ s and the 811.51 nm wavelength of its transition to the $^3D_3$ state, to which a laser may be easily tuned. The gas that will travel from this discharge region will have a thermal velocity of $\sim 300$ m/s for Krypton and a kinetic energy equivalent to $\sim 300$K. However, for final trapping purposes, a kinetic energy in the mK range and a thermal velocity of $\sim 1$ m/s is desired.

![Figure 2: Excitation of Kr to Metastable State[7]](image)

Before the atoms are further slowed, the metastable Kr beam must be collimated. This will be achieved through a process called transverse cooling, in which laser light that is red-detuned from the main 811.51 nm $^3P_2$–$^3D_3$ Kr transition will be used in a two-dimensional optical molasses. After the transverse cooling region, the $Kr^*$ beam will enter the Zeeman slower. The Zeeman slower will use a counter-propagating (with respect to the direction of the atomic beam) red-detuned laser beam, to slow the atoms with a photon scattering force, along with a spatially varying magnetic field. This field will be used to offset the changing doppler shift of the slowing beam, so that it will not fall out of resonance with the laser beam. After this process, the beam should reach the desired low kinetic energy and thermal velocity needed to be trapped in the magneto-optical trap (MOT). In the MOT, the slowed $Kr^*$ atoms will be trapped by a pair of anti-Helmholtz coils that create a quadrupole magnetic trapping field and 6 counter-propagating red-detuned lasers that trap the desired atoms in the center of the MOT chamber. Each atom trapped in the chamber will scatter near-resonant photons that can be detected with a photodiode, thus enabling single atom counting of Kr in a Xe sample.

### 1.3 Lasers

Fig. 4 shows the laser setup for the ATTA System. This laser is an example of an extended cavity diode laser (ECDL), which uses a diffraction grating and mirror to selectively tune the wavelength of the laser light. As mentioned before, the laser is to be slightly red-detuned from the 811.51 nm wavelength of the atomic transition in order to slow the atoms. There is another factor that must be taken into account when calibrating the laser - the atomic linewidth of the $^3P_2$–$^3D_3$ Kr transition. An atomic transition can be described by a Lorentzian curve, which is a probability distribution for atomic excitation or decay. By definition, the linewidth of the atomic transition is the full width at half maximum (FWHM) of this curve. In the case of the $^3P_2$–$^3D_3$ Kr transition, the linewidth is 5.56 MHz[10]. It is important that the laser’s linewidth be slightly smaller than that of the atomic transition. This ensures that there is a low probability of the red-detuned laser being blue shifted with respect to the $Kr^*$ atoms, thus causing an undesired increase in their energy. The linewidth of the laser is determined by the laser cavity configuration and can be measured by a Fabry-Perot Interferometer.

![Figure 4: The Setup for the ATTA laser system[3]](image)

### 1.3.1 Fabry-Perot Interferometers

A Fabry-Perot interferometer is a two mirror cavity that can be used to analyze an incoming laser beam. Specifically, a confocal Fabry-Perot cavity contains two highly reflective mirrors whose radii of curvature are equal to the cavity length[2]. Fig. 5 shows a confocal resonator, which illustrates light’s travel through a Fabry-Perot interferometer.
As shown in Fig. 5, light travels approximately 4 cavity lengths in a Fabry-Perot interferometer. Therefore, the free spectral range (FSR), or the width between adjacent peaks seen in one mode of the light emerging from the cavity is

\[ FSR = \frac{c}{4r} \]  

where \( c \) is the speed of light and \( r \) is the radius of curvature of the mirrors (and thus the cavity length)[2]. The finesse of the cavity is given by

\[ \text{Finesse} \simeq \frac{1}{F_{ref}^2 + \left( \frac{H^2}{\lambda^2} \right)}^{1/2} \]  

where \( H \) is the radius of the laser beam, and \( \lambda \) is the wavelength of the laser light[2]. \( F_{ref} \) is given by

\[ F_{ref} = \frac{\pi R^{1/2}}{1 - R} \]  

where \( R \) is the reflectivity of the mirrors[2]. The resolution, or linewidth, of the cavity is

\[ \Delta v = \frac{FSR}{F_{ref}} \]  

This gives a lower bounds on the linewidth of incoming light that can be measured using a Fabry-Perot interferometer[2]. Usually, a photodiode is placed on the back of the Fabry-Perot, and the FWHM of the signal from the photodiode gives the linewidth of the laser light travelling through the Fabry-Perot.

Additionally, the signal from a Fabry-Perot interferometer can indicate if the laser beam has multiple transverse modes, which is undesirable. A transverse mode in a laser is defined by a specific “transverse intensity profile” of the laser beam[9]. A laser will usually oscillate on multiple transverse modes, but it is possible to keep the oscillation to a single mode[9]. In order to do this, the laser cavity, in this case the components of the ECDL, can be arranged so that all undesired modes destructively interfere[9]. Due to the Gaussian nature of laser light, these modes only apply to stable laser cavities[9]. The confocal Fabry-Perot cavity is stable, and therefore can be used to look for multiple modes in the laser[9]. Sets of different-height peaks in the output signal of a Fabry-Perot indicate multiple modes running in the laser.

## 2 Experiment

The purpose of the experiment was to develop a self-contained laser linewidth measurement system. The components of this system were to be a Fabry-Perot interferometer, its driver, a photodiode, and a photo-diode amplification circuit.

### 2.1 Fabry-Perot

Due to the relatively narrow linewidth, \( \sim 6 \text{ MHz} \), of the \( ^3P_2 - ^3D_3 \) Kr transition, a Fabry-Perot with a resolution of less than \( 6 \text{ MHz} \) was needed to verify that the laser beam had a sufficiently small linewidth. For other laser tests, a commercial Fabry-Perot with a large FSR of 10 GHz and a resolution of 67 MHz had been purchased. This Fabry-Perot interferometer, the Thorlabs SA210-7A, is shown in Fig. 6.

In order to measure a smaller laser linewidth and check for small multi-mode peaks, a homemade Fabry-Perot had previously been constructed (Fig. 7) with mirrors with a reflectivity of greater than 99.5% and a cavity length of 7.5 cm, held inside an invar tube[2]. This setup had been used so that the FSR of the cavity was \( \sim 1\text{Ghz} \) and the resolution was between 5 and 6 MHz. One mirror had been attached to a cylindrical piezoelectric crystal (PZT) that would expand and contract depending on the voltage applied to it. In order to scan through a full wavelength of incoming light, the PZT could be moved one quarter of the wavelength, changing the cavity length by \( \lambda/4 \). However, no means of PZT amplification had been acquired.

### 2.1.1 Piezo Master

The PZT used was an APCI 42-1011 - a cylinder wall electrode that, according to its specifications, should have an expansion factor of \( 1.4651 \times 10^{-9} \text{ m/V} \). From this, it was determined that 138.47 V was needed to move it the minimum required distance (81.51 nm/4)
to scan one FSR of the incoming laser light. A Piezo Master (Fig. 8), Viking Industrial Products VP7206-24H805, was found to be a suitably inexpensive PZT amplifier and was purchased. Its specifications stated that it would require a 24V power supply, had an 800V range, a 400V offset, and had a gain of 200. This would enable the Fabry-Perot to be swept over several free spectral ranges. Once the Piezo Master was acquired, its performance was tested using a known input while measuring the output.

![Piezo Master](image1)

**Figure 8: The Piezo Master**

The Piezo Master was then mounted into an aluminum box, with its leads soldered into bnc outputs. It was powered as before and its output was connected to the leads of the PZT. The Fabry-Perot was aligned in the laser beam, with a commercial Thorlabs photodiode behind it and a focusing lens in front of it. Fig. 9 shows the path of the laser light. The output of the photodiode was measured while voltage was applied to the PZT. This data was compared to that from when the laser was ramped through the cavity and from the commercial Fabry-Perot in order to analyze the actual FSR of the Fabry-Perot cavity, the actual voltage needed to sweep the Fabry-Perot cavity one FSR, and the linewidth of the laser beam.

![Fabry-Perot Alignment](image2)

**Figure 9: Fabry-Perot Alignment: 1.Alignment mirrors, 2.Focusing lens, 3.Fabry-Perot interferometer, 4.PZT leads, 5.Photodiode position**

### 2.2 Photodiode Circuit

The photodiode used to align the Fabry-Perot is used for many alignment purposes in the whole ATTA experiment. Therefore, a new photodiode detector needed to be made. Previously, a photodiode detector circuit, whose diagram is shown in Fig. 10, had been built and soldered into a detector box to measure the light exiting the Fabry-Perot cavity. The circuit used an OPA228PA-ND op amp, a Thorlabs FDS100 photodiode, two 5.11 MΩ resistors, a 140 pF capacitor, and a 12V power supply. An op amp was used, because of its low output impedance (≤ 10Ω) so that the output could be connected to about any circuit or oscilloscope without loading the circuit.

![Photodiode Circuit](image3)

**Figure 10: The Photodiode Circuit[4]**

According to the responsivity curve of the photodiode used in the circuit (Fig. 11), the photodiode should create a current of 0.5305 A/W. The way the circuit was set up, this current should be multiplied by the total resistance of the two resistors to produce a certain output voltage. Even at low input powers of e.g. 5 nW, the output voltage should be around 30 mV. Unfortunately, tests showed that the circuit simply worked as an on-off switch for incoming light, either outputting 10.87V or 0.083V, instead of reacting linearly to the light.

![FDS Series Responsivity Curve](image4)

**Figure 11: FDS Series Responsivity Curve[5]**

The circuit was then taken apart, and the individual components were analyzed. Once a possible solution was found, the amplification circuit was soldered together and placed in the photodiode box with output bnc connectors (Fig.12). A chamber for the photodiode was designed and secured in place behind the Fabry-Perot (Fig. 13). The output of the photodiode was accessed via a bnc isolated from ground and connected by a cable to the amplification circuit. The circuit was tested and improved upon in order to output the best signal for laser linewidth measurements.
3 Results and Discussion

3.1 Piezo Master

The Piezo Master was tested with the expectation that it would multiply input voltage by a factor of 200, with an offset of 400V. However, when the Piezo Master was tested with the function generator (input frequency of 35 Hz), this was not found to be the case. Fig. 14 gives the experimental minus theoretical dc offset from 400V of the output voltage of the Piezo Master vs. input voltage. The curve was fit linearly, as labeled on the graph, and an equation for for the voltage output vs. voltage input was derived:

\[ V_{out} = 212.8V_{in} + 6.108V \]  \hspace{1cm} (5)

This equation was tested and accurately predicted the output dc offsets for various input voltages, as well as the output peak to peak values. The equation was thus determined to represent the characteristic output of the Piezo Master. It is possible that the Piezo Master behaved in this way simply due to the fact that the input power was 24.2 V, slightly greater than the required 24V.

Fig. 15 shows the signal measured with the commercial photodiode after the homemade Fabry-Perot was aligned and the Piezo Master was connected to the PZT, while Fig. 16 shows the corresponding amplified ramp voltage applied to the Fabry-Perot. The numbers on the two correspond in time, showing that a pair of peaks one FSR apart appeared for each ramp of the PZT, as expected. Additionally, the absence of additional pairs of peaks indicates that the laser was operating in a single mode, as desired.
From these graphs, the actual voltage needed to sweep the cavity one free spectral range was calculated. First, the times between peak pairs was determined. The corresponding times on the amplified ramp voltage curve were determined, and the voltage differences within these time pairs were measured to be the V/FSR. The three numbers were averaged, giving a value of 212.8 V/FSR, much larger than the 138.5 V/FSR calculated. This may be because 4.37 mm of the 15 mm PZT was noticed to be protruding from the invar tube, thus resulting in a shorter length of the PZT, 13.63 m, within the cavity. The expansion factor was recalculated, as it depends on initial length, to be 1.1094 x 10⁻⁹ m/V. Therefore, the new required V/FSR was calculated to be 182.9 V/FSR, much closer to the measured value.

Fig. 17 shows the signal from when the Piezo Master was turned off and the laser was ramped through the homemade Fabry-Perot cavity, while Fig. 18 gives the laser ramp voltage. The letters on the two graphs correspond in time. The height of the main peaks corresponds to the height of the peaks in Fig. 15, indicating that the data acquired using the PZT is reasonable.

The laser was ramped 6.8 ms, with 5 ms on the oscilloscope equal to 2 GHz. Therefore, the laser was ramped 2.72 GHz, so there was 2.72 GHz between neighboring maxima and minima for the laser ramp signal. From Fig. 18, the average time of 0.1136 s between maxima and minima indicated that each second on the graph was equivalent to 23.755 GHz. Averaging the times between peak pairs in Fig. 17, an average FSR of 0.943 GHz was calculated. This is slightly smaller than the predicted FSR of 0.9993 GHz, but the values are reasonably close. Again, the discrepancy may have to due with the protrusion of some of the PZT, which may have caused an increase in the distance between the two mirrors.

Since the FSR of the cavity and the V/FSR have been calculated, the data in Fig. 15 can be used to determine the linewidth of the laser peaks. The average time between peak pairs was determined to be 0.0427 s, which corresponds to one FSR of 0.943 GHz. The FWHM of the peaks in seconds were measured, averaged, and converted into GHz to give laser linewidth of 150.2 MHz. This is much greater than desired and definitely within the scope of the 5.59 MHz resolution of the cavity. However, this measurement can be checked with the data from the commercial Fabry-Perot.

Fig. 19 shows the zoomed-in signal from the same (non-ramped) laser light through the commercial Fabry-Perot, while Fig. 20 gives the corresponding Fabry-Perot ramp voltage. From the specifications of the commercial Fabry-Perot, the FSR is 10 GHz and the ramping is 5 V/FSR, so it was ramped 2 GHz for every volt. From Fig. 20, it was then determined that 63.63 GHz corresponds to 1 s. Going back to Fig. 18, it was determined that the FWHM, the laser linewidth, was 154.1 MHz. This number is close to the one measured in the homemade Fabry-Perot, indicating that the homemade cavity is an accurate measuring device. This linewidth, however, is much larger than desired, indicating that the laser needs to be recalibrated before use in the ATTA system.
After some testing, with the resistors replaced by 1.5kΩ resistors in order to test with more powerful light, it was discovered that the op amp’s negative voltage supply had previously been connected to ground. This was remedied by providing 11.83 V to the positive voltage input and -11.89 V to the negative voltage input, while leaving the rest of the circuit the same (Fig. 22). Fig. 23 shows that this circuit was successful in providing a linear voltage change as a function of power incident on the photodiode.

3.2 Photodiode Circuit

Since the homemade photodiode circuit was not working, the FDS100 Thorlabs photodiode was tested as soon as the circuit was taken apart. Fig. 21 shows the current through the photodiode circuit as a function of input power. In the lower power regime, which is the region of interest, the responsivity of the photodiode was 0.4830 A/W, which is reasonably close to the expected value of 0.5305 A/W. With this photodiode in place, the output of the circuit in Fig. 9 should have been:

\[ V_{out} = (R_1 + R_2)(0.4830\, \text{A/W})P_{in} \]  

\[ \text{(6)} \]
After the circuit was soldered with the 5.11M\(\Omega\) resistors in place and with +/- 12 V from batteries (Fig. 12), the circuit was tested with the photodiode in place behind the Fabry-Perot (Fig. 13), but the only output was noise. After that, the circuit was taken back out of the box, and the components were tested. All seemed fine. After realizing the fragility of the wires connecting the circuit to the box and battery holders, the 12V batteries and their holders were replaced with 9V batteries with more sturdy connections. The circuit was again tested with the photodiode in place behind the Fabry-Perot and a bnc cable connecting it to the amplification circuit. This time there was a signal like expected (Fig. 24).

![Homemade Photodiode Circuit - Output Voltage vs. Input Power](image)

Figure 23: Photodiode Circuit Test

However, for the data in Fig. 24 to be taken, the acquire average method had to be used. This was due to the noise in the signal from the circuit (Fig. 25). The frequency of the noise was measured to be around 32 KHz, so a low pass filter with a resistor of 693\(\Omega\) and a capacitor of 99.2nF was added to the circuit, filtering out any noise above 1.15kHz. The new circuit is shown in Fig. 26. After the filter was added to the circuit, the noise was greatly reduced, as seen in Fig. 27 and data could be taken without using the acquire average method (Fig. 28). The output peaks were still un-tampered with, as the low pass filter did not affect the ramping frequency of 37 Hz. From the data, it appears that a working photodiode detector had been built for the system.

![Homemade Photodiode Circuit Noise and Unamplified Fabry-Perot Ramp Voltage](image)

Figure 25: Noise From the Homemade Photodiode and Fabry-Perot Output

![Homemade Fabry-Perot: Unamplified Ramp Voltage and Photodiode Signal](image)

Figure 24: Homemade Photodiode and Fabry-Perot Output

![Final Photodiode Amplification Circuit](image)

Figure 26: Final Photodiode Amplification Circuit

![Homemade Photodiode Circuit After Low Pass Filter](image)

Figure 27: Noise Reduction in Homemade Photodiode and Fabry-Perot Output
The goal of the experiment was to develop a high resolution laser linewidth measurement system for the ATTA project. A PZT driving device was acquired and calibrated and successfully used to examine the features of the Fabry-Perot Cavity and the laser. Using this method, it was determined that the FSR of the cavity was 0.943 GHz and the voltage needed to sweep the cavity one FSR was 212.8V. The data provided a measurement for the laser’s linewidth, corroborated by the commercial Fabry-Perot data, and revealed that the linewidth is much larger than desired.

The original photodiode detector circuit was taken apart and put together many times. Finally, the circuit was able to produce data from the light exiting the Fabry-Perot cavity. A low pass filter was then added into the circuit to reduce noise. Therefore, with the combination of the working Fabry-Perot driver and the photodiode circuit, a reasonably successful system was created to measure the linewidth of the ATTA laser.

However, at the very end of the measurements, the final circuit started to pick up noise from the environment that drowned out the signal when it was soldered into its box. Time ran out, so the problem was not properly solved. However, in the future, shorter wires that have a decreased likelihood of picking up noise could be used. The wires could also be carefully placed under the circuit board for shielding purposes. Additionally, for future work, a computer program could be implemented to measure the linewidth of the laser as the data is being taken.

Acknowledgements

I would like to thank Claire Allred and Luke Goetzke for mentoring me in my research on the ATTA Project. I am also grateful to Tanya Zelevinsky, Elena Aprile, and their research groups. For making the research experience possible, I would like to thank the NSF and the Nevis Labs REU Program.

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