Optimizing Strontium Optical Clocks

by

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Whether you know it or not strontium clocks and their effects permeate our lives, improving them. Since their invention, they have slowly been getting more and more accurate as technologies and the components that play a part also get better. In order to help our current running clocks I worked on characterizing a new atomic beam oven from AtomSenors to determine if it is a good fit to replace our current ovens from Aosense, either as an adequate substitution or even an improvement.

Dedication

To all my grandparents, those still here, and those who have gone.

Acknowledgements

A special thank you to Jun Ye for being my advisor throughout this process and reigniting a passion for science. The entirety of the strontium group was wonderful in helping with every question I had. Special thanks to Maya, who introduced me to everything, and Lingfeng who worked with me on this project.

And lastly, thank you to my family who has listened to me talk about this work and opportunity in circles. They have done so much for me and I can not thank them enough.

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Introduction

1.1 History of Time

Timekeeping is as nearly as old as civilization itself; innately human. While all animals are capable of noting changes in time, like monarch butterflies making the journey from Canada to Mexico yearly as the seasons change or your pet demanding dinner when it's a few minutes late, humans are the first to keep track of the passage of time. Hundred of thousands of years ago ancient humans used celestial bodies to track the season and months, even days, to guide their everyday lives with their farming techniques and holidays. As technology improved the sundial was invented and first recorded in Ancient Egypt to help people mark the hours of the day allowing for a leap in the accuracy of timekeeping. For anything more specific than the hour of the day new methods needed to be created to allow for the level of precision.

The pendulum clock is the most marked improvement in recent times switching from the current technology to the mechanical era. The swinging of a weighted mass first thought of in the mid-1600s kept track of time by having every two seconds be the period of the pendulum swing. At the time of their invention, they were accurate to about 15 seconds a day progressing to only losing less than a second per year by the 1930s. Due to their accuracy, they became widely used in middle-class households, making way for precise train schedules and work shifts for the average worker. The increased precision of the second also propelled naval travel forward as it allowed astronomers to better track the movement of celestial bodies.

While these clocks held the gold standard for 270 years in 1927 another jump was made in the form of the then-new quartz clock that employed oscillators based on the electro-mechanical resonances of the quartz crystals. The oscillation period for these crystals is significantly smaller than that of the previously mentioned pendulum allowing for the current measure of time to be split into even smaller increments. Improving the precision at which humans could tell time, now these clocks only lost a second in around thirty years. This new form of timekeeping took clocks from the classic grandfather clock stuck in a hallway to allowing time-keeping to become fully portable as quartz crystal clocks could shrink to fit inside a wristwatch.

Not to discredit the accomplishment of the amazing aforementioned devices, but there is one main drawback in all of the systems. They are mechanical. Meaning that they use a relative timescale as opposed to a more robust absolute timescale. Depending on a variety of environmental factors each pendulum and quartz crystal clock have a severely limited ability to replicate oscillation period across different clocks. This limited these clocks to being used primarily locally as they still relied on the movement of celestial bodies to be calibrated, a significantly slower period of oscillation compared to the intervals the pendulum and quartz clocks could produce. Creating a need for a newly invented, more precise clock.

1.2 Atomic Clocks

In recent years we have been able to employ atoms or molecules, and the newly discovered quantum mechanics to create a new kind of clock that is more precise than the previously mentioned mechanical and celestial-based clocks. As we learned from pendulum clocks, the oscillations of a period are the key component of how we define any small interval of time. In atomic clocks, the oscillation periods stem from an atom's excitement between two hyperfine energy levels of its structure. This structure that comes with any atom or molecule allows them to absorb a variety of frequencies of electromagnetic radiation to stimulate this oscillation between select energy levels. These energies are relatively isolated from external factors affecting the radiation frequency making it a good, consistent choice. In the strontium-87 isotope, we focus on the transition between $^1S_0$ - $^3P_0$. The exact transitions are determined using $v = \Delta E/h$, where h is Planck's constant and ΔE is the difference of energy between the desired levels. For our transition, we use a laser that is 430 terahertz and has an equivalent wavelength of 698 nanometers; to our naked eyes, it appears red.

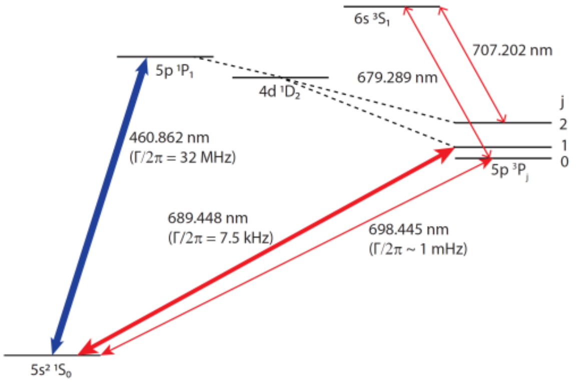

Figure 1.1: Above is a simplified diagram of the relevant states and their corresponding transitions, in both nanometers and hertz. Focusing particularly on the transitions between $^1S_0$ to $^1P_1$ at 698 nm and $^1S_0$ to $^3P_0$ at 461 nm, as these will be the most relevant in this thesis.

To get to the point of measurement for these atoms we first obtain a cloud of pure strontium atoms with an atomic beam oven that heats a solid sample to 450 C, its sublimation point, and pumps these atoms into a sealed vacuum chamber. They are trapped using several lasers in a magneto-optical trap to be cooled to the mircoKelvin range using Doppler laser cooling. These ultracold atoms are loaded into whatever particular configuration, based on the individual clock itself. Once, there the atoms are excited with the previously mentioned 698 nm laser to the $^3P_0$ level from the ground state. It releases precise electromagnetic radiation equal to the frequency of the laser when decaying down to the ground state that we record and can compare to a reference oscillator that produces its own highly accurate and stable signal. The frequency of this radiation is ultimately what we use as the basis of the clock.

As science as a whole progresses since the first atomic clock today's cesium atomic clocks have reached amazing accuracy levels of roughly one part in 10^{-16}, meaning that in 300 million years NIST-F2 will lose or gain only one second [1]. Our own strontium-based 1D lattice clock has reached stability of only losing or gaining one second after running for fifteen billion years [2].

1.3 Uses of Atomic Clocks

Since their development, atomic clocks have been essential in a wide range of scientific and technological advancements. The most applicable to the everyday person is the Global Positioning System (GPS), a global navigation satellite system created and operated by the United States Space Force. GPS, like all global navigation satellite systems, works by measuring the time delays between multiple GPS satellites and transforming these delays into a time coordinate and three spatial coordinates on Earth. Other global navigation satellite systems created by other governments follow the same process using their satellites like Beidou from China, Galileo from the European Union, and GLONASS from Russia to name a few. Precision timing even plays into financial trading transactions for systems like high-frequency trading. the clocks will keep accurate measurements of transactions between any buyer and seller better than a millisecond allowing to block off illegal trading that may occur prior to the agreed-upon time, which becomes particularly useful in international trading when time zones play a key factor.

Precise atomic clocks push forward several areas of science, sometimes providing proof for previous only theoretical predictions. In 2021, our 3-D lattice clock measured a linear frequency gradient that when compared was consistent with the gravitational redshift Einstein predicted in his theory of general relativity, stating that clocks at different gravitational potentials will tick at slightly different rates corresponding to the clock's physical coordinates [3]. It's even hypothesized that an atomic clock could possibly measure dark matter and gravitational waves using quantum entangled atoms [4].

Arguably most important purpose of all atomic clocks is their definition of the second, our current best measurement of time. The current standard of the second is defined by the oscillations between the ground state hyperfine transition of caesium-133 atom, 9,192,631,770 oscillations to be precise, established in 1968. As the definition of the second becomes more precise we can measure time more accurately aiding in several of the applications listed above. This definition of the second is also used in defining other international system (SI) units like the meter, ampere, kelvin, mole, kilogram, and candela following the 2019 redefinition of the international system of units[5]. For example, since 2019 an ampere is defined as one coulomb of charge going past a certain point per second where one coulomb is a defined constant, $1.602176634\times10^{-19}$ C.

1.4 Outline of Thesis

Now that some context and background information has been has been provided I want to dive into the specifics of what I did. In the next chapter, Chapter 2, I will be discussing some of the principles behind how an atomic oven works in an atomic clock. In Chapter 3, I describe the setup and preparation process of the oven chamber we created to characterize a strontium atomic beam oven. I will go over the laser set-up we used, creating the vacuum to a suitable level, and the general final configuration for measurement. Then the actual results of my measurements of the oven's absorption are in Chapter 4. This also includes a comparison of the performance between the atomic clock I analyzed and the Aosense oven that's currently in use. Finally, in Chapter 5, I discuss the practical application of the results and the implications of my final results, and new possible directions of where to take improving strontium atomic clocks.

Chapter 2

Initial Basics of an Atomic Clock

2.1 Atomic Beam Oven

The first initial step of almost all atomic clocks is getting a cloud of atoms in a vacuum from the original solid material. This step is where an atomic beam oven comes into play. Now, this is not the same type of oven you could use to bake cookies in. These ovens reach higher temperatures, think 500 C compared to your kitchen oven of 500 F, to heat the solid sample to a point of sublimation. Sublimation is the process of solid changing phases to a gas without first going through a liquid phase. These are specifically produced for a variety of elements like calcium, ytterbium, cesium, strontium, and rubidium; depending on the heat range required for the element. For strontium, we operate the oven at 450 C for sublimation to occur, and in its chamber then the oven directs all the atoms out of a small opening to direct it into the connected vacuum chamber for manipulation.

Seeing how important precision is for our atomic clocks it is key that we have a good, reliable, and functioning oven at the beginning of the initial apparatus choosing what type of oven and from what company carries a heavy weight. We currently use the strontium atomic ovens supplied by AOSense. We have used these for while and quite like them. However, we have historically run into the issue of needing to replace our ovens, whether it be because they broke or we need to replace the strontium sample inside more often than ideal. So while AOSense allows us to send the oven back for repairs or oven reloading it takes weeks in shipping alone setting back progress on new clocks and delaying measurements on current working ones. In an ideal world, we would be able to focus funds on buying a handful of backup ovens on deck to replace any broken ones. However, like most labs money becomes an issue as AOSense ovens run a little high, making it difficult to mass-buy them. So I looked at characterizing an atomic oven produced by an Italian company, AtomSensors, as a possibly cheaper option to have on hand to replace when another oven breaks if the two ovens are comparable enough that we feel that using this new oven does not lessen our precision in the clocks.

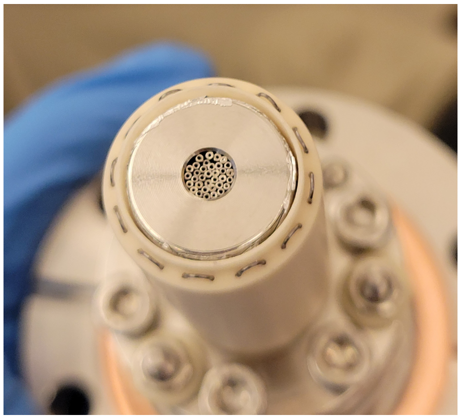

Figure 2.1: This picture shows the output for the AtomSensor oven. It is a collection of smaller atomic beam outputs to create the overall output of the oven.

2.2 Doppler Laser Cooling

After the strontium has been sufficiently heated and we now have a gaseous cloud of atoms to manipulate we need to cool the cloud down to the microkelvin range to minimize unwanted effects that can occur at higher temperatures, like time dilation. We have to find a way to cool these atoms, without the atoms solidifying or interacting with anything else. This is where laser cooling comes into play. In 1997, Claude Cohen-Tannoudji, Steven Chu, and William Daniel Phillips won the Nobel Prize for their development of laser cooling and trapping [6]. They utilized the natural momentum of a photon so that when an atom or molecule absorbs a photon it will gain some momentum in the same as the absorbed photon. Whenever an atom absorbs a photon that carries its own momentum of dependent on its wavelength, the law of conservation of momentum says that the atom absorbs this momentum. After the atom comes down from its excited state to its original ground state a photon is emitted by spontaneous decay the conservation of momentum still holds so the atom experiences momentum change. However, the photon is emitted in a random direction every time, so when many of these decay events are taken into account the atom has no total momentum from spontaneous emission. Over time this repetition of absorption and emission of photos reduces the velocity of the atom, cooling it.

2.2.1 Laser Set-Up

Knowing that the strontium 87 isotope interacts with 461 nm light as it does with the previously mentioned cooling is how I characterized the oven. With the setup implemented the laser will pass through the vacuum chamber just a the end of the nozzle so it can hit the majority of the atoms. The photons will be absorbed moving each atom to a higher energy state, $^3P_0$.

Eventually, the newly excited atoms will return to their pre-excitement energy level, for strontium this is the ground state. Strontium is actually a well-picked element for laser cooling because all the relevant transitions decay back to the ground state where it can not go lower, as wherein some other elements like transition metals do not have this convenience and are not used as commonly. Regardless of the element, returning to the original energy state will release the energy that was absorbed in the form of a photon, the process called fluorescing. An example of this for strontium is shown in Figure 2.2.

With all this information we are causing the atoms to fluoresce to know that the setup is working prior to the measurements. It is also one of the beautiful things to be able to physically see in this process. It is important to note that when the photon is emitted from the atoms their direction is random and while it will not be a major player in the final absorption measurements it will possibly affect it if the emission of the photon randomly points towards the photodetector.

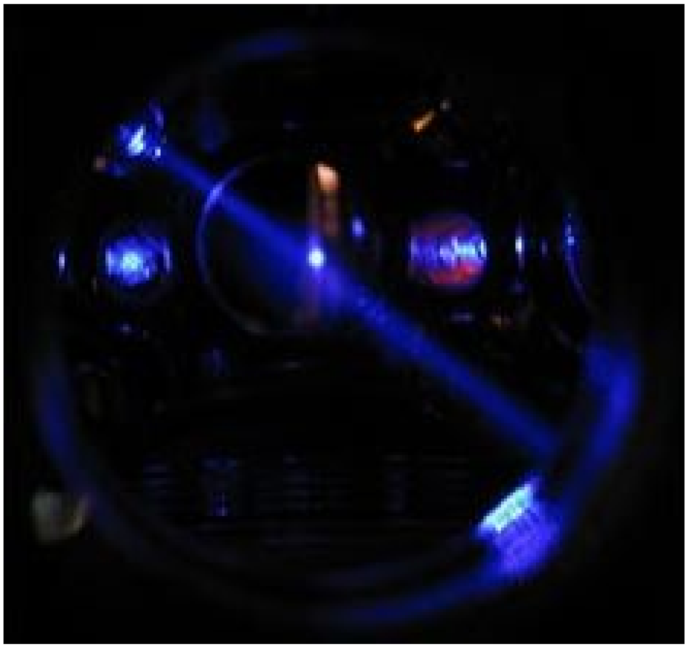

Figure 2.2: The above is an example of strontium atoms fluorescing when a 461 nm laser is shined on them. It is quite pretty.

2.3 Example Clock: Sr 1

Our best clock is the 1-D lattice optical clock. As with every atomic clock, it is based on the oscillations of the atoms between two energy levels. Each clock has its own way to maintain the previously mentioned laser-cooled atoms. In our clock with the best accuracy of 3.5 x 10^{-19}[7]. We employ a shallow 1-D Lattice. This is where the atoms are tightly trapped in a one-dimensional 'pancake' optical lattice. The shallow piece comes from the light trapping of atoms that allows easy tunneling of atoms between other lattice sites. The trapped atoms are stimulated by a laser and then measured. The more atoms we can stimulate the more measurements we can take and the more accurate it can be. If that's our goal then making sure that we can get as many atoms to the lattice sites by getting the maximum possible strontium atoms out of the oven is a primary goal.

Chapter 3

Characterizing the Oven

3.1 The Vacuum Chamber

If we really want to only observe the interactions that the output strontium atoms have with the laser light and only these interactions, we can't risk the possibility that there are other atoms or molecules in the path of the laser or any molecules reacting with the pure strontium. So we have to isolate these outgoing atoms from the environment using an ultra-high vacuum (UHV) chamber. This is one of the main four types of vacuum focused on removing as much of other contaminants as possible; exactly what we want. The typical range of pressure for UHV is 10^{-9} to 10^{-12} Torr, much, much lower than our atmosphere.

3.1.1 Baking Out

Now that the chamber has been put together we can begin the process of truly creating a vacuum. This process is very scientifically named baking out the chamber. We will heat up the chamber several times for a long time period in order to evaporate all residual particles inside so they can be pumped out and removed, creating a vacuum. The steps are as follows:

(1) Despite saying this would cover the baking out procedure I want to backtrack to briefly discuss building the chamber. The materials need to make UHV are generally stainless steel or aluminum and are as such specially made parts. Some of the parts were bought specifically for this project, others were scavenged from around the lab. The parts that were ordered came relatively contamination-free, but the one we found had to be cleaned

to minimize the amount of baking that would need to be done. The chamber was then carefully put together with each joint having a copper ring put between the flanges so that it can swell and form a perfect seal.

(2) Once the main chamber has been built we then attach several machines to pump out soon-to-be-evaporated molecules. We attached a turbomolecular pump, an ion-getter pump, and a residual gas analyzer (RGA). Both the turbomolecular pump, or turbo pump, and the ion-getter pump serve to physically remove the molecules that are evaporated. While the RGA tracks any trace of a variety of particles including hydrogen, helium, machine oil, water, nitrogen, oxygen, carbon dioxide, and so on until it reaches desirable levels that are predetermined. We were looking for a low 10^{-9}.

(3) Now everything is actually ready and the baking itself can begin. It starts with taping temperature sensors at various points across the chamber, primarily on the flanges and the middles of any lengthy pieces of the chamber like the tube connecting the chamber to the turbo pump. We also put extra sensors on each of the viewports of the oven, roughly three spread out evenly. Since the viewports are glass if the heat distribution across them is uneven there is the chance that it will crack, defeating the whole process.

(4) The heat is applied through heat wraps. These are thin, almost scarf-looking ribbons covered in woven fiberglass (found out the hard way) for insulation. These are wrapped all around the chamber, mindfully avoiding crossing the wraps to avoid a heat spot and trying to spread the wraps out even so the whole chamber receives even heating. If not then the atoms will settle in the coldest area preventing them from being pumped and actually reaching UHV.The heat wraps did have to reach right up to the machine attached to get there. The heat wraps are connected to the adjustable power source to control exactly how hot they get. It was focused on 150 C.

(5) The next step is a tad odd. In order to more evenly bake the chamber and conserve power

by reducing the heat lost we have to insulate the chamber as much as possible. So terribly scientifically we used massive amounts of foil. Careful to wrap the viewports so the foil does not make contact with them and affect the surface. Then the rest of the is packed over many times, crinkled to maximize the insulation. Making sure to cover where ever the heat wraps were put. To ensure that no major spots were missed the heat wraps are turned on and then different areas of the foil covering the chamber were checked for any heat drafts coming off of it and then subsequently covered with more foil.

(6) Now we can actually bake by slowly over the course of several hours turning the power up on the sources to ensure it does not heat up too fast and finally having the heat wraps reach a temperature of 150 C and this is consistent across the sensors. Then the bake continues for a few days tracking the decline in pressure and particles in the chamber via the RGA; getting to 10^{-15}.

(7) Once the pressure level goes down significantly we stop the baking and take off all the foil and heat wraps and sensors. the chamber is cooled and while the pump is still going the pressure increases from the pressure when it was baking.

(8) Depending on the pressure level we will need to bake again. For this project, it was baked roughly four separate times. It follows the same process that was described in the last four steps of the temperature sensors, heat wraps, foil, baking, and coming down from baking. This cycling is repeated until we reach the desired pressure of 10^{-11} Torr when not actively baking.

(9) Now that there is some level of vacuum we have to attach the oven. This will involve breaking the vacuum for as briefly as possible. It doesn't neglect all the previous work that baking was done because that still removed the machine oil and dust but the air is still being introduced into the system.

(10) We have to recreate the prior level of UHV, so steps three through eight are repeated this

time taking into account that we have to be careful with the oven as well as the viewports making sure the oven is still heated up but isn't sending strontium atoms into the chamber.

(11) At the end of this we have reached UHV with a pressure of 10^{-11} Torr and can confidently say the chamber is ready to use for measurement.

Figure 3.1: Sadly, the only picture I have depicting the heat wraps and foil, Specifically, the heat wraps are covering the end of the oven with the foil in the background covering the viewports.

3.2 Apparatus Set-Up

The meat of the project was to create the physical apparatus that would be used to test the AtomSensor atomic oven. It was done in two stages: one for the optical piece and another for the vacuum chamber. Both came together to take the final measurements.

3.2.1 Laser Set-Up

The first thing I did both on this project and in Jun's lab as a whole was to construct an optical set-up that could be moved from the original lab to an open space where we could build the oven. Figure 3.2 focuses on this setup with the Roman numerals being used to emphasize the key components with an explanation for each one listed below.

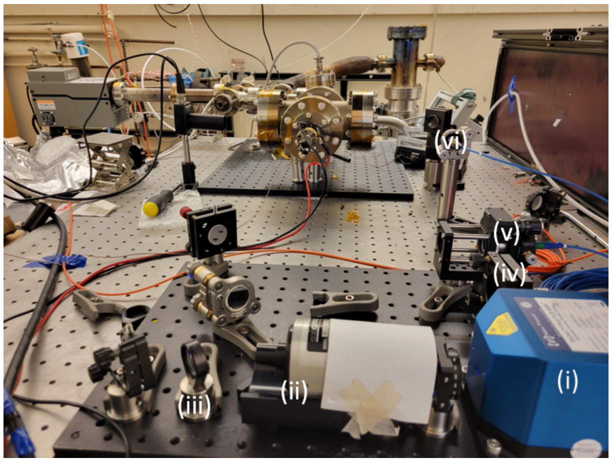

Figure 3.2: The picture is of the wall optical set-up to monitor the laser wavelength and send the laser through the chamber.

i This indicates the source of our laser the laser head. It has a wavelength of 460.862 nm which we will use for the 461 nm laser we need to characterize. The wavelength can also be read as 650.5039 THz, which is worth mentioning because that is how the wavemeter will read and monitor it.

ii This is the optical isolator with a very scientifically sound note card taped over it for safety, in case of laser reflection. The isolator maximizes how much light can get through while stopping any back reflections that would over time damage the laser itself.

iii Here is a beam sampler to take a single controlled beam and create two separate beams, one stronger than the other. The stronger one follows the path to the v. The other, the weaker one, follows an inner path to the iv path.

iv The weaker path leads to the input for a multi-mode fiber, the orange wire in the background. I hooked this fiber to a wavemeter so I could keep track that the laser was adequately aligned and the laser was oscillating within the range that I wanted it to.

v Since when the optical setup was created we had not created the chamber at all, the laser could not go straight through the chamber we had the stronger laser path go into a single-mode fiber. This specific fiber is designed for 461 nm hence the name single-mode.

vi This is the output point of the single-mode fiber from v. It aligns with the edge of the end of the output of the oven through the viewport.

3.2.2 Final Measurement Set-Up

Figure 3.3 is a picture taken of the experimental set-up while not in use with the notable components indicated by the Roman numerals. It does contain some of the optical pieces, but these were expanded upon in Figure 3.2 and Section 3.2.1.

i While already addressed I will mention it again. This is a laser with a wavelength of 460.862 nm rounded to 461 nm, or 650.5039 THz that we used to characterize the oven.

ii The input point for our multi-mode fiber in orange that connects to the wavemeter so we can monitor the wavelength, leading off to the left of the picture.

iii This is the input point for the single-mode fiber in blue that takes the light in and sends it through to be sent out from the other iii that aligns perpendicularly to the mirror about halfway up in the image.

iv The first viewport that the light first passes through. In ideal conditions, the viewport is completely clean and absorbs no photons of light, Unfortunately, ideal and reality do not always align, and as the oven operates a thin film of atoms sticks to the window. This does not have a massive impact on the output or results but it is worth noting that not all the light is being absorbed by strontium atoms coming out of the oven at one time.

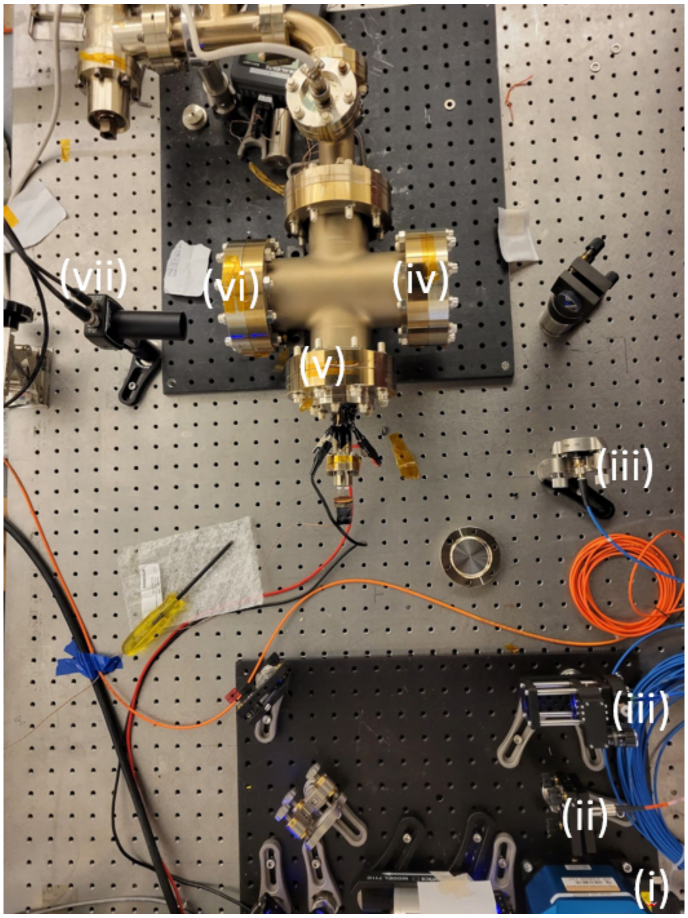

Figure 3.3: This is a labeled diagram of the set-up we used to characterize the AtomSensor oven including the previously mentioned optical system and the vacuum chamber. Pay no mind to the various tools and trash in the background, the whole thing was terribly messy constantly.

v This flange is the connection of the oven to the vacuum chamber. It puts the end of the oven perfectly perpendicular to roughly the center of the viewports. At the end of the oven pointing down the picture red and black wires are attached to the oven. This is used to power and heat the oven up to the desired temperature.

vi Here is our second viewport where the light will leave, varied by how much of the light is absorbed by the atoms if the oven is on and operating. Like the first viewport, this one also runs the risk of being coated by a thin layer of strontium atom that will absorb some of the light that does pass through the atoms coming from the oven, making the absorption of the oven appear slightly higher in the final analysis.

vii This is the final step at the photodetector where whatever light comes out the other side of the chamber is detected That information is then sent to the computer to be recorded which will give us the final results discussed in the next chapter.

Chapter 4

Results

4.1 AtomSensor Results

Using the results from the photodetector we are able to extrapolate a few key details about the AtomSensor oven and from there determine the final conclusion on whether it is usable or not. The biggest one is the absorption/transmission rate. It tells us roughly how much light is allowed to pass through the cloud of atoms and how much light is actively being absorbed by the cloud. From this information, we can calculate the flux of the atomic oven and determine at different temperatures how fast the atoms are leaving the oven.

4.1.1 Absorption

Absorption of the atomic beam can not be measured directly as the photodetector only measures whatever light is leftover after absorption, called the transmission. Using this transmission we can extrapolate the absorption by looking at the inverse of transmission, That is to say when the transmission is low absorption is high, and when the transmission is high the absorption is low. The low transmission points occur when the laser is no longer detuned from 461 nm and matches the energy difference hyperfine levels.

Experimentally getting zero transmission is very difficult. While we try to isolate the photodetector from other light as much as possible it isn't perfect and can still detect some regular light. As well as the previously mentioned spontaneous emission that can mean random burst photon can be shot directly into the photodetector. Getting full transmission is also difficult in the

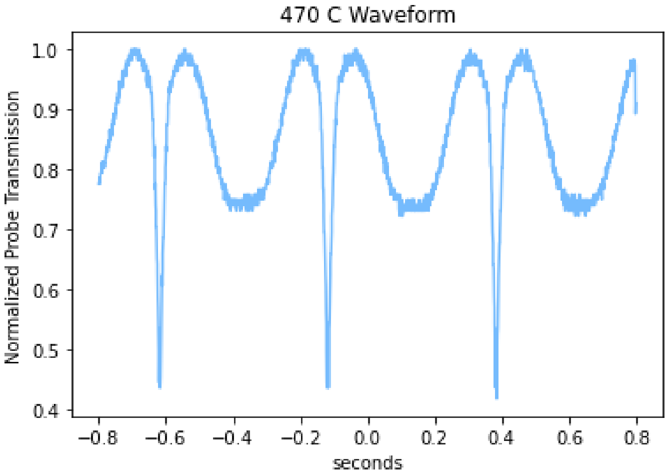

Figure 4.1: Above is the normalized transmission waveform from the photodetector while the oven was operating at 470 C. The sharp dips down are where the probing laser had the correct wavelength, 461 nm, and absorbed and excited the strontium atoms.

experiment. In section 3.2.2 I mentioned that the viewports collected a thin layer of atoms that can block some light and this did block some light passing through the chamber when the laser was completely detuned.

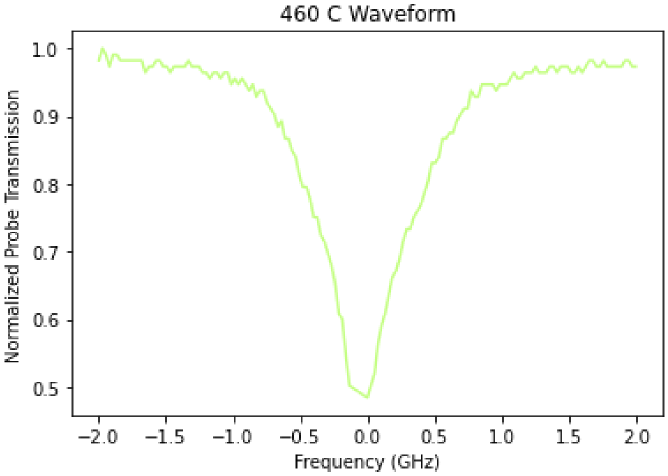

Figure 4.2: Similar to figure 4,1, but at a different temperature of 460 C and focused in on one of the sharp dips for the transmission when the frequency is not detuned. The lower the dip the better the absorption.

To best analyze these waveforms it helps to narrow focus down to just one of these sharp valleys. The one in Figure 4.2 shows it is much easier to discern how much of the light was able to pass through the chamber.

4.1.2 Flux

Flux in a general sense refers to the movement of an object through an area in a set in a period, or the rate of 'flow'. In the context of the oven, the flux is the rate of emission of strontium atoms. The final flux can be a result of several different factors such as the type of atom, the pressure of the vacuum chamber, and the temperature of the oven. We can assume the first two to be constants within our system. So the flux should increase as we increase the temperature of the oven.

There is a preference for higher flux as it increases accuracy and precision. The flux alters

Table 4.1: Here is an example of a table with its own footnotes. Don't use the `\footnote` macro if you don't want the footnotes at the bottom of the page. Also, note that in a thesis the caption goes **above** a table, unlike figures.

Temperature of Oven (C)	Max. Atomic Transmission
440	60.69%
450	52.84%
460	48.44%
470	46.50%
480	40.44%
490	38.12%
500	37.22%

the number of atoms that can be available to use. Too low and the measurement is biased because of fewer atoms to detect or too high and the measurements are just generally inaccurate because the detector can become over-saturated.

The equation to find the flux is $f = \rho v/beam$, with $v/beam$ being the velocity of the atomic beam.

At 450 C the flux was 5.5e13 and at 480 C the flux was 8.1e13.

4.2 Comparison to AOSense Oven

With all this information about the AtomSensor oven, it is panning out to be a good choice. However, it needs to be put against the AOSense oven to truly be meaningful. It needs to perform at least at the same level as the AOSense oven

Consulting both the above probe transmission graphs in Figures 4.3 and 4.4 we can roughly find the transmission the laser has through the vacuum chamber by looking at each temperature's corresponding curve. For all the temperatures displayed for AtomSensors show a lower rate of transmission implying a higher rate of absorption.

For all temperatures and measurements, absorption, and flux, AtomSensors outperforms AOSense. The absorption of AtomSensors is much better indicating that it is either putting out

$$\begin{aligned}\rho =& \frac{1}{V_{\text{int}}} \times \mathcal{P}_{\text{max}} \times \frac{\Omega_{\text{tot}}}{\Omega_{\text{ph}}} \\ & \times \left(\frac{\hbar\omega_0 \Gamma s}{2\sigma_t\sqrt{2\pi}} \int_{-\infty}^{+\infty} \frac{\exp\left(-v_t^2/2\sigma_t^2\right)}{1+4\left(\left|\mathbf{k}\right| v_t/\Gamma\right)^2} dv_t \right)^{-1}\end{aligned}$$

Figure 4.3: This is the equation pulled from a paper [ref] that was used to calculate the atomic density for the flux equation. Most of the constants involved are dependent on the oven that is being interrogated. The transverse velocity is separately dependent on the temperature. This constant can be simplified to 10^9 with little variation in the range we are characterizing in.

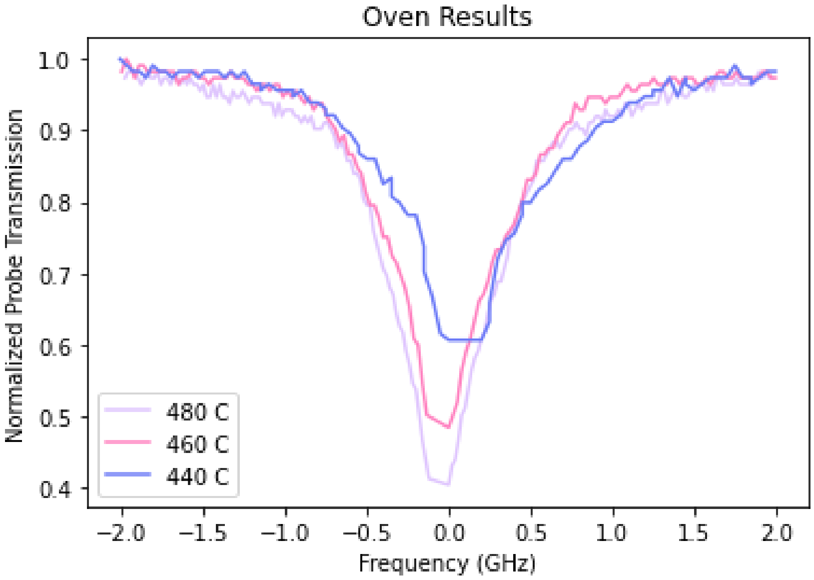

Figure 4.4: This is a graph created from the data we gathered spanning from 440 C to 500 C.

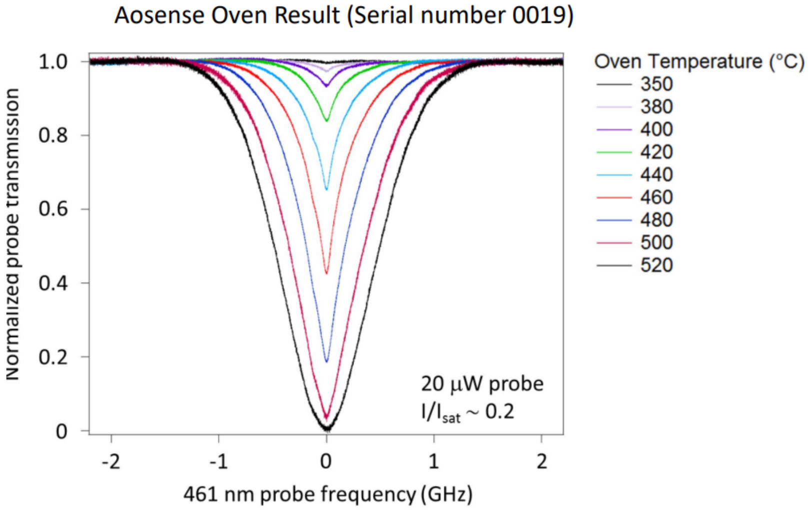

Figure 4.5: The above graph was provided by AOSense as included information about their atomic beam oven. I believe it is an idealized graph not taken from experimental data like ours was.

Table 4.2: Below is a comparison between AtomSensor and AOSense at similar temperatures displaying the corresponding absorption and flux of the ovens and their temperatures. The absorption is measured right outside the nozzle. Assuming the beam has a 2mm width according to the quote. The on-resonance cross-section is used when calculating the flux.

Company	Oven Temp (C)	Max. Absorption	Flux (s^{-1})
AtomSensors	450 C	85.65%	5.5e13
	480 C	94.1%	8.1e13
AOSense	460 C	57.6%	1.6e13
	480 C	81.4%	3.2e13

more Sr atoms or that the atoms being out are less densely packed together The flux is closer to the results provided for AOSense leading me to believe that the atoms are coming out of the oven are less densely packed and instead are more spread out.

Chapter 5

Conclusion

5.1 Discussion

Looking at the results focusing on the comparison between AtomSensor and AOSense, I would say that the AtomSensor oven outperformed the AOSense one. While at a first glance at the two transmission graphs, it might appear that AOSense did better as it at one point reaches 0 transmission or complete atomic absorption. This allows occurs at an oven temperature of 520 C so when comparing the graphs accurately compare not necessarily the shape but the individual curve for each temperature, When this is done we notice that AtomSensor did better than AOSense. I do not want to push the AtomSensor oven to the 520 C limit that AOSense since it was unnecessary for our purposes but I suspect it would reach the same predicted zero transmission/complete absorption perhaps even at a sooner temperature.

Outside of absorption Atom Sensor did better than AOSense in the flux, measurements on the same order of magnitude but AtomSensor ending up with the larger flux. Therefore the Italian oven is outputting strontium atoms at a faster rate than our current oven's rate. This should help with both the accuracy and precision of our clocks. I would like to see a before and after of using this clock in a clock to see if the accuracy and precision do shift before a definitive statement is made. If it is true that the Italian oven makes a significant difference then I would say that these should be implemented after the AOSense has run its course and then continue to buy AtomSensor as a replacement.

5.2 Future Implications

Given how well this AtomSensors's atomic beam oven works I would endorse buying a few more of these ovens to be pre-loaded with strontium so they can be quickly implemented into a system in need of an atomic beam oven, as well as looking into some of their other products as possible cheaper alternatives to any pieces the lab may need. I also feel comfortable telling other groups and labs about this oven option for similar experiments if they are looking to cut costs or looking for an atomic beam oven outside of the traditional companies. However, in dealing with the company and the information that was received with the oven I suggest that any piece of equipment that we purchase from them be characterized in a similar fashion as the oven was. With that in mind, AOSense has more history both as a company as a whole and within the lab, so I would not venture that we should switch completely to AtomSensors. These should be used as a good replacement come the next time one of the oven breaks but I do not believe them to be that great of an improvement to break vacuum on any current experiments in order to swap out existing ovens for this one.

While it is not immediately pushing forward the precision of our current clocks keeping an eye on new developments in both technology and science is what will allow both accuracy and precision to increase on optical clocks. Having options for what parts to use and taking note of what companies are putting on the market is paramount in keeping the clocks sharp ad as accurate as possible. Overall, these AtomSensors ovens are a good choice and tool to have handy in the lab.

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