

Uncertainty in κ_0 for Potassium in ^3He Polarimetry

A thesis submitted in partial fulfillment of the
requirement for the degree of Bachelor of Science
in Physics from the College of William and Mary in
Virginia

by

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April 2019

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Acknowledgments

Special thanks to Professor Todd Averett, my supervisor and guide throughout the process of creating my senior thesis. Also thanks to other professors in the department: Irina Novikova for giving advice and for providing access to the Titanium Sapphire Laser in her lab, Seth Aubin for his continual support of all senior students throughout the year, Jeffrey Nelson for being my advisor through the whole of my journey as an undergraduate in the physics department, and all of the other professors of William and Mary who made my college education one to cherish.

Thanks to all of my classmates, in and outside the physics department, for reminding me to keep my sense of humor and for nurturing the work ethic and love of learning I needed to keep myself moving through all of my academic life. Particularly, thank you Ravn Jenkins, Jack Jackson, Anne Blackwell, Jack Almeter, Adam Abate, George Denny, Austin Kalasky, Jessica Sydnor, and Charles Soulen for the help and support you all provided me and everyone else in the department through the years.

Lastly, thank you to my family for being my bedrock. The excitement, wonder and curiosity you all have is infectious and it was what inspired the direction of my academic career.

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Abstract

Polarized helium-3 nuclei are used extensively in subatomic collision experiments as polarized targets. They can be thought of as little bar magnets that can be aligned parallel or anti-parallel to an external magnetic field, with the end result being a target that can scatter particles from a beam passing through. These experiments require precision at the 2% level to make meaningful observations, so any steps taken to reduce uncertainty in the ^3He polarization is an important step forward in understanding subatomic physics. My research focuses on reducing the uncertainty involving a constant, κ_0 , that has to do with the magnetic interactions between two molecules coming in contact and altering the atomic splitting caused by the external field. The constant is used to obtain the target's polarization from EPR measurement. To this end, I will be exploring various possible ways κ_0 is uncertain in the data due to apparent shifts in a baseline resonance frequency. My work has consisted of creating a new oven and testing its effectiveness. This equipment includes glass cells filled with helium-3, rubidium (Rb), and potassium (K) and ovens used to heat these cells to the point where the metals turn into vapor. I designed a new oven with the intention to provide greater flexibility during experiments, as the previous oven was designed with the cell inaccessible once it was mounted. The new oven was then used to obtain κ_0 for rubidium and potassium.

Chapter 1

Introduction

Nuclear physicists at Jefferson Lab use glass cells filled with polarized helium-3 as nuclear targets during experiments. The helium cells can be polarized through a process known as Spin-Exchange Optical Pumping (SEOP) where a high power laser polarizes potassium and rubidium in the cell, which can then spin polarize the helium nuclei. However, these targets are only useful to the extent to which we can know the fraction of helium that is polarized in the cell. The polarization of ^3He has been, and continues to be, the largest source of uncertainty in the measurements. Uncertainty in the polarization is partly due to uncertainty in a constant involved in calibrating the polarization equation. The purpose of this research is to reduce this uncertainty by understanding the constant κ_0 to a greater degree of accuracy.

Polarization in these cells is determined by measuring the effect the polarized helium's magnetic field has on the hyperfine transitions of rubidium and potassium. κ_0 is a dimensionless constant with temperature dependence that is related to the Fermi Contact Interaction [2] which describes the mechanics of collisions between helium nuclei and alkali metals. This interaction cannot be calculated in detail theoretically due to its complexity, so the following experiment is performed to isolate the interaction in the lab with the goal of determining κ_0 to within 2% error.

Chapter 2

Experimental Setup

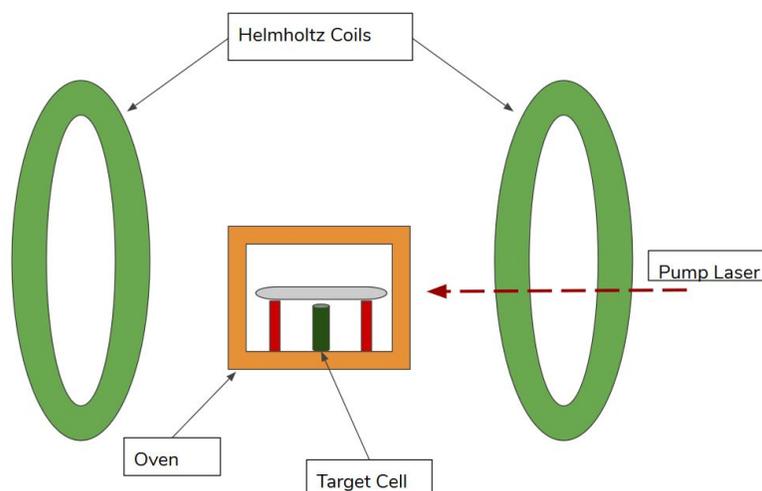


Figure 2.1: Experimental Set Up -- From a horizontal view, the larger coils provide the holding field. The cell is placed at the center of the holding field in the oven. Not shown are two smaller coils used for NMR positioned in front of and behind the oven from this perspective.

A constant magnetic holding field of 20 G is supplied by two Helmholtz coils that are on either side of a support structure. As shown in figure 2.1, this structure consists of a box that contains the cell (oven), a series of holes that allow the oven to be rotated by using pegs on the bottom of the oven to position the oven on a support plate, a hot air delivery system, and two smaller Helmholtz coils to the sides of the oven that are used for Nuclear Magnetic Resonance (NMR) measurements. The use of ferromagnetic components is minimized so that the magnetic field is uniform.

The oven used at the beginning of the experiment needed a hose attached to it so that we could supply heated air and bring the cell inside to temperatures on the order of 190 to 230°C that will vaporize the alkali metals within. We use E-type thermocouples to monitor the temperatures within the cell by taping them to its surface and threading their wires through air-outtake holes on the sides of the oven. Any adhesive we use has to be stable at high temperature, so we use room-temperature-vulcanizing (RTV) silicone and Kapton tape. The cell is mounted with RTV in a rectangular glass tube which is mounted in the oven. A D1 pumping laser is aligned at a 45 degree angle to the holding field so that it is always incident on the entire length of the cell as shown below

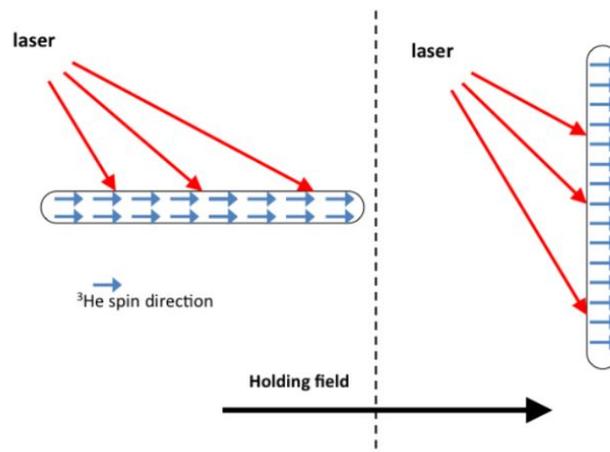


Figure 2.2: Cell Rotation and Laser Incidence -- We want to be able to find the contribution to the hyperfine splitting caused by the helium-3 polarization, but not the geometry of the cell. Rotation of a cylindrical cell lets us detect the changes to helium-3 spin direction relative to the cell orientation while still giving full exposure to the pump laser [2]

The laser is intended to polarize the alkali and subsequently the ^3He . An Electron Paramagnetic Resonance (EPR) coil is in the oven at the base of the casing in the form of a small 10 turn coil of copper wire with the purpose of driving hyperfine transitions of the alkali. At a

resonant frequency, the hyperfine transitions cause emission of D2 light which is detected with a photodiode attached to the oven. The oven also had pegs made from fiberglass so that it can be secured to the base of the holding field structure through holes in a plate that allows the cell to be transverse or longitudinal to the holding field direction.

Adiabatic Fast Passage (AFP) is the process by which we orient the spins of the helium parallel or antiparallel to the holding field. The constant κ_0 is proportional to $B_0 \pm B_{He}$ where B_0 is the holding field strength and B_{He} is the contribution of the helium to the field strength. The helium-3 adds to the field if the nuclear spins are parallel to the holding field and subtracts if antiparallel. The use of AFP to change the spin direction is called a spin flip and we use the technique in conjunction with cell rotation to find κ_0 .

Chapter 3

Theory

We find a cell's polarization by detecting changes in the hyperfine splitting of the alkali metals' energy levels while in a magnetic field. This splitting comes from both the constant holding field we provide and is further split by the spin of the helium-3 which either adds to or subtracts from the total field depending on whether the spins are parallel or antiparallel. The EPR coil supplies a frequency that excites the hyperfine transitions in the electron's ground state, depolarizing the electrons so that they are pumped by the D1 laser. The electrons then fall back to their ground state, emitting D2 light in the process. The orientation of the helium-3 spins alters the resonant EPR frequency for D2 light emission by shifting the hyperfine structure of the energy levels in the alkali. We sweep the NMR RF through the Larmor frequency of helium-3 for 4 seconds in the process of AFP. This is enough time to flip the spins of the helium-3 and so change the resonant EPR frequency. The changes in the hyperfine splitting during a spin flip correspond to a reversal in the helium's alignment with the holding field from parallel to antiparallel orientations, and this causes a change in resonant frequency of D2 emission. The measurement is then repeated with the cylinder alternating between longitudinal and transverse to the holding field. The hyperfine structure of the alkali can be described with the Breit-Rabi Formula for a single valence electron [1]:

$$E_{F=I\pm\frac{1}{2}} = -\frac{h\Delta w}{2(2I+1)} + \mu_B g_I m_F \pm \frac{h\Delta w}{2} \sqrt{1 + \frac{2m_F x}{2I+1} + x^2}$$

$$x \equiv \frac{\mu_B B (g_J - g_I)}{h\Delta w} \quad \Delta w = A(I + \frac{1}{2})$$

Figure 3.1: Breit-Rabi Formula -- Describes the change in energy in the hyperfine levels where I is the spin of the nucleus, J is the angular momentum of

the valence electron, F is the coupling of I with J with quantum number m_F , g_I and g_J are the gyromagnetic ratio of the nucleus and electron magnetic moments to the respective angular momentum quantum numbers, A is the hyperfine splitting constant for either Rb or K, and Δw is the hyperfine splitting in the absence of a magnetic field B .

A change in energy can be attributed to the various factors contributing to the total field including spin exchange and the holding field, which changes the EPR frequency as we move the oven or flip the spins. The experimentally observed changes in frequency in each orientation of the oven correspond to an equation from the two below:

$$\begin{aligned}\Delta\nu_L &= \frac{d\nu_{EPR}(F, M)}{dB} \mu_{He} n_{He} P_{He} \left(\frac{8\pi}{3} \kappa_0 + \left(4\pi - \frac{8\pi}{3} \right) \right) \\ \Delta\nu_T &= \frac{d\nu_{EPR}(F, M)}{dB} \mu_{He} n_{He} P_{He} \left(\frac{8\pi}{3} \kappa_0 + \left(2\pi - \frac{8\pi}{3} \right) \right)\end{aligned}$$

Figure 3.2: Frequency Change Equation -- For longitudinal and transverse orientations respectively. ν_{EPR} is the frequency shift detected through EPR as a function of the quantum number F with substate M which are associated with the hyperfine levels. μ_{He} is the magnetic moment of helium-3, n_{He} is its number density, and P_{He} is the polarization. The numbers in parentheses are geometric parameters related to the magnetic field of $B_0 + B_{He}$. [1]

These equations can be brought together and solved for κ_0 :

$$\kappa_0 = \frac{3(\Delta\nu_L + \Delta\nu_T)}{8(\Delta\nu_L - \Delta\nu_T)} - \frac{1}{8} \quad [1]$$

However, there is a polarization loss every time the nuclei are flipped. Losses during AFP can be minimized by finding an optimum AFP conditions for the system, but the system still does not exhibit a sufficient lifetime to measure κ_0 without correcting for the losses in polarization.

We calculate κ_0 by first finding the mean resonant frequency between the uses of AFP or rotation of the oven, assigning values of f_1 , f_2 , and so on as time increases. We use these averages to find the baseline frequency during each flip:

$$b_1 = \frac{f_1 + f_2}{2}$$

It should be noted that the baseline can only be calculated from shifts in resonance caused by AFP, not from oven rotation. We then calculate the difference between the baseline and resonant frequencies before and after a flip to correct for losses caused by AFP.

$$\Delta f_{BLn} = f_L - b_n$$

$$\Delta f_{ATn} = f_T - b_n$$

Where subscripts B and A refer to a difference before or after flip n , and subscripts L and T refer to the cell's orientation to the field. These values can then be further manipulated into the following:

$$A_1 = \frac{\Delta f_{AL} - \Delta f_{BT}}{\Delta f_{AL} + \Delta f_{BT}}$$

$$A_2 = \frac{\Delta f_{BL} - \Delta f_{AT}}{\Delta f_{BL} + \Delta f_{AT}}$$

Here A_n refers to the asymmetry between flips in either oven orientation [1]. The average of the two results in a constant, $A = \frac{A_1 + A_2}{2}$, which, if we approximate our system to be an infinite cylinder we can substitute it into our equation for κ_0 to get:

$$\kappa_0 = \frac{3}{8A} - \frac{1}{8} [1]$$

This method of analysis means we need two flips, one transverse and one longitudinal to calculate κ_0 once. The uncertainty persisted in this data because there are visible shifts in EPR frequency that are not caused by AFP in our measurements.

Chapter 4

System Corrections

The first thing I did before I began moving towards my experiment was become acquainted with the process of collecting spin-flip data, shown in figure 4.1 below.

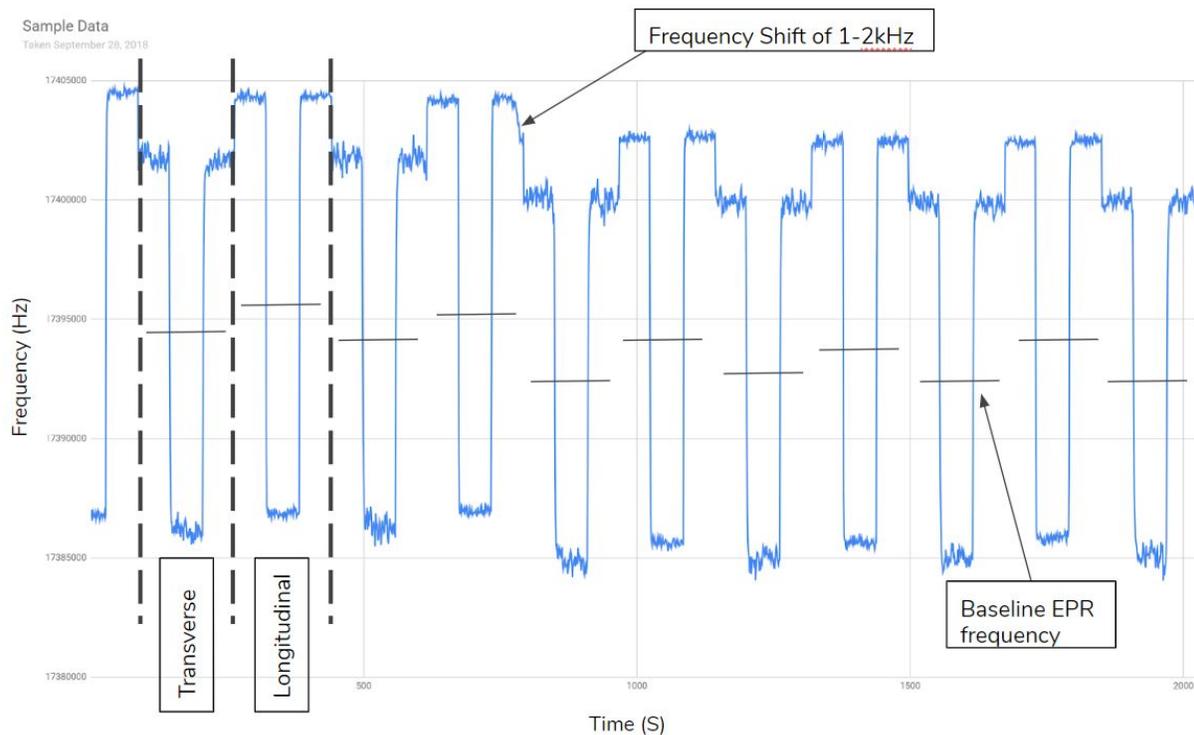


Figure 4.1: Initial Sample Data -- September 28, 2018 -- This sample demonstrates the unwanted shifting observed in the old oven before repairs were made: the baseline frequency is changing when it should remain constant (illustrated by horizontal black lines). Each plateau represents the resonant frequency between AFP sweeps for 40 seconds.

My goal was to design and create my own oven that could be more easily opened for access to the mounted cell for alterations or maintenance.

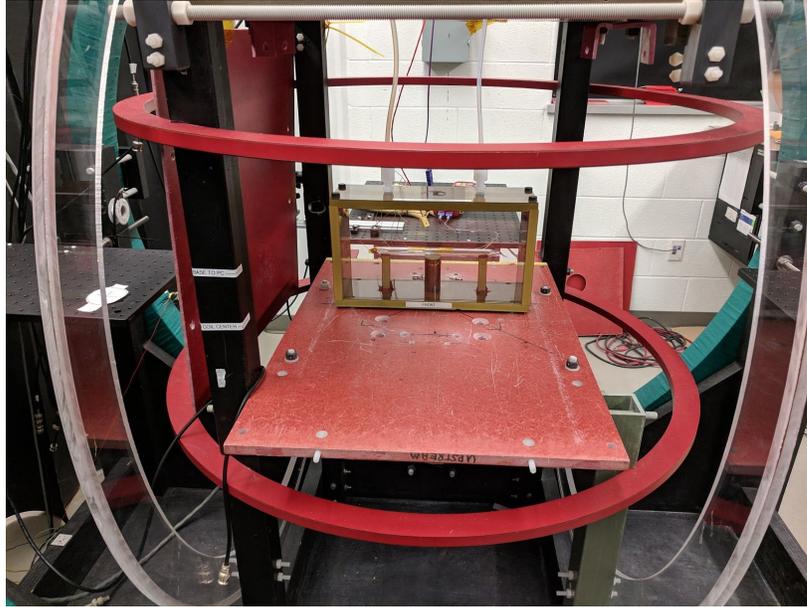


Figure 4.2: Mounted New Oven -- shown in the transverse orientation. Photodiode is not yet attached and will be put on top of the oven over a glass viewing window

This new oven is made from Torlon, a heat resistant plastic, and has a removable top and glass panels so that I can make changes to the interior of the oven as needed as I look at different causes for the uncertainty in κ_0 . It also uses a cell with less alkali because we believe it will decrease the likelihood of condensation on the cell walls. The previous oven had been observed to have condensed alkali metal in the path of the pumping laser. The concern with the condensation is that the alkali could become polarized and alter the local magnetic field so that it is no longer constant with cell orientation and therefore skews our results. Besides these three distinctions, it is functionally identical to the old oven: the cylindrical cell is mounted with RTV, has E-type thermocouples, and has pegs coming out of its bottom for securing it to the holding structure.

I also replaced the glass casing in the old oven and reduced the condensation on the inside of the cell involved. I did this by taking the oven apart entirely, and placing the cell in a

oven with uneven heating so that a tip of the cell was at a relatively cool temperature compared to the rest, which is still hot enough to vaporize the alkali metal. It is ideal to have the metals concentrated at one end of the cylinder, with the alkali metal only being at other locations in the cell while vaporized. Preliminary tests of the new oven demonstrated a comparable signal with smaller noise, resulting in much clearer data for further troubleshooting and data collection.

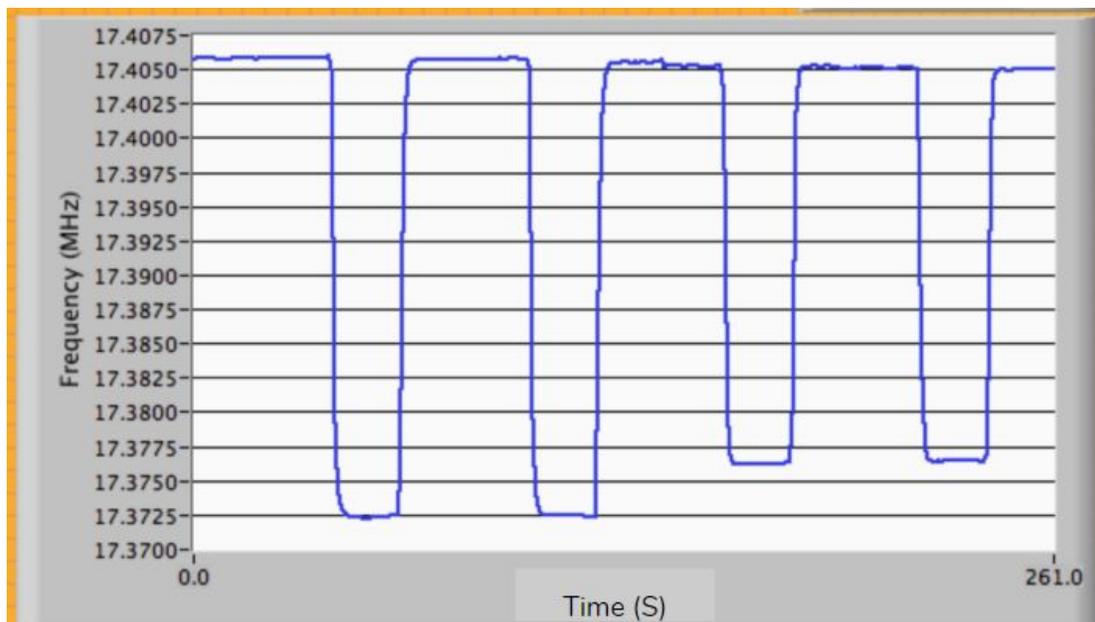


Figure 4.3: New Oven Data -- December 7, 2018 -- the first two flips are when the cell is in the longitudinal orientation and the last two are in the transverse orientation. This serves as a much more clear illustration of the change in the baseline frequency.

The data with the new oven showed that the baseline shifts are remaining in the system despite the changes in experimental setup. A magnetometer sensitive to 1 milligauss was set up near the experiment in order to detect shifts in the field coming from sources outside of the experiment. All ferromagnetic objects were removed or replaced inside the lab and it was discovered that the elevator outside the lab was shifting frequency by 1 kHz as it changed floors. We got permission to park the elevator in the basement of the building while recording data.

Chapter 5

Data Collection and Analysis

In order to know the accuracy of our system, we set out to measure κ_0 for rubidium- before finding it for potassium because rubidium has been used in target cells for much longer than potassium and so its κ_0 is known with greater certainty. This exercise can tell us if our system is able to effectively gauge the effect. The number found by Mikhail Romalis during his dissertation [1] at a temperature of 180°C was $6.21 \pm 1\%$. Below is the data collected in this measurement and each κ_0 value for the measurement duration.

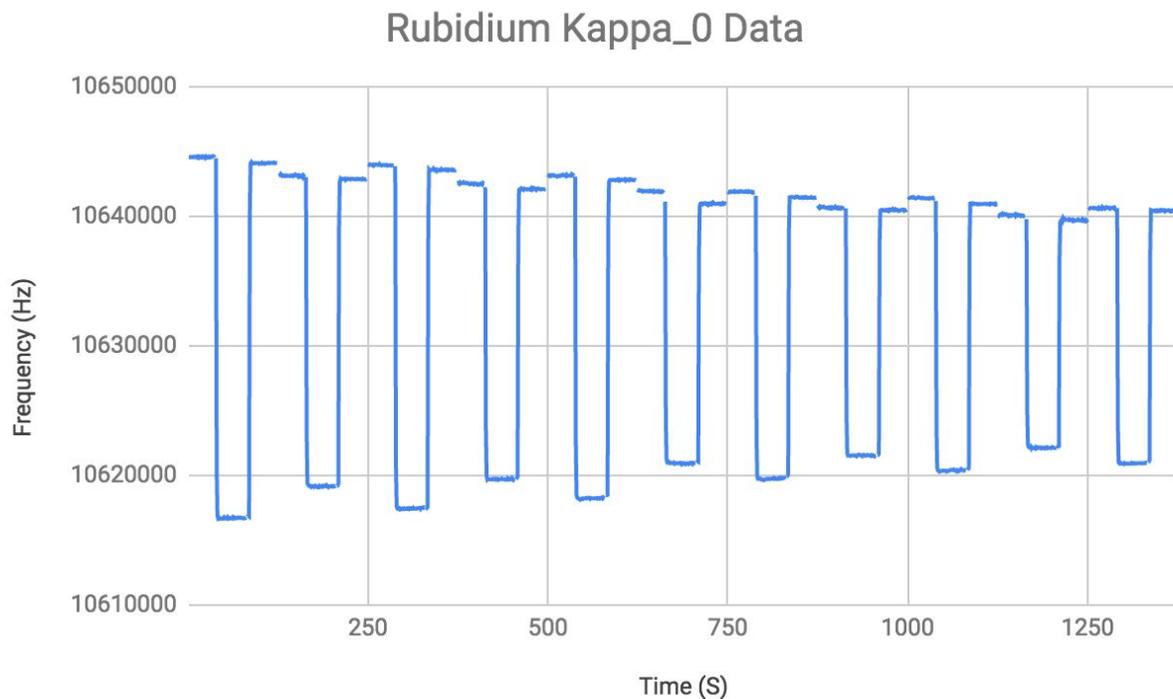


Figure 5.1: Rubidium κ_0 Data: file AFP_2019_03_14_12_04.dat

The following is the process of calculating κ_0 : first we get the average frequency at each plateau for a group of three adjacent spin flips for a total of 9 averages:

	f_1	f_2	f_3
Flip 1	10644586	10616731	10644112
Flip 2	10643132	10619180	10642881
Flip 3	10643964	10617473	10643588

Then we find baseline frequency for each AFP by averaging f_1 to f_2 and f_2 to f_3 for 6 numbers:

	b_1	b_2
Flip 1	10630659	10630422
Flip 2	10631156	10631031
Flip 3	10630719	10630531

Next we calculate A_1 and A_2 to then get A and finally a measurement of κ_0 :

$A_1 = \frac{\Delta f_{AL} - \Delta f_{BT}}{\Delta f_{AL} + \Delta f_{BT}}$	$A_2 = \frac{\Delta f_{BL} - \Delta f_{AT}}{\Delta f_{BL} + \Delta f_{AT}}$	$A = \frac{A_1 + A_2}{2}$	$\kappa_0 = \frac{3}{8A} - \frac{1}{8}$
0.0668	0.0556	0.0612	5.46

We can repeat this process for every set of three spin flips. From this data we can calculate an average κ_0 for the rubidium set: 5.96 with a standard deviation (σ) of 0.25. We can then divide σ by the average κ_0 to find the percent uncertainty: 4.19%. The baseline shift observed in this data set is approximately 600 Hz. The uncertainty is in part caused by our small data set, and so this test does show that our system is likely to be running properly. We then went on to measuring with potassium which has a projected value at 210°C that is 6.12 [1]:

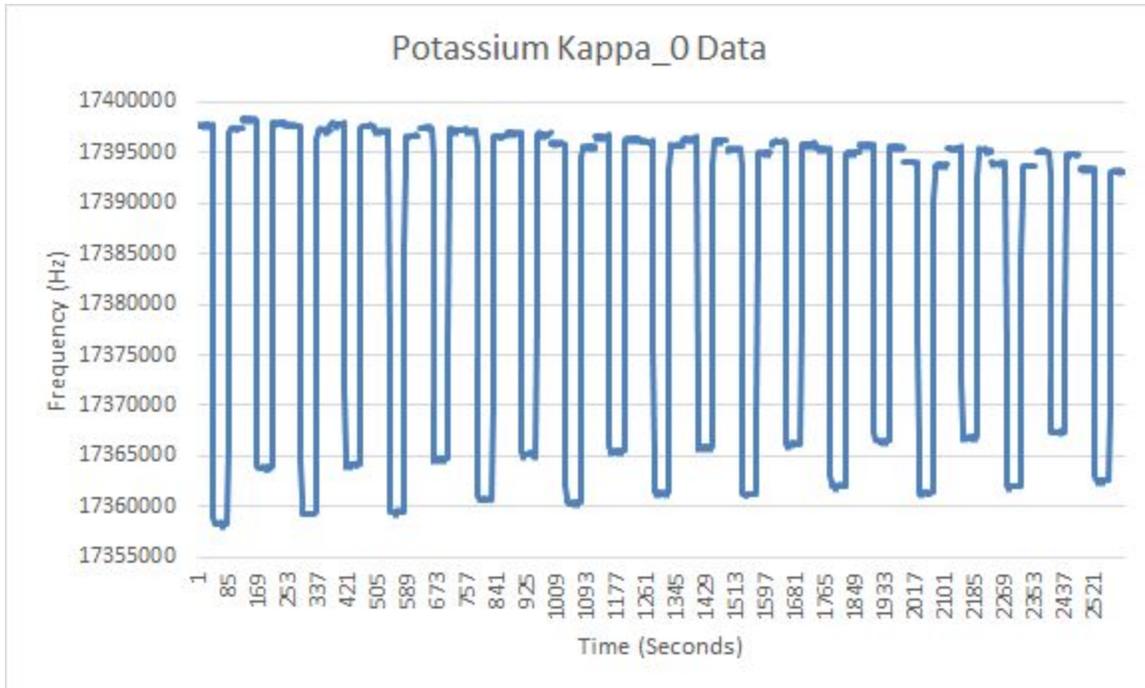


Figure 5.2: Potassium κ_0 Data: file AFP_04_11_12_39.dat

Through the same procedure as with the rubidium, we can find a value for potassium. This data has an average for potassium's κ_0 of 6.15, a σ of 0.082, an uncertainty of 1.33%, and an average baseline frequency shift of 500 Hz.

Chapter 6

Conclusion and Outlook

The data we recorded for potassium exceeds expectations for the system, as our goal was to get uncertainty below 2%. There are many factors that can hamper the experiment such as nearby metal objects, uneven heating of the cell, and atmospheric perturbations due to solar wind. The shift in accuracy from our rubidium measurements to the potassium experiment potentially had to do with the temperature of the system because the amount of vaporized alkali plays an important role in keeping the polarization up between flips, so an oven running at 180°C will have much steeper losses than one run at a 210°C or higher.

There are still a lot of potential issues to investigate before we know the lab has minimal systematic errors with regards to κ_0 , and more measurements with potassium to make before we can say we are closer to knowing the value for the constant. Our efforts this year have shown that we are closer to achieving this goal, and that it will be definitively settled in the near future.

References

- [1] M. Romalis, Dissertation, Princeton University, 1997
- [2] N. Penthorn, Senior Honors Thesis, College of William and Mary, 2014