

To the Graduate Council:

I am submitting herewith a dissertation written by Love Richburg entitled “Detector Cooling, Temperature Dependent Studies, and Waveform Analysis for the Nab Experiment.” I have examined the final paper copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Physics.

Dr. Nadia Fomin, Major Professor

We have read this dissertation
and recommend its acceptance:

Dr. Nadia Fomin

Dr. Tova Holmes

Dr. Jamie Coble

Dr. Miguel Madurga

Accepted for the Council:

Dixie L. Thompson

Vice Provost and Dean of the Graduate School

To the Graduate Council:

I am submitting herewith a dissertation written by Love Richburg entitled “Detector Cooling, Temperature Dependent Studies, and Waveform Analysis for the Nab Experiment.” I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Physics.

Dr. Nadia Fomin, Major Professor

We have read this dissertation
and recommend its acceptance:

Dr. Nadia Fomin

Dr. Tova Holmes

Dr. Jamie Coble

Dr. Miguel Madurga

Accepted for the Council:

Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Detector Cooling, Temperature Dependent Studies, and Waveform Analysis for the Nab Experiment

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Love Richburg

December 2025

© by Love Richburg, 2025
All Rights Reserved.

dedicated to the broken ones

Acknowledgements

None of this would have been possible without the Nab collaboration, my friends, and my family. It is not possible to exhaustively cover the role that each of these people has played, so I will offer highlights.

My research advisor, Nadia Fomin, who recruited me into the research group when I was unsure of what research to pursue and never let me quit even though I tried. She also constantly encouraged me to leave my comfort zone and ask people around me questions. I am so thankful for that because half of the people on this list would not be here if not for that, and I would not have nearly as many exciting things to show.

Josh Pierce, who talked me through how things work in a way that resonated with my brain.

Seppo Penttila, who was always open to offer advice and encouragement. Also, I would not have found anything at the beamline my first year without his help.

John Ramsey, the chief engineer, who was always happy to offer support whether it was in solving engineering problems or just checking in on me as a fellow human.

Leah Broussard, my SCGSR mentor, who helped me navigate the people and the unexpected twists of science.

Russell Mammei, who always offered support when I was preparing for conference presentations and would easily have hour long conversations with me about life that left me feeling uplifted.

Wolfgang Schreyer, who relieved me of being the only cooling system expert around.

Josh Hamblen, who provided critical simulation support for the proton detection efficiency analysis project.

Stefan Baeßler, who was always willing to deep dive on the minutiae with me.

Jason Fry, who traded places with me, he started at ECU my first year at UT. He also spreads positive energy wherever he goes, and I am happy to have the opportunity to work more closely with him in the near future.

Frank Gonzalez, who was the first post doc I worked with closely on Nab, and was consistently encouraging when I bounced thoughts off of him.

Hunter Presley, read my thesis and gave me so many super helpful comments (literally you would be suffering way more if he had not read it).

Nick Macsai, who helped get the heater for the thermal profile measurement ready on a tight timeline.

Di'Arra Mostella, who joined Nadia's group at the same time as me, and worked on the detector cooling system with me during covid times.

Jin Ha Choi, one of the first (non-UT) Nab grad students that I met. It feels like we've been in it forever. He always helped bridge the gap between me and the rest of the detector team when I felt like an outcast.

August Mendelsohn, who helped me learn how to build "The Sandwich."

Austin Nelsen, another one of the original (non-UT) Nab graduate students that I met at ORNL. We talked about the cooling systems for the detectors the preamplifiers together.

Andrew Hagemeyer, who is the "Mini-Chamber" expert, and offered me invaluable advice while I was working with it.

Arlee Shelby, who I only met recently, but I already have massive respect for the work she is doing with the detector dead layer characterization, RSIS, and detector calibration efforts. I am always happy to see her around.

Zachary Garman and Holden Pate, who were my mentees, I appreciated the opportunity to teach them, and their support on various efforts.

Isaiah Wallace, we always had fun conversations about what we were working on, bounced ideas off of each other, and he made so many pictures for me.

Rebecca Godri, who became my friend in the early days of us working together in Nadia's group. I would not have made it through these past few years without all of her moral support.

Heather Garland, who I met because of a zoom class during covid times, and who I am now abundantly grateful to have as my friend. She cheered me on during the late nights leading up to the completion of this document.

Harini Radhakrishnan, who despite not working in the same research group as me, or even in the same building, still managed to become my friend. She offered me so much support during the writing stages.

Kaley Outlaw, who has always stubbornly believed in me (more than I did at times). Her persistent confidence in me uplifted me on some of my lowest days.

Mark Ciocca, who has brought so much warmth into my life. Without him, I would have starved to death during in these past few weeks of writing.

Henry Richburg, Darby Campbell, Renee Richburg, Hannah Richburg, Rosalie Richburg, Amy Richburg, and William Richburg ← My siblings, I literally would not be here without these people.

Otto, my new baby nephew, who inspired me to try to finish my PhD a little faster.

My mother, Lisa Richburg, who always listened and offered support, and celebrated all the small wins with me. I would not be here without her either (obviously).

My father, Robert Richburg, who used to dream with me about what it would be like to earn a PhD. He used to wax about how you had to discover something new—something no one else had ever thought of before, and we would brainstorm all kinds of ideas. I wish I could tell him about what I ended up doing.

Pooka, who adopted me in 2018. She is my heart and soul doggie, and has seen me through some of the darkest moments.

"Pretty much every experiment I've ever worked on has been held together by duct tape and dreams" –Leah Broussard

Abstract

The Nab experiment, currently (2025) taking data on the Fundamental Neutron Physics Beamline at the ORNL Spallation Neutron Source, uses an unpolarized neutron beam to precisely measure two of the free neutron beta decay correlation parameters to probe physics beyond the Standard Model. The electron-neutrino correlation coefficient, a , will give us access to investigate CKM unitarity, and the Fierz interference term, b , will enable us to put bounds on the existence of scalar and tensor currents in the weak interaction. We aim to measure a with unprecedented precision ($\Delta a/a \approx 1 \times 10^{-3}$) to enable a first row CKM unitarity check on the same level of precision as those made with super-allowed fermi decays. The Nab experiment uses two highly-segmented, thick, large-area silicon detectors at either end of a 7 m tall magnetic spectrometer to measure the electron energy and the proton time of flight, which can be used to construct nearly the full phase space of neutron decay, and make determinations of a and b .

This work encompasses the finalization of the detector cooling system design, implementation, and characterization. The detector cooling system is now surpassing design goals. It is capable of cooling the upper detector to ~ 100 K and the lower detector to ~ 115 K with better than ± 0.5 K stability. The system is also capable of stabilizing detector temperatures over a dynamic range from the minima up to room temperature, so it is well-suited to support temperature dependent studies. This feature was utilized to study the temperature dependent gain shift in three of the Nab detectors. Waveform analysis of ^{207}Bi source signals was carried out to

show that the gain shifts on each of the studied detectors was below the suggested requirement of 1×10^{-4} for ± 0.5 K. These waveform analysis techniques were then applied to investigate the proton detection efficiency. A method for estimating the proton detection efficiency's impact on $\Delta a/a$ was explored, the $\Delta a/a$ for one pixel was reported, and the results will be useful to future analyses.

Table of Contents

1	Introduction	1
1.1	Formal Welcome and Setting of Expectations	1
1.2	Nuclear/Neutron Decay History	1
1.3	Standard Model	5
1.3.1	What makes up the SM?	6
1.3.2	SM Interactions	8
1.3.3	CP Violation	10
1.3.4	The Electron-Neutrino Correlation Coefficient in the SM	11
1.4	Free Neutron Beta Decay Experimental Status	14
1.4.1	Status of Neutron Lifetime Measurements	15
1.4.2	Status of λ Measurements	16
1.4.3	V_{ud} Values	16
1.4.4	Outlook	17
2	Nab Experiment	18
2.1	Getting into Nab	18
2.2	The Systematic Uncertainties	23
2.3	The Neutron Beam	24
2.3.1	Beam Polarization	26
2.4	The Magnetic Spectrometer	27
2.4.1	High Voltage Electrodes	29

2.4.2	The $E \times B$ Electrode	29
2.5	The Detector Systems	29
2.5.1	Silicon Detector Principles of Operation	30
2.5.2	Thickness	32
2.5.3	Segmentation	32
2.5.4	“The Sandwich”	34
2.5.5	Detector Armor	36
3	Nab Detector Cooling System	38
3.1	Motivation and Challenges for Cooling the Nab Detectors	38
3.2	Nab detector cooling system design	41
3.3	Temperature Sensor Locations	46
3.4	Performance and Discussion	47
3.5	Heat Loads	54
3.6	Long Term Stability	58
4	Temperature-Dependent Detector Studies and Analysis	59
4.1	Electron-Hole Pair Creation Energy	59
4.2	The Anatomy of a Waveform	62
4.3	Analysis for September 2023 Source Studies	64
4.3.1	Setup	64
4.3.2	Analysis and Discussion for September 2023 Data	66
4.4	Analysis for May 2025 Source Studies	69
4.4.1	Setup	69
4.4.2	Plots and Discussion for May 2025 Data	69
4.5	Future Work	72
5	Nab Detector Thermal Profile	79
5.1	Initial Mini-Chamber Thermal Profile Measurement	81
5.1.1	Thermal Radiation Shield for the Mini-Chamber	84

5.1.2	Results of the Initial Thermal Profile Measurement	85
5.2	Final Thermal Profile Measurement	86
5.2.1	FET Pogo Pin Board Nichrome Wire Heater	87
5.2.2	Calibrated Platinum RTD for the Final Thermal Profile Measurement	88
5.2.3	Cooling Considerations for the Final Thermal Profile Measurement	90
5.2.4	Results of Final Thermal Profile Measurement	90
6	Systematic Uncertainty in the Electron Neutrino Correlation Coefficient Due to Proton Detection Efficiency	93
6.1	Method	97
6.2	Analysis and Discussion	99
6.2.1	Future Work	109
7	Conclusion	110
	Bibliography	114
	Vita	123

List of Tables

2.1	Comparison of most updated a measurements from aSPECT and aCORN to Nab projection	19
3.1	Temperatures at different positions in the system	51
4.1	Approximate slopes of ϵ_{ph} vs. temperature	61
4.2	September 2023 summary of temperature dependent data runs	66
4.3	May 2025 summary of temperature dependent data runs for upper detector	70
4.4	May 2025 summary of temperature dependent data runs for lower detector	70
4.5	May 2025 Summary of Slopes of Mean vs Temperature Plots for Upper Detector	70
4.6	May 2025 Summary of Slopes of Mean vs Temperature Plots for Lower Detector	71
4.7	Gain variation calculated for a 0.5 K change	72
5.1	Initial thermal profile measurement results	85
5.2	Final thermal profile measurement temperature ranges	92
5.3	Final thermal profile measurement temperature offset between detector face and armor	92

List of Figures

1.1	Apparatus for Neutron Decay Measurement at X-10	4
1.2	Standard Model of Particle Physics	7
1.3	Feynman diagram of neutron decay	11
1.4	Status of λ	16
1.5	Status of V_{ud}	17
2.1	Proton phase space (26)	20
2.2	Neutron decay	22
2.3	Table of Uncertainties from (26).	23
2.4	Proton beam on target at SNS	25
2.5	Beamline 13 Configuration	26
2.6	Beamline 13 Configuration	27
2.7	Nab magnetic spectrometer (26)	28
2.8	Cut view of the detector system schematic (26).	30
2.9	Nab silicon detector geometry	33
2.10	“The Sandwich”	34
2.11	Exploded detector electronics	35
2.12	Rogers board and the ohmic face of a detector	35
2.13	Detector armor	36
3.1	Big picture layout of the cooling system equipment location relative to the Nab apparatus	40

3.2	Detector cooling system flow diagram	42
3.3	Detector cooling system insulation vacua	43
3.4	Primary heat exchanger	44
3.5	Nab detector cooiling transfer line high voltage feed through	44
3.6	Cooling line connection to the detector system	45
3.7	Key components within the detector system	46
3.8	Cold head and primary heat exchanger with temperature sensor location labels	47
3.9	Cut view of detector system with temperature sensor location labels .	48
3.10	Plot of inactive temperature stability for the upper detector system .	49
3.11	Plot of temperatures accessed by the cooling system during a dynamic temperature study	50
3.12	Plot of temperatures for upper detector 6/21 - 6/22 2023	52
3.13	Plot of temperatures for lower detector 6/20 - 6/21 2023	53
3.14	Plot of cooling system temperatures used in heat load calculations . .	55
3.15	Cooling capacity for Sumitomo cold heads	56
3.16	Heat load diagram	57
3.17	Plot of temperatures for upper detector November 2024	58
4.1	Summary of temperature dependent electron hole pair creation energies in silicon from literature	60
4.2	Example waveform	63
4.3	Map of 2023 Pixels for 207-Bi study	65
4.4	Gaussian fits to temperature dependent peak gain shift	67
4.5	Plotted summary of gain shift with temperature	68
4.6	Gaussian fits to 207-Bi peak	74
4.7	Parameters of gaussian fits to temperature dependent peaks	75
4.8	Gaussian fits to 207-Bi peak	76
4.9	Parameters of gaussian fits to temperature dependent peaks	77

4.10 Parameters of gaussian fits to temperature dependent peaks for pixel 1063 and 1066	78
5.1 Thermal profile for detectors produced in Ansys by John Ramsey . .	80
5.2 Back face of a detector	80
5.3 Mini-Chamber Set Up	82
5.4 Thermal anchoring for thermal profile measurement	82
5.5 Position of temperature sensors for the initial thermal profile measurement	83
5.6 Mini-Chamber radiation shield	84
5.7 Position of the fourth temperature sensor which was installed for the final thermal profile measurement	87
5.8 FET pogo pin board nichrome wire heater	89
5.9 Plot of temperatures during final thermal profile measurement	91
6.1 Commissioning Tear Drop 2023	94
6.2 Commissioning Proton Energies 2023	94
6.3 Commissioning Tear Drop 2024	95
6.4 Commissioning Proton Energies 2024	96
6.5 TOF vs proton energy for Run 7244	97
6.6 Run 7244 Proton Events on Pixel 51	100
6.7 Pixel 51 Location	101
6.8 Simulated proton efficiency plots	102
6.9 Simulated relationship between energy dependent detection efficiency and uncertainty on a vs. threshold	104
6.10 Gaussian fits to Run 7244 proton peak on pixel 51	105
6.11 Run 7244 Proton hit energy vs. $1/\text{TOF}^2$	106
6.12 Run 7244 estimated proton hit energy vs. initial proton energy	107
6.13 Run 7244 estimated proton detection efficiency vs. initial proton energy	108

Chapter 1

Introduction

1.1 Formal Welcome and Setting of Expectations

Welcome to my thesis dissertation.

You may be here for the potentially world-definition-changing physics that the Nab experiment aims to measure, or perhaps just because you are a person who agreed to be on my committee. I stayed for the excitement that is a high-precision experimental endeavor, so that is what the majority of this document will address. We do not get to produce results every day, but, we do get to think about how the minute details of the experimental setup will impact the final results constantly. If you were hoping for a dry, one hundred page document, this is not for you! (Mostly because it is a dry (insert actual page count here) document, but I can at least pretend that I have managed to make the task of reading this less monotonous!)

1.2 Nuclear/Neutron Decay History

Henri Becquerel discovered nuclear decay in 1896 when he observed a blackening of photographic plates that were unintentionally left near uranium-sulfide crystals. Although Becquerel made the initial discovery of radioactivity, much of the work in the following years to identify and isolate radioactive elements produced in the decay

of uranium was attributed to Pierre and Marie Curie. Ernest Rutherford also started researching what were then termed “Becquerel” rays in 1899. Years later, the series of experiments that he and his students performed led to the famous gold foil experiment, and in 1911 he published the discovery of the nucleus (37).

Rutherford’s interest in nuclear physics did not end there. In 1920, he published the “Bakerian Lecture: Nuclear constitution of atoms” wherein the first suggestion of what we would later come to know as the neutron was published (52). Here, Rutherford discusses a series of experiments that involved bombarding nitrogen and oxygen with alpha particles. He claimed to observe the liberation of a mass 3, charge 2 particle from the O and N nuclei by the alpha collision. Later, Rutherford’s student, Patrick Blackett showed through the use of a cloud chamber that the nitrogen atoms were actually integrating the alpha particles to become oxygen atoms and the emitted particle was a proton (the first observation of transmutation) (12). Despite not having the correct interpretation, thinking about what implications his observations could have on the “constitution of nuclei” led Rutherford to the concept of the neutron. He considered the emitted particle to be three hydrogen nuclei bound together with one electron and hypothesized that if such a thing were possible it would be likely for there to exist a hydrogen nucleus bound tightly to an electron such that it formed a neutral particle (52). This was the first description of the neutron, and it existed only as a concept for quite some time.

A decade later, in the early 1930s, Walther Bothe and Herbert Becker observed energetic radiation coming from beryllium that had been bombarded with alpha particles. They speculated that this might be some form of gamma radiation. Irene Joliot-Curie (daughter of Marie Curie) and Frederic Joliot-Curie performed similar experiments and found that passing the radiation through hydrogen increased the levels of radiation. James Chadwick noted that the initial gamma radiation hypothesis failed to explain the observed energy. If instead one supposed that the radiation was a neutral, massive particle, conservation of energy and momentum would be satisfied. With this argument, James Chadwick discovered the neutron (17) (18).

The initial explanation of the neutron did not suggest that it could decay. In Rutherford's picture, a neutron was a bound state between a hydrogen nucleus (a proton) and an electron, which would imply that its mass was too small for it to spontaneously decay. In addition, Chadwick's early neutron mass measurement revealed a similar mass to that of the proton, again not enough mass for it to be unstable (17). Around the same time, Heisenberg and Iwanenko questioned the Rutherford picture of the neutron. They suggested that it was an elementary spin $1/2$ particle, and one of the two main constituents of nuclei, the other being protons (rather than protons and electrons as Rutherford envisioned). Still, there was no evidence that supported free neutron decay (57).

Just a few years after Chadwick's discovery of the neutron, in 1935, Chadwick and Maurice Goldhaber published a paper on their investigation of the neutron mass which revealed the mass to be either 1.0084 or 1.0090 amu depending on whether they used an average of older disintegration values or the results of a newer measurement as inputs for hydrogen and deuterium masses. Their work determined the neutron mass by impinging gamma rays on deuterium. The cross section of interaction was constrained by the binding energy of the deuteron. Once they had the binding energy of the deuteron, they used that along with the masses of hydrogen and deuterium to calculate the neutron mass. The results indicated that both of their possible neutron masses were heavier than the hydrogen atom, marking the first evidence that supported free neutron decay. Furthermore, they posited that in order for spin to be conserved, one of the neutron's decay products must be a low-mass, spin $1/2$, neutral particle, a neutrino (19).

The first observation of neutron beta decay was at the X-10 Graphite Reactor at Oak Ridge National Laboratory around 1950. (There was an early record of the measurement in spring of 1948 in the American Physical Societies proceedings (6), but the final results were submitted by Snell and his collaborators for publication on March 6, 1950 (55). Just one week before John Michael Robson's neutron decay results from the Chalk River pile in Canada (51)). The graphite reactor was designed

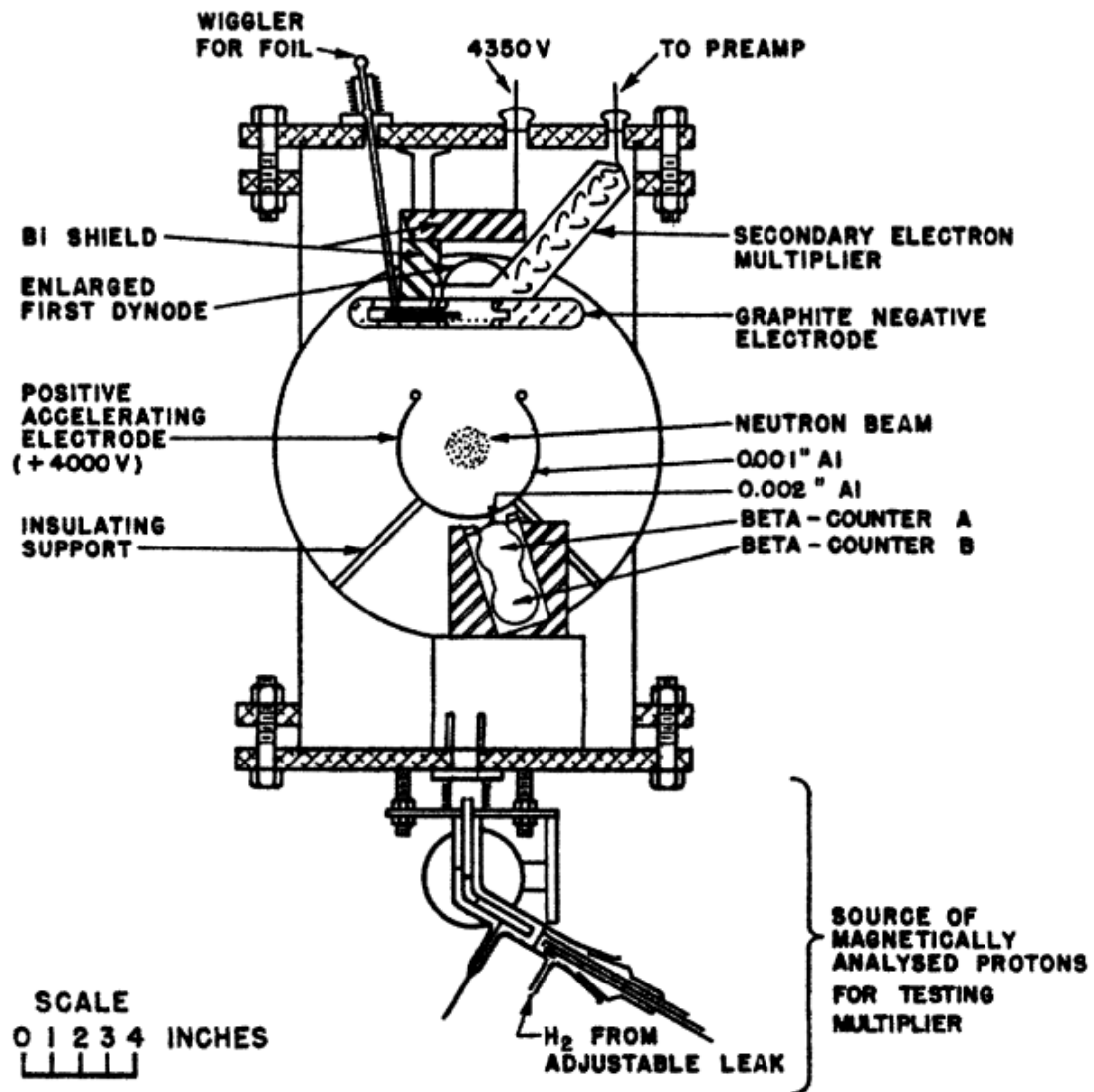


Figure 1.1: This is the apparatus that was used in the first neutron decay experiment at the X-10 Graphite Reactor (55).

for the production of plutonium. It utilized neutrons from the fission of U-235 to convert U-238 into Pu-239 with graphite as the moderator. This reactor was one of the first sources with sufficient flux of slow neutrons to support the observation of free neutron decay (57). The work of Snell et al. to make the first observation of free neutron decay was possible because there were channels cut through the concrete shielding that surrounded the graphite reactors to allow neutrons to pass through.

Before entering the measurement apparatus, the beam passed through a magnetic field to clear out secondary electrons from the graphite reactor(6). Protons and electrons were observed in coincidence and which led to the conclusion that neutrons must decay into those products. Snell et al. also recognized that they had not made a precise measurement of the neutron lifetime, but they still put a range on the possible neutron half-life of 10 to 30 minutes. Achieving a precise neutron lifetime measurement is non-trivial. Early challenges due to the neutral charge of the neutron making it difficult to store and detect, have been met with the development of a field worth of techniques. Now, discrepancies between results from different measurement techniques (discussed in a little more detail in Section 1.4.1) have led to an ongoing dilemma. So, seventy years later we are still studying free neutron beta decay.

1.3 Standard Model

The theory that we use today to describe free neutron decay is the Standard Model (SM) of particle physics. It is a powerful model that describes the electromagnetic, strong, and weak forces. This model is the culmination of years of work by many scientists. It is an exemplary demonstration of modern progress in physics where the credit is spread over many individuals instead of just being owed to one genius. Collaboration is necessary because modern problems in physics require a massive amount of resources in the form of time, money, and thinking people. The SM describes electromagnetic interactions between charged particles, the strong force which confines quarks, and the weak force which governs particle decay via a single (several page long) Lagrangian.

While the SM is an elegant solution to particle interactions and there has been a lot of success with using it to predict and describe particle behavior, it does have some limitations. It does not address gravitational interactions between particles at all. Of course, the strength of gravity between the fundamental particles described in the SM is very small compared to the strength of the electromagnetic force, the

strong force, and the weak force. Neutrinos were initially modeled as massless within the SM, but after neutrino flavor oscillation due to different neutrino masses was observed, several terms were added to account for it. Another weakness of the SM is that it does not address dark matter or the baryon asymmetry in the observable universe. The SM is an extremely useful tool, but it is clear that physics beyond the SM (BSM) must also exist to fully describe reality. This results in a call for both a better understanding of the SM parameters and an investigation of BSM physics.

1.3.1 What makes up the SM?

This subsection and the following heavily reference (13). The SM describes particle interactions in the framework of quantum field theory (QFT). In QFT, fields are the fabric of reality and the particles that we observe are excitations in these fields. Developing a quantum field theory for something is typically done by writing out a Lagrangian or Hamiltonian for the field and then treating it as a quantum mechanical system. The SM is represented by the gauge group:

$$SU_c(3) \times SU_L(2) \times U_Y(1). \tag{1.1}$$

Particles of the SM appear as fields in the SM Lagrangian. Within the SM the particles can be grouped into two categories, those that make up the matter of the system (fermions) and those that bring about interactions or act as force carriers (bosons).

Fermions are spin 1/2 particles and can be broken down into two subcategories, quarks and leptons. Within each group of fermions there are three generations, each subsequent generation is more massive than the previous. The masses of particles, which are primarily determined by experimentation, provide extremely important boundary conditions for the SM. There are six quarks and six antiquarks. The six quarks are shown in purple in Fig. 1.2 and their antiquark counterparts are represented by the same symbols with the addition of a bar over them. There are also six leptons

Standard Model of Elementary Particles

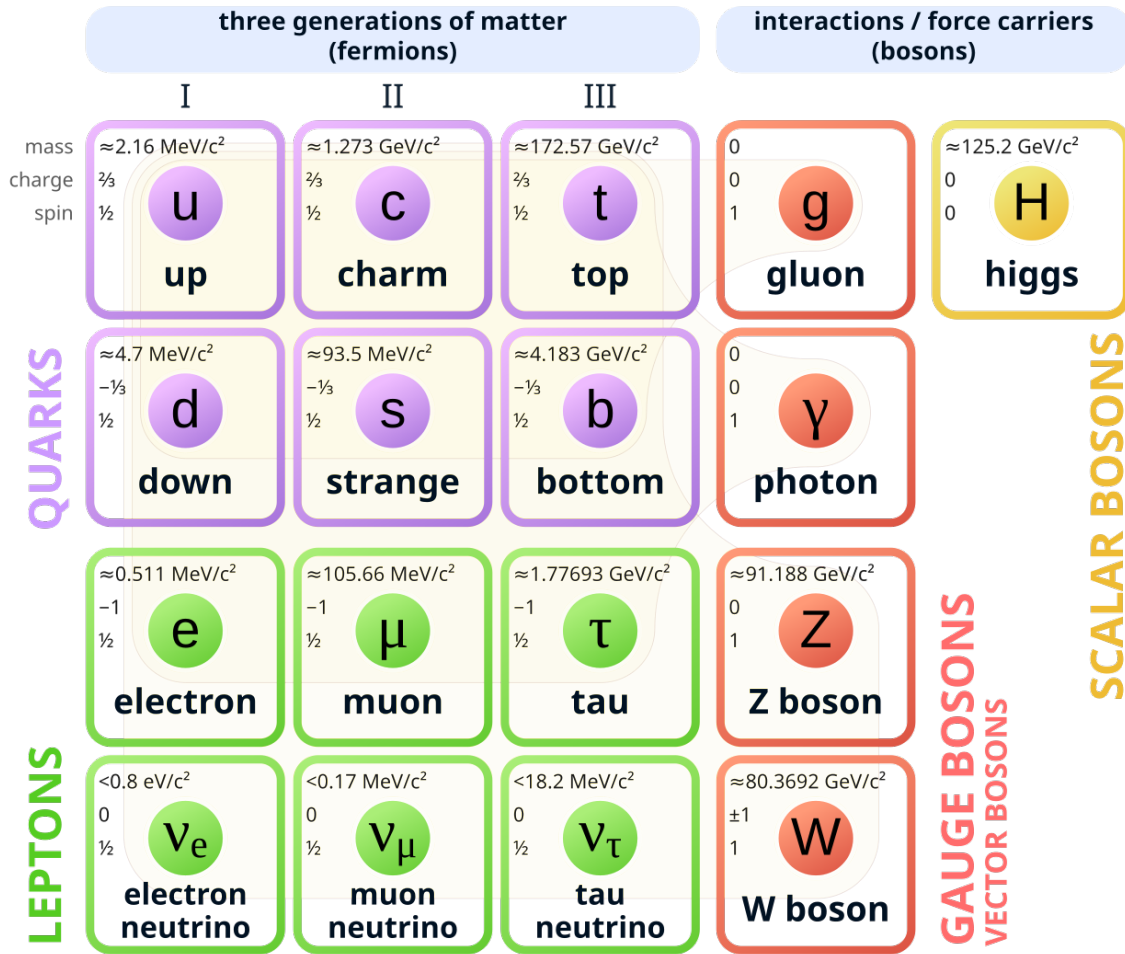


Figure 1.2: These are the elementary particles described by the Standard Model (Commons).

with corresponding antileptons. The leptons are shown in green in Fig. 1.2, and their antilepton counterparts are represented in the same manner as the antiquarks. Thus, all known matter and antimatter can be represented with these 12 fermions and their corresponding antiparticles. Antimatter fermions have the same masses as matter fermions but opposite charge. In the case of quarks which also carry color charges, antiquarks have opposite color charges as well. The color charges available for quarks are red, green, and blue, and for antiquarks, we have antired, antigreen, and antiblue.

Quarks are naturally bound by the strong force into colorless particles (the net color charge adds to zero). Particles composed of quarks are called “hadrons.” There is a special subset of hadrons called “baryons” which are made up of three quarks. Protons (two up quarks and one down) and neutrons (two down quarks and an up) are prominent examples of baryons.

Bosons are spin 1 or 0 particles. Vector bosons (or bosons with unit spin) are represented in red, and the single scalar boson, the Higgs particle, is represented in yellow in Fig. 1.2. The Higgs couples all particles to mass; essentially it is what makes matter massive. The gluon mediates interactions between quarks. The photon, the Z boson, and the $W^\pm$ bosons mediate electroweak interactions.

1.3.2 SM Interactions

Higgs couplings. All particles couple to the Higgs boson with a strength of m/v where m is the particle’s mass and v is the symmetry-breaking vacuum expectation value ($v = 246$ GeV) (13). With exception to the top quark, all known particles have $m \ll v$ and thus couple weakly to the Higgs. Another way of thinking about this is that the heavier a particle is, the more strongly it will couple to the Higgs. The Higgs couples to itself, and the strength of its self-interaction is determined by its mass. The expression that relates the strength of its self-coupling to its mass is:

$$2\lambda = (m_H/v)^2. \tag{1.2}$$

The Higgs is not involved in flavor changing, if a fermion emits a Higgs it will not change flavor. This can be seen in the lagrangian that represents the Higgs coupling in that the Higgs-fermion couplings are automatically diagonalized when expressed in terms of mass eigenstates (13).

The Higgs conserves charge (C), parity (P), and time reversal (T) symmetries.

Strong interactions. These interactions are mediated by gluons. When a fermion emits a gluon, it undergoes a color quantum number transition but will never

undergo a flavor change. They are termed “strong” because the spectrum of strongly interacting particles cannot be described perturbatively in the gluon coupling, g_3 . All interactions that fall under this category, independent of particle type, have the same interaction strength, g_3 . The gauge group that mathematically represents the SM can be partitioned into two pieces. The one that represents the strong sector, $SU_c(3)$, and the product that represents the weak sector, $SU_L(2) \times U_Y(1)$. Therefore, particles which carry strong-interaction quantum numbers can be split into their own class. Quarks and gluons are the only SM elementary particles which carry the strong-interaction quantum numbers, and thus composite particles which are made up of quarks and gluons are termed “hadrons.” The spin 1/2 fermions that do not interact via the strong force are termed “leptons” (13).

Strong interactions *mostly* conserve the C, P, and T symmetries. There is one term, Θ_3 , involved in gluon self-interactions that violates CP-symmetry. This term is, however, very small. Its size is bounded experimentally by the neutron’s intrinsic electric dipole moment (EDM) (13).

Electroweak interactions.

Electroweak interactions encompass interactions that are mediated by the photon, Z boson, and $W^\pm$ boson. Electroweak boson self-interactions result from the coupling of spin 1 bosons to themselves. They are described by cubic and quartic terms that arise from the $SU_L(2)$ gauge boson field strength. These self-interactions conserve C, P, and T symmetries.

Interactions that involve the $W^\pm$ boson and fermions are known as charged current interactions. These interactions are the only ones which result in fermion flavor changes and are responsible for the majority of particle decays as a result. Leptons all participate in these interactions with equal strength, g_2 , this is known as *weak universality* (13). This does not apply to weak interactions involving quarks. The weak interaction strengths between quark flavors are described by the Cabbibo-Kobayashi-Maskawa (CKM) matrix (the CKM matrix is explored in more detail in Section 1.3.4). Charged current interactions violate CP symmetry (13). If it is shown

that the CKM matrix cannot be made real by a suitable choice of fields, then T symmetry is violated. T is violated for hadronic charged current interactions and is conserved for leptonic charged current interactions.

Neutral current interactions couple to Z bosons and never involve more than one flavor of fermion, so no flavor change is induced by them. The lack of experimental observation of flavor change in neutral current interactions helped predict the existence of the charm quark. The neutral current interactions violate C and P symmetries, but not T .

Electromagnetic interactions are mediated by the photon. They conserve C , P , and T symmetries.

1.3.3 CP Violation

CP violation is one of the three conditions that Andrei D. Sakharov outlined as an explanation for the baryon asymmetry in the universe (54).

The weak sector is the main source of CP violation in the SM. Under the assumption that the universe started with zero baryonic content, the SM predicts that after the Big Bang equal amounts of matter and antimatter would have been created, but matter dominates. This phenomenon is called baryon asymmetry. The known CP violation in the weak sector described by the SM is not enough to explain the extent of the baryon asymmetry in the universe (22). This leads to an abundance of conceptualization of possible sources for additional CP violation. To test the explanations that lie within the weak sector, experimentation with a fundamental weak process is ideal. Free neutron beta decay is a suitable candidate for this role because it is the simplest baryonic weak interaction process. It also provides access to test additional aspects of the SM.

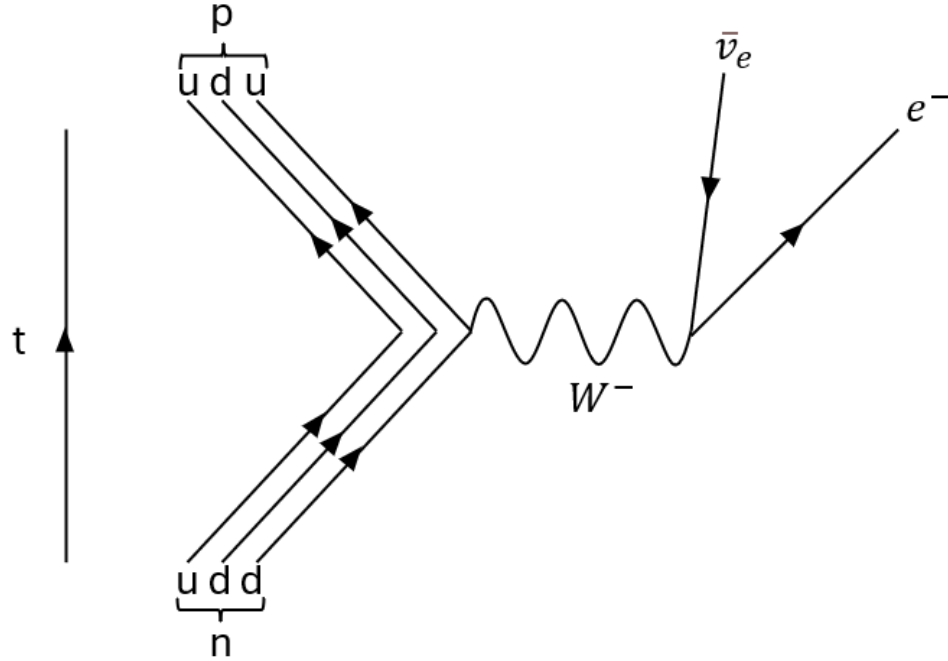


Figure 1.3: This Feynman diagram represents the decay of the free neutron. The up (u) and down (d) quarks are shown for the neutron and proton. One of the d quarks becomes a u quark. The W^- boson mediates the interaction and nearly instantaneously decays into an electron (e^-) and electron antineutrino ($\bar{\nu}_e$). On the left time (t) is indicated to show that the decay proceeds from the neutron into the proton, electron, and electron antineutrino.

1.3.4 The Electron-Neutrino Correlation Coefficient in the SM

Free neutron beta decay occurs when one of the down quarks in the neutron (udd) emits a W^- boson and transitions to being an up quark. Subsequently, the W^- boson decays to an electron and an electron anti-neutrino. At the highest level this looks like:

$$n \rightarrow p^+ + e^- + \bar{\nu}_e, \quad (1.3)$$

where the W^- boson is not included because it is very short-lived. The average lifetime of the free neutron is $\tau_n = 878.4 \pm 0.5$ s according to the Particle Data Group (PDG) (3). The neutron decay rate is given by:

$$\Gamma = \frac{1}{\tau_n} = \frac{f^R m_e^5 c^4}{2\pi^3 \hbar^7} |V_{ud}|^2 (|g_V|^2 + 3|g_A|^2), \quad (1.4)$$

where f^R is a phase space factor, m_e is the electron mass, g_A is the axial vector coupling constant, and g_V is the vector coupling constant. Notice that V_{ud} is a term in the neutron decay rate expression in Eq. 1.4. This is of interest because V_{ud} is the largest element of the top row of the CKM Matrix and therefore has the strongest contribution to the uncertainty of the unitarity check for the top row of the CKM Matrix. It is convenient to express the decay rate in terms of $\lambda = g_A/g_V$ and further simplify by using the relationship between g_V and V_{ud} . This results in:

$$\frac{1}{\tau_n} \propto |V_{ud}|^2 |g_V|^2 G_F^2 (1 + 3\lambda^2), \quad (1.5)$$

where G_F is the Fermi weak coupling constant. It is apparent from Eq. 1.5 that, given the value of G_F , a measurement of the neutron lifetime and of the ratio $\lambda = g_A/g_V$ can be used to make an extraction of V_{ud} . It is reasonable to treat G_F as a well-known physical constant. The PDG (1) reports it as:

$$G_F/(\hbar c)^3 = 1.1663787(6)10^{-5} \text{ GeV}^{-2}. \quad (1.6)$$

So, the quantities required to determine V_{ud} are the neutron lifetime and λ from neutron beta decay. Currently, the most precise measurements of V_{ud} come from $0^+ \rightarrow 0^+$ nuclear decays which are subject to nuclear corrections (33). A competitive determination of V_{ud} from neutron decay would require an uncertainty of $\tau_n \leq 0.3$ s of the neutron lifetime and a relative precision of $\Delta\lambda/\lambda \leq 3 \times 10^{-4}$ (25).

As mentioned above, the CKM Matrix, V_{CKM} , describes the quark flavor changing weak interaction strengths. It currently contains three generations of quarks, and is

defined as unitary within the SM.

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}. \quad (1.7)$$

. From the 2022 PDG Review (59), the average of the 15 most precise V_{ud} measurements from superallowed transitions is $|V_{ud}| = 0.97373 \pm 0.00031$.

If the CKM Matrix is not unitary it could indicate the existence of a fourth generation (or more) of quarks, or it may be due to the existence of right-handed currents, other non-standard couplings, or some other exotic phenomenon (25).

The differential form of the decay rate of the the neutron given in terms of the decay correlation coefficients is

$$dW \propto \frac{1}{\tau_n} f(E_e) \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e \cdot E_\nu} + b \frac{m_e}{E_e} + A \frac{\sigma_n \cdot \vec{p}_e}{E_e} + B \frac{\sigma_n \cdot \vec{p}_\nu}{E_\nu} \right] \quad (1.8)$$

where $\vec{p}_e$ and $\vec{p}_\nu$ are outgoing electron and neutrino momenta, σ_n is the neutron spin, E_e and E_ν are the electron and neutrino energies, and $f(E_e)$ is the β energy spectrum (25; 36). The correlation coefficients (a , A , and B) are named,

a : Electron-neutrino correlation,

b : Fierz interference,

A : β -decay asymmetry, and

B : Proton asymmetry

They can be related to λ as follows:

$$a = \frac{1 - \lambda^2}{1 + 3\lambda^2}, \quad (1.9)$$

$$A = -2 \frac{\lambda(\lambda + 1)}{1 + 3\lambda^2}, \quad (1.10)$$

$$B = 2 \frac{\lambda(\lambda - 1)}{1 + 3\lambda^2}. \quad (1.11)$$

Dubbers shows the relative sensitivity of several of the correlation parameters. These values are determined by taking the derivative with respect to λ of Eqs. 1.9, 1.10, and 1.11 and then evaluating them with approximate values of λ , a , A , and B . The results for the relative sensitivities from Dubbers' paper with $\lambda \approx -1.27$ are summarized below (22):

$$\partial_\lambda a/a = -2.8, \quad a \approx -0.10,$$

$$\partial_\lambda A/A = -3.2, \quad A \approx -0.12,$$

$$\partial_\lambda B/B = 0.077, \quad B \approx 1.0.$$

It is apparent from these results that a and A are significantly more sensitive to variations in λ than B .

1.4 Free Neutron Beta Decay Experimental Status

The objective of this section is to show how messy the landscape of measurements made from the free neutron beta decay is. One response to such a landscape is to make higher-precision measurements. In addition, multiple independent experimental methods are used. Each of which are subject to different systematic effects. Another

common response is to implement some kind of blinding technique during data analysis to prevent the analyst’s bias from skewing results. Blinding is where some value in the data either has a shift added to it or a statistically significant portion of the data is removed during the initial analysis process and then reintroduced later during un-blinding, so that during the blinded phase of analysis the expectation of reaching a particular answer does not influence the choices of the analyst.

1.4.1 Status of Neutron Lifetime Measurements

A longstanding enigma in the neutron physics field is the neutron lifetime puzzle (57). There are two primary methods for measuring the neutron lifetime: storage and beam (57). Storage experiments essentially trap a known number of neutrons and then count the neutrons that remain after a given period of time—they count the living. Beam measurements count neutron decay products. The counts and a measurement of the neutron fluence are used to determine the neutron lifetime—they count the dead (57). There is a 4σ difference between bottle and beam neutron lifetime determinations. Explanations for this discrepancy range from the free neutron having some dark sector decay branch to the need to understand our systematic uncertainties better.

The PDG neutron lifetime is dominated by neutron storage experiments since there are more high precision storage experiment results available. They currently exclude beam measurements from the PDG average of 878.4 ± 0.5 s. It is noted by the PDG that including the most precise beam measurement pushes the average to 878.6 ± 0.6 s (5). The most recently published results for the neutron lifetime are from the UCN τ experiment which employed a magnetogravitational trap to make a measurement of record precision, $877.75 \pm 0.28_{\text{stat}} + 0.22 / - 0.16_{\text{syst}}$ s (31).

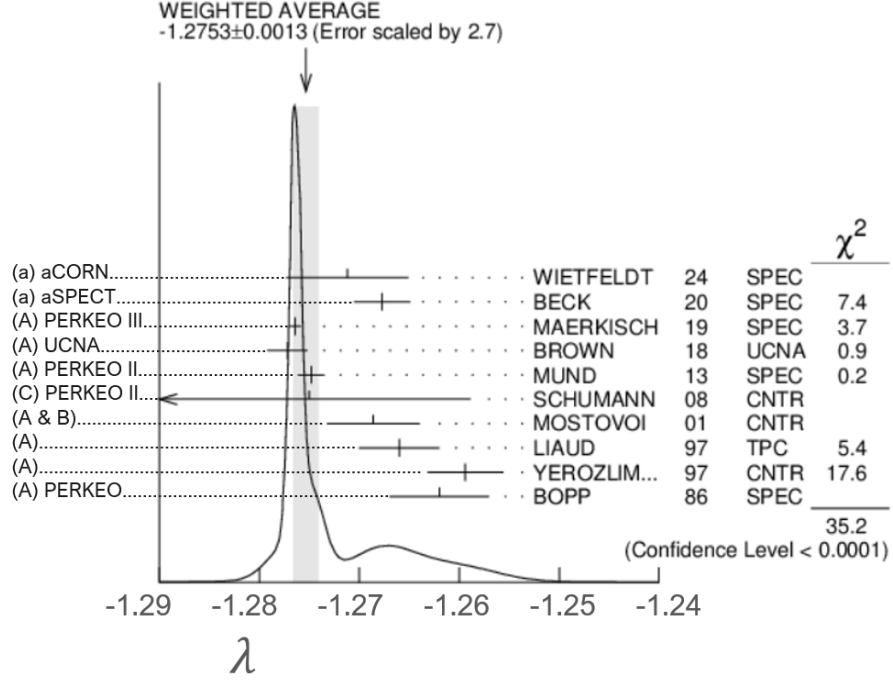


Figure 1.4: This shows the current landscape of extractions of λ from different correlation parameters (47).

1.4.2 Status of λ Measurements

It was mentioned in Section 1.3.4 that A and a are the most sensitive to variations in λ (22). This is reflected in the landscape of measurements presented in Fig. 1.4. The majority of the experiments (seven out of ten) use A to extract λ . The two most recent measurements made extractions from a . These measurements are subject to different systematic effects than extractions of λ that utilize A .

1.4.3 V_{ud} Values

The plot shown in Fig. 1.5 summarizes the status of the work towards extracting V_{ud} from neutron decay. The band of V_{ud} values determined from $0^+ \rightarrow 0^+$ decays (blue horizontal band) fall short of CKM unitarity. V_{ud} from neutron decay requires τ_n (red diagonal bands, one for bottle and one for beam results) and λ (yellow vertical bands, one for A and one for a results), so where these bands overlap are the possible V_{ud}

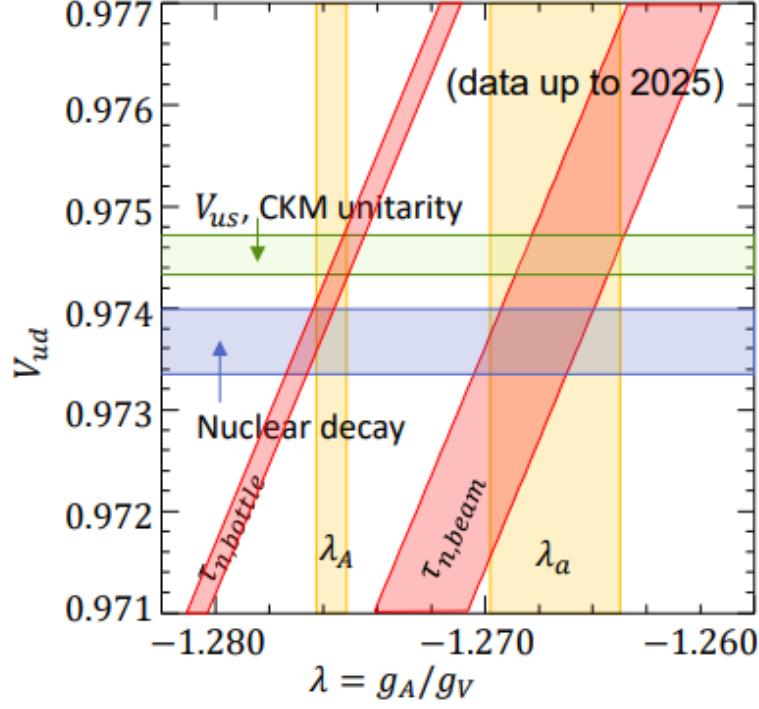


Figure 1.5: This shows V_{ud} vs. λ . The horizontal bands show values that would satisfy unitarity and the existing consensus from $0^+ \rightarrow 0^+$ decays. The diagonal bands correspond to neutron beam and storage (UCN) lifetime measurements. The vertical bands are λ values extracted from a and A (8).

values. Pairing bottle neutron lifetimes with A extractions of λ yields regions that overlap with both unitarity and the current most precise results from nuclear decay. The same can be said for pairing beam lifetimes with a extractions of λ .

1.4.4 Outlook

The neutron physics field is responding to this environment by pushing the boundaries of systematic uncertainties to lower values, developing novel techniques, and handling analysis carefully (with techniques like blinding and employing multiple independent analysis teams). BL3, an upcoming beam lifetime experiment aims to measure the neutron lifetime with an uncertainty on par with that of the recent UCN τ storage experiment (58). Most importantly to this thesis, the Nab experiment will make the most precise determination of a from neutron decay so far.

Chapter 2

Nab Experiment

2.1 Getting into Nab

Free neutron beta decay is a useful tool to study aspects of the weak force described in the SM (22). Neutron lifetime measurements and beta decay correlation coefficients are used to constrain SM parameters and probe possible BSM physics. One of the aspects of the weak force that is currently of particular interest is the unitarity of the CKM quark mixing matrix.

The first aim of the Nab experiment is to determine a with relative uncertainty $\Delta a/a \sim 1 \times 10^{-3}$. This will be the most precise determination of a that has ever been made with a free neutron beta decay experiment (Table 2.1) (10; 56). This a will be used to make a determination of λ and subsequently a determination of V_{ud} to test the unitarity of the CKM matrix (27; 35; 40). The most precise assessments of V_{ud} have come from super-allowed Fermi transitions (59) which require nuclear corrections. With Nab’s projected precision in a and next-generation neutron lifetime measurements, extractions of V_{ud} via the free neutron will be competitive with those of the aforementioned superallowed transitions and free of nuclear corrections.

The second aim of Nab is to determine the Fierz interference term, b , to $\Delta b \sim 3 \times 10^{-3}$ for the free neutron from the decay electron energy spectrum. The

Table 2.1: Comparison of most updated a measurements from aSPECT (10) and aCORN (56) to Nab projection.

Experiment Name	Year	a	Uncertainty	$\Delta a/a$
aSPECT	2024	-0.10402	± 0.00082	7.9×10^{-3}
aCORN	2024	-0.10779	± 0.00183	1.7×10^{-2}
Nab (projected)	-	-	-	$\sim 1 \times 10^{-3}$

Fierz interference term vanishes in the SM. A nonzero value of b would be indicative of BSM physics such as a scalar or tensor coupling in the weak interaction.

Nab is installed on the Fundamental Neutron Physics Beamline (FNPB) at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL). During data-taking a pulsed beam of unpolarized neutrons from the SNS passes through the 7 m tall asymmetric magnetic spectrometer (see Fig. 2.7). Neutrons that decay within the fiducial decay volume of the spectrometer each decay into a proton, electron, and electron antineutrino. The experiment was designed to detect decay electrons and protons in coincidence and measure the electron energy and proton time of flight (TOF). The proton momentum is then extracted from the proton TOF during analysis. Decay products are detected by large-area, thick, highly-segmented silicon detectors at the upper and lower ends of the spectrometer. To reduce systematic uncertainties in the proton TOF, the length of their flight path is maximized by only detecting them in the upper detector which is much further from the decay region than the lower detector. The electrons are detected at both ends of the spectrometer.

With the proton momenta and the electron energies, we build the phase space in Fig. 2.1. All possible states that can be accessed from the neutron decay are represented within the iconic tear drop shape. The Nab physics analysis aims to extract a from this decay phase space.

To obtain a from the plot in Fig. 2.1 we start from the differential decay rate already given by Eq. 1.8, but shown again here for convenience:

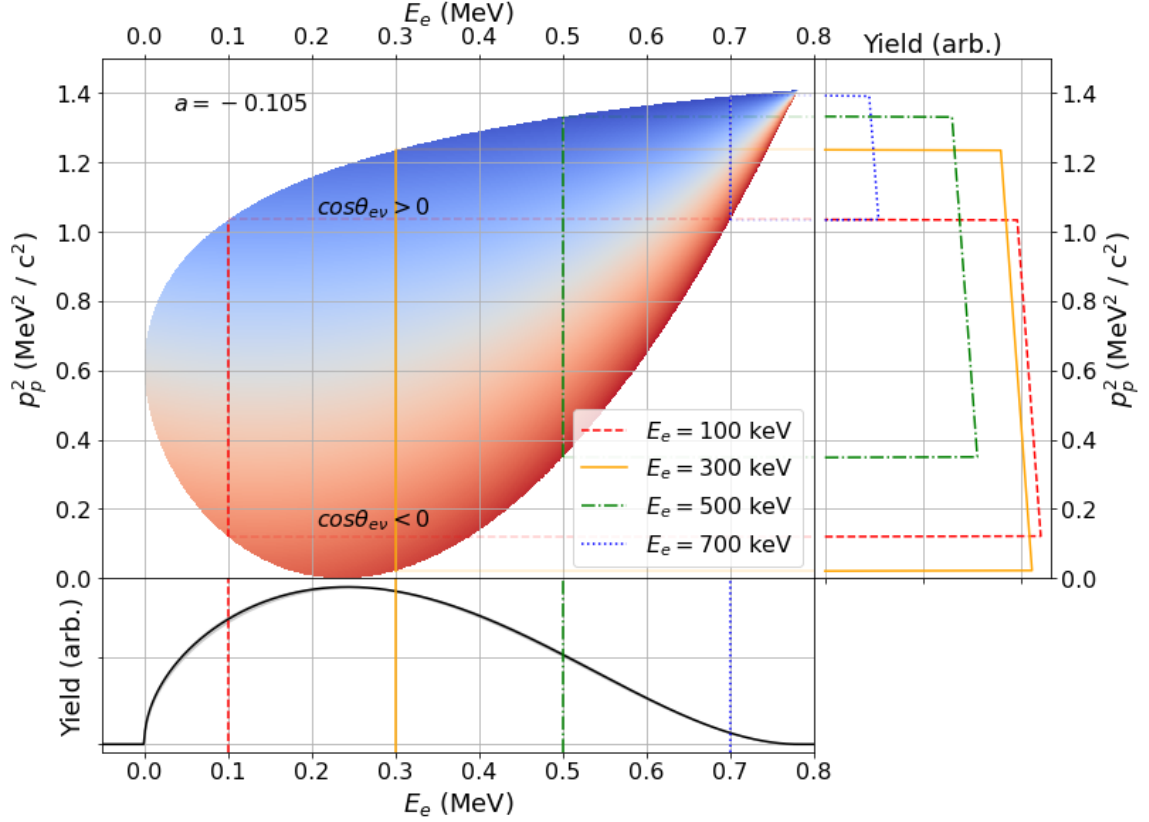


Figure 2.1: Proton phase space (30). The shape of the phase space is determined purely by kinematics and conservation of momentum. The outside edges of the tear drop correspond to the extremes of $\cos(\theta_{ev}) = 1$ (the decay electron and antineutrino go in the same direction) and $\cos(\theta_{ev}) = -1$ (the decay electron and antineutrino go in opposite directions).

$$dW \propto \frac{1}{\tau} f(E_e) \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e \cdot E_\nu} + b \frac{m_e}{E_e} + A \frac{\sigma_n \cdot \vec{p}_e}{E_e} + B \frac{\sigma_n \cdot \vec{p}_\nu}{E_\nu} \right].$$

We can then eliminate the contributions from terms with capitalized coefficients because the Nab experiment utilizes an unpolarized neutron beam, so $\sigma_n = 0$. Thus,

$$dW \propto \frac{1}{\tau} f(E_e) \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e \cdot E_\nu} + b \frac{m_e}{E_e} + A \frac{\cancel{\sigma_n \cdot \vec{p}_e}}{E_e} + B \frac{\cancel{\sigma_n \cdot \vec{p}_\nu}}{E_\nu} \right],$$

$$\Rightarrow dW \propto \frac{1}{\tau} f(E_e) \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e \cdot E_\nu} + b \frac{m_e}{E_e} \right].$$

Supposing that $b = 0$ as it does in the SM and rolling the leading coefficients into the proportionality operand, we obtain:

$$dw \propto 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e \cdot E_\nu}.$$

This can be further reduced by carrying out the dot products, which yields:

$$dw \propto 1 + a\beta \cos(\theta_{e\nu}), \quad (2.1)$$

where $\beta = v/c$, and $\cos(\theta_{e\nu})$ is the angle between the outgoing decay electron and antineutrino (see Fig. 2.2).

So, now, if we focus on a single electron energy (make β a constant), we have a linear expression where a is the slope. This is equivalent to taking a vertical slice at one electron energy in the plot in Fig. 2.1. Some examples of this are shown on the right side of the plot (the trapezoidal shapes). In the plot, the upper edges of the trapezoids correspond to $\cos(\theta_{e\nu}) = 1$ and the lower edges correspond to $\cos(\theta_{e\nu}) = -1$, so a is slightly negative (Dubbers uses an estimate of $a \approx -0.1$ (22), and you can see recent a values from neutron decay experiments in Table 2.1). In practice this plot will be a 2D histogram of the experimentally observed decay events, so the heights of the trapezoids will come from the number of events at each $\cos(\theta_{e\nu})$. Thus, the slightly negative a indicates that there is a small preference in neutron decay for the outgoing trajectories of the decay electron and antineutrino to be in opposite directions. This method of determining a is useful because measurements

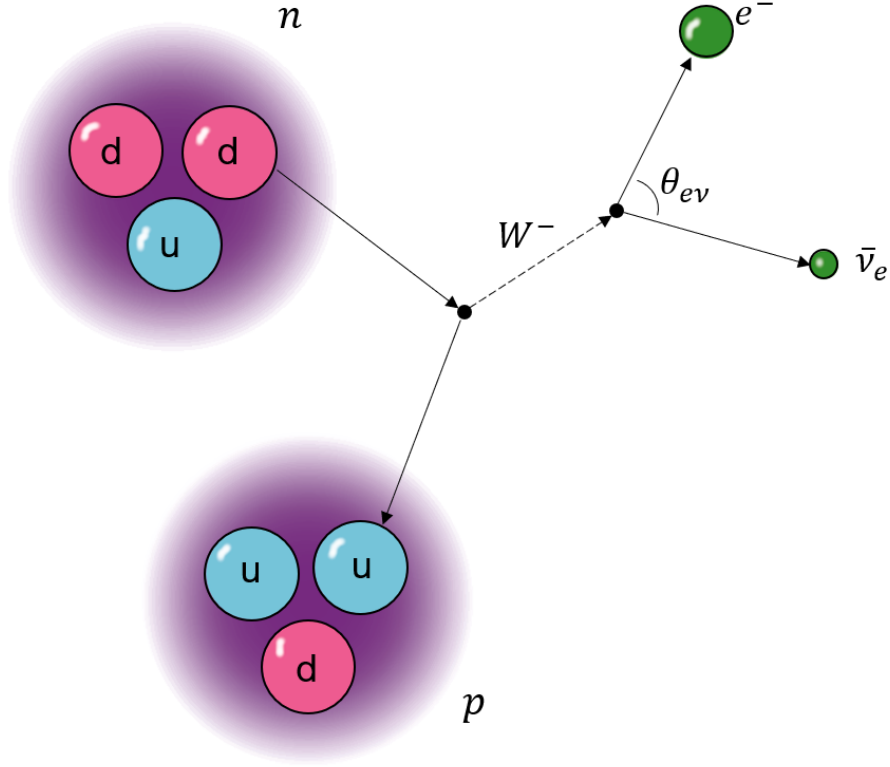


Figure 2.2: A cartoon of neutron decay that shows the neutron decaying to a proton, electron, and electron antineutrino via the W^- boson. The angle between the outgoing electron and antineutrino is labelled, θ_{ev} .

from each electron energy provide access to potentially different systematic effects. This allows for a check of the understanding of those effects and how corrections are employed.

The second parameter of interest, b , is a measure of the deviation from the SM electron energy spectrum. It will be determined from the same configuration in which a is determined and later in a separate, dedicated configuration. The initial effort of Nab focuses on extracting a , so that will be the main focus of this section.

2.2 The Systematic Uncertainties

The uncertainty budget is crucial for Nab to produce competitive results that will serve to test CKM unitarity and probe BSM physics. The uncertainty budget which was prepared prior to commissioning of the Nab experiment is presented in the table below (Fig. 2.3). The total uncertainty is found by adding all of the contributions in quadrature. This uncertainty budget is a useful tool for benchmarking the performance of each subsystem and informing areas of interest for improvements throughout the commissioning process.

Experimental parameter	Principal specification (comment)	$(\Delta a/a)_{\text{SYST}}$
Magnetic field:		
curvature at pinch	$\Delta\gamma/\gamma = 2\%$ with $\gamma = (d^2 B_z(z)/dz^2)/B_z(0)$	5.3×10^{-4}
ratio $r_B = B_{\text{TOF}}/B_0$	$(\Delta r_B)/r_B = 1\%$	2.2×10^{-4}
ratio $r_{B,DV} = B_{DV}/B_0$	$(\Delta r_{B,DV})/r_{B,DV} = 1\%$	1.8×10^{-4}
L_{TOF} , length of TOF region		(*)
U inhomogeneity:		
in decay / filter region	$ U_F - U_{DV} < 10 \text{ mV}$	5×10^{-4}
in TOF region	$ U_F - U_{\text{TOF}} < 200 \text{ mV}$	2.2×10^{-4}
Neutron beam:		
position	$\Delta\langle z_{DV} \rangle < 2 \text{ mm}$	1.7×10^{-4}
profile (incl. edge effect)	slope at edges $< 10\%/cm$	2.5×10^{-4}
Doppler effect	(analytical correction)	small
unwanted beam polarization	$\Delta\langle P_n \rangle < 2 \cdot 10^{-5}$ (with spin flipper)	1×10^{-4}
Adiabaticity of proton motion		1×10^{-4}
Detector effects:		
E_e calibration	$\Delta E_e < 200 \text{ eV}$	$2 \cdot 10^{-4}$
shape of E_e response	$\Delta N_{\text{tail}}/N_{\text{tail}} < 1\%$	4.4×10^{-4}
proton trigger efficiency	$\epsilon_p < 100 \text{ ppm/keV}$	3.4×10^{-4}
TOF shift (det./electronics)	$\Delta t_p < 0.3 \text{ ns}$	3×10^{-4}
TOF in accel. region	$\Delta r_{\text{GROUND EL.}} < 0.5 \text{ mm}$ (preliminary)	3.4×10^{-4}
electron TOF	(analytical correction)	small
BGD/accid. coinc's	(will subtract out of time coinc)	small
Residual gas	$p < 2 \cdot 10^{-9} \text{ torr}$	3.8×10^{-4}
Overall sum		1.2×10^{-3}

Figure 2.3: Table of Uncertainties from (26).

As commissioning is now (2025) in its later stages with transition into production data-taking underway, it is becoming clear that the observed uncertainties in the system may not align with those in the uncertainty budget. Understanding the systematic uncertainties as they are for each dataset that is analyzed is an important part of the process to reaching a high precision result.

2.3 The Neutron Beam

The SNS is a high intensity, pulsed neutron source. It is currently the brightest neutron source in the world. Prior to the ongoing power upgrade it had a time-averaged proton power of 1.4 MW (24). During the spring 2025 beam cycle the SNS has reached a power of 1.8 MW. The FnPB @ SNS was designed to take advantage of this source of pulsed, cold neutrons to service fundamental neutron physics experiments. Because the neutron beam is pulsed, the neutron source is off when the slow neutrons reach the apparatus (24). This typically reduces backgrounds in the detectors (24).

The SNS accelerates a beam of H^- ions through a roughly 330 m long linear accelerator. The accelerated ions pass through a diamond stripper foil that removes the electrons, leaving behind protons which are collected in an accumulator ring. Protons are then released from the accumulator ring at a rate of 60 Hz onto a liquid mercury target. The impact of the energetic protons (~ 1 GeV) on the mercury nuclei knocks neutrons free in a process called spallation to produce a 60 Hz pulsed neutron beam. Neutrons then pass through a supercritical hydrogen moderator that is approximately 20 K (see Fig. 2.4) (24). The neutrons exit the moderator cooled to the slow neutron regime (also called cold neutrons; 0 to 0.025 eV). They are guided by a super-mirror coated neutron guide with a slight curve in it to the Nab spectrometer. Two beamline choppers allow for selecting a specific neutron energy range. The neutrons will take a certain amount of time to reach the choppers based on their energy, so the chopper timing can be set based on how long it will take neutrons

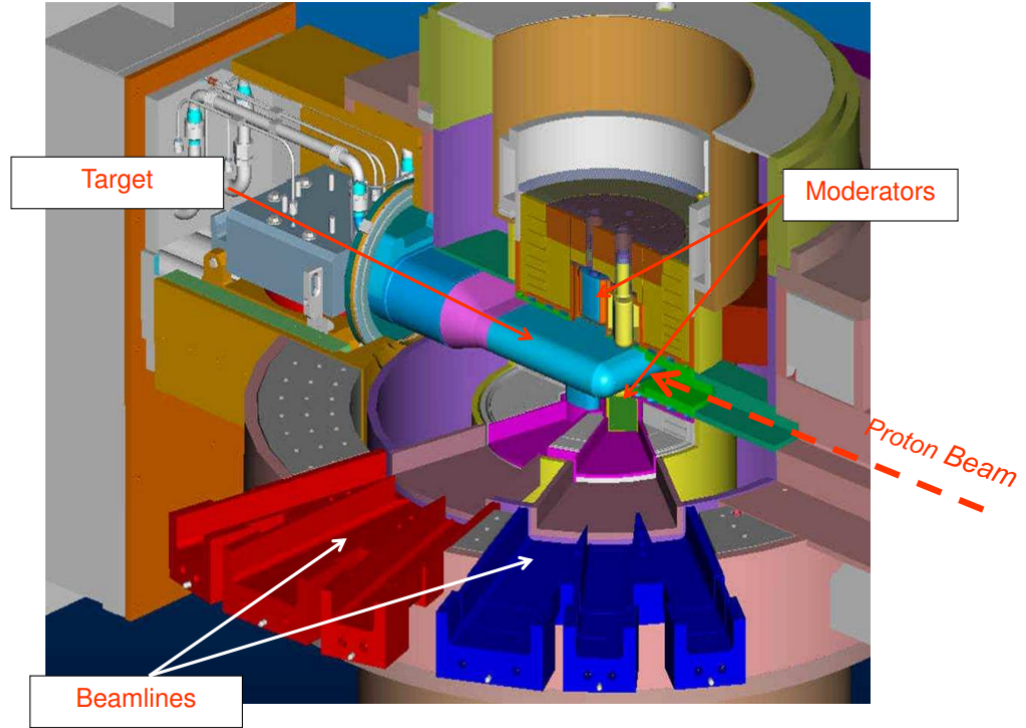


Figure 2.4: Proton beam impinging on the liquid mercury target at the SNS at ORNL. Four moderators surround the target. Each moderator is viewed by multiple beamlines (24).

of the desired energy to reach them. The choppers are rotating disks with an aperture for neutrons to pass through. They are composed of carbon fiber composite that is coated in a layer of ^{10}B . ^{10}B is well-suited for absorbing neutrons since it has a high neutron capture cross section. The beamline configuration leading up to the Nab apparatus is shown in Fig. 2.5. Just before entering the decay volume of the Nab spectrometer the neutron beam passes through a collimation system (Fig. 2.6)

Approximately 1000 neutrons per second are expected to decay within the fiducial decay volume of the magnetic spectrometer. Only a fraction of these events will be detected. To obtain the necessary statistics for the Nab uncertainty goals, data collection is expected to run for 2 years.

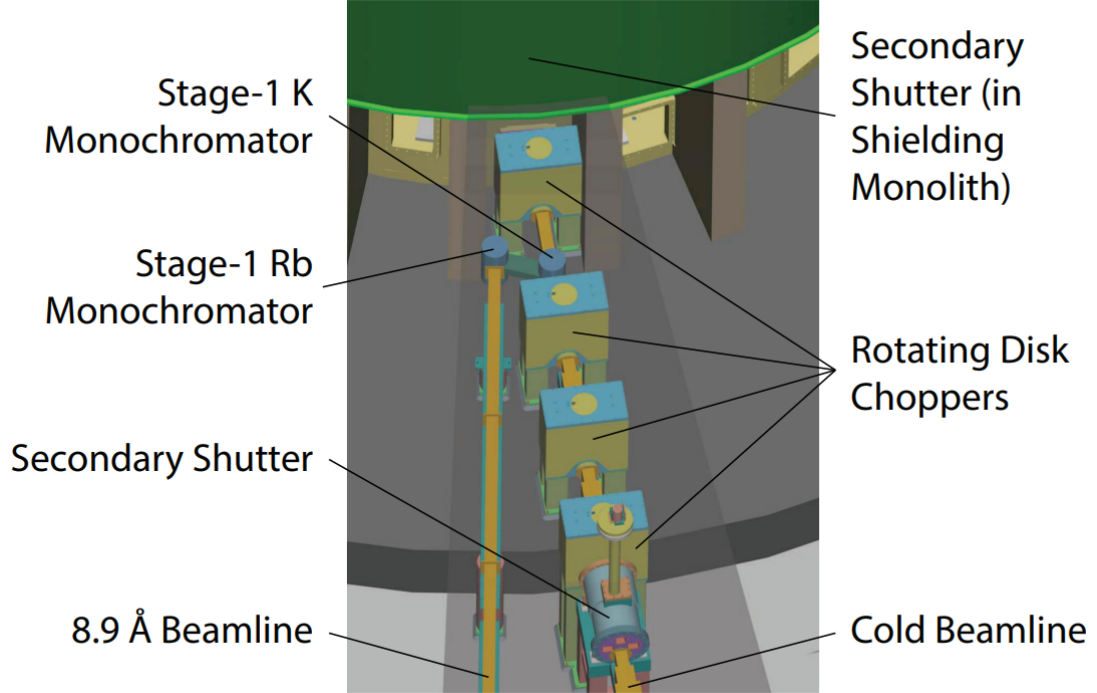


Figure 2.5: The FnPB consists of a secondary shutter that is located within the shielding monolith that surrounds the liquid mercury target, a series of choppers, and designated secondary shutter for the cold beamline which Nab is installed on (BL-13B) (24).

2.3.1 Beam Polarization

The Nab experiment requires an unpolarized neutron beam. The SNS is an unpolarized neutron source, and as such we expect the beam to be unpolarized. However, the neutrons are guided to the Nab apparatus by a slightly curved, nickel-coated beam guide, so it is possible that this could introduce some small polarization to the neutrons. An adiabatic fast passage (AFP) spin flipper will be implemented to measure beam polarization. A successful measurement of the beam polarization with the AFP spin flipper will constrain the beam polarization to less than 2×10^{-5} . The work on this is ongoing and an update can be seen here (29).

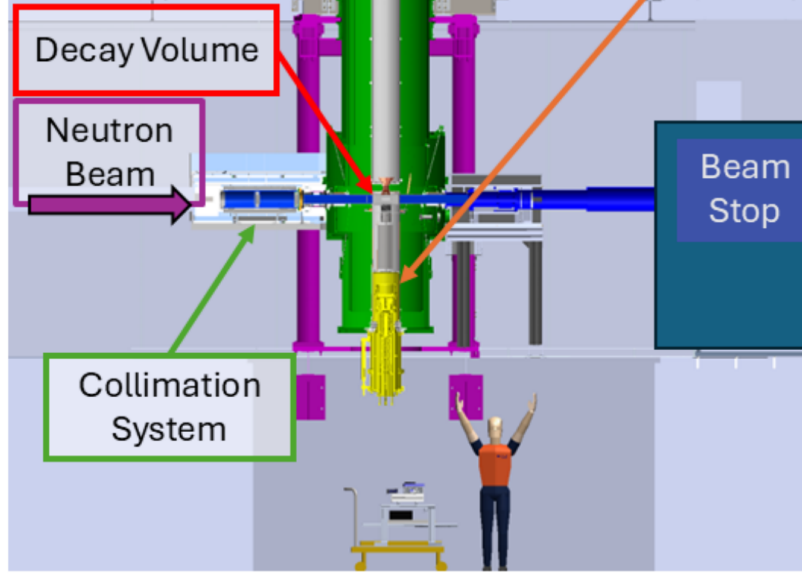


Figure 2.6: Once the neutron beam passes the designated secondary shutter for the cold beamline (Fig. 2.5) it passes through a collimation system and into the decay volume of the Nab spectrometer (30).

2.4 The Magnetic Spectrometer

The Nab magnetic spectrometer is a 7.5 meter tall, cryogen-free, superconducting magnet. It is the largest cryogen-free magnet in the world (43)! Cooling is provided by four Gifford McMahon cryocoolers. The bore of the magnetic spectrometer is maintained at ultra-high vacuum. At the upper and lower end of the magnet are large-area, thick, highly-segmented silicon detectors (23). The neutrons decay in one of the higher magnetic field regions (2 T). The magnetic field guides the decay electrons to the upper and lower detectors. The 4 T magnetic filter serves to deflect protons that do not have a sufficient upward momentum to the lower end of the magnet. Protons that pass the filter are further longitudinalized as the field expands to the upper detector. Protons used to determine a will only be detected in the upper detector.

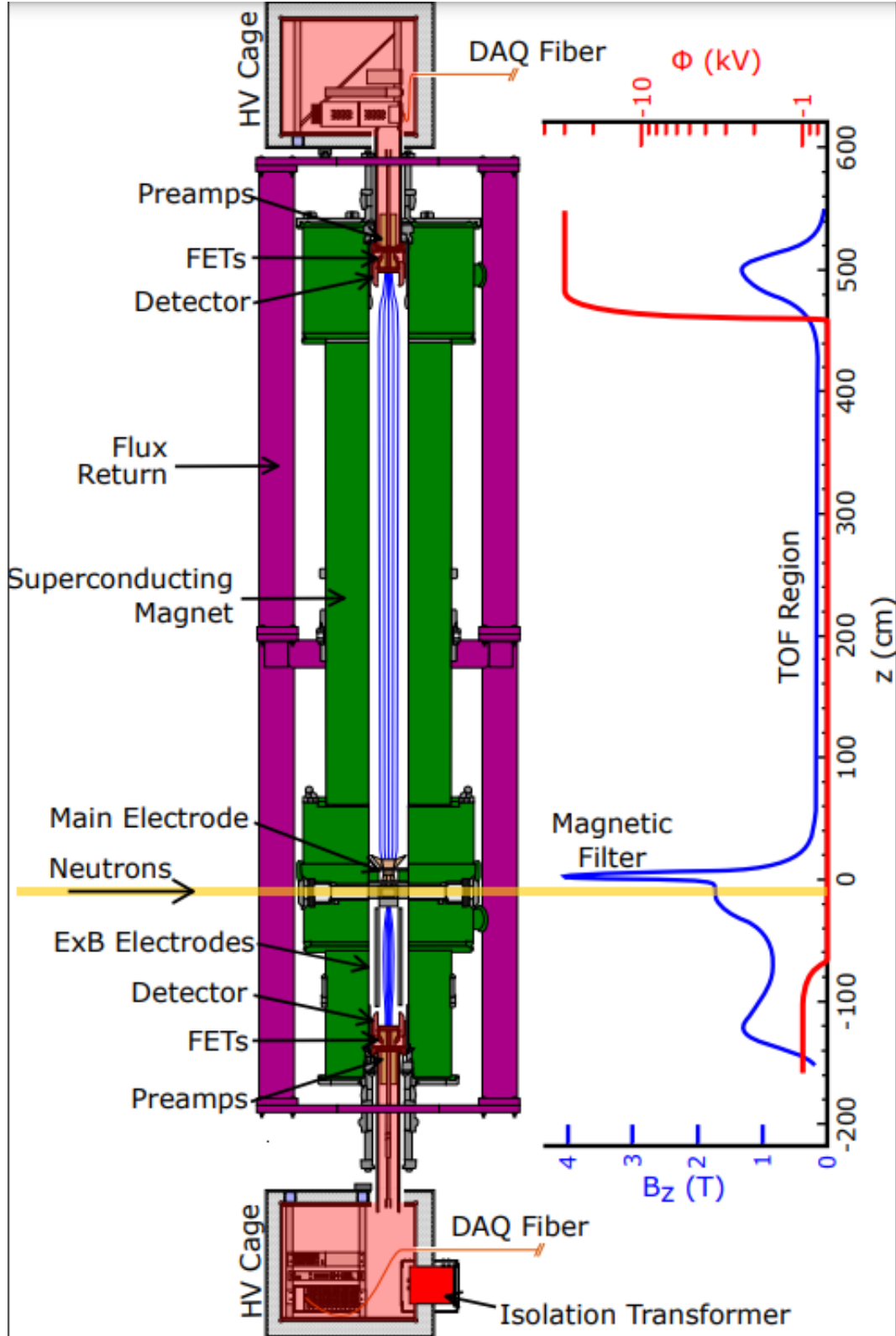


Figure 2.7: Nab magnetic spectrometer (26). The plot on the right shows the electric potential in red and the magnetic field strength in blue.

2.4.1 High Voltage Electrodes

Each detector is fitted with an electrode shell (see Fig. 2.8 in the detector systems subsection) that can be biased to high voltage. The upper detector electrode is biased to approximately -30 kV to accelerate the protons just before they hit the detector. This is necessary for the protons to be detected because the maximum proton energy of ~ 751 eV is not enough for them to penetrate the dead layer of the detector. After being accelerated the protons have about 30 keV of energy. Approximately 10 keV is lost to the dead layer of the detector. So, the expected average detected proton energy is 20 keV. The lower detector electrode will be held at +1 kV to help prevent electrons from backscattering from the lower detector to the upper detector. So far, the high voltage has not been implemented with the lower detector system.

2.4.2 The $\mathbf{E} \times \mathbf{B}$ Electrode

The $\mathbf{E} \times \mathbf{B}$ electrode was designed to mitigate effects from backscattered protons (see Fig. 2.7 just below the incoming neutron beam for an image). It creates an electric field perpendicular to the magnetic field lines to push protons that go towards the lower detector to the side. A secondary benefit of the $\mathbf{E} \times \mathbf{B}$ electrode is that it will also clear protons that have been trapped in the lower region of the spectrometer by the magnetic field. The design voltage for the $\mathbf{E} \times \mathbf{B}$ electrode is ~ 1 kV.

2.5 The Detector Systems

Each detector system consists of the electrode shell, the field-effect transistor (FET) assembly, a ceramic high voltage break, the amplifier assembly, and a G-10 insert that acts as an electrical insulator between the electronics and the exterior shell of the detector mount as shown in Fig. 2.8.

The detector and electrode shell are inserted into the bore of the magnetic spectrometer which is held at ultra-high vacuum. There is a vacuum break behind the

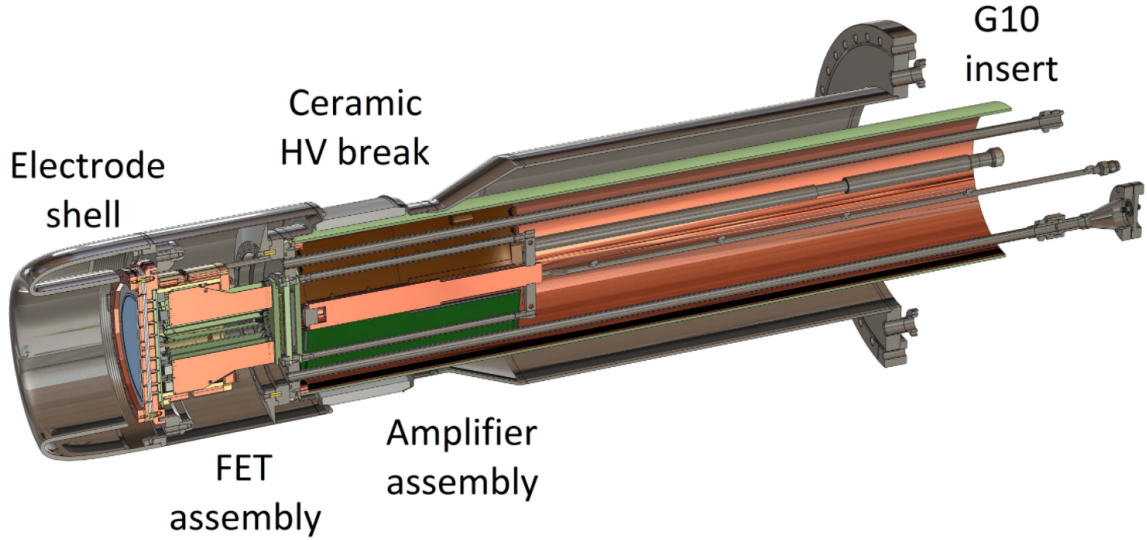


Figure 2.8: Cut view of the detector system schematic (26).

detector (this will be further discussed below in section 2.5.4), and the FET assembly is housed within the FET volume which is held at roughly 10^{-4} Torr. The amplifier assembly is in air.

2.5.1 Silicon Detector Principles of Operation

Silicon is a semi-conductor. This means that there is a characteristic energy band gap between the valence band of electrons and the conductance band of the bulk silicon. This intrinsic band gap means that silicon's valence electrons take a set amount of energy to be promoted to the conductance band. At room temperature, the energy band gap for silicon is ~ 1.12 eV (34). This feature of silicon means that we can use it as a charged particle detector. Incoming charged particles will impart their energy on valence electrons until they come to a stop within the material. The energy required for a charged particle to knock a valence electron into the conductance band is called the electron hole pair (ehp) creation energy. The ehp creation energy is greater than the band gap energy. Despite this, the ehp creation energy is constant at a given temperature, around 3.62 eV at room temperature (39). So, then we just need a way to observe the creation of electron hole pairs within the silicon.

To see how this is done, we must first delve a little into the properties of silicon. In practice, pure (or intrinsic) silicon is not obtainable. A manufactured silicon lattice will contain impurities that impact the concentration of electrons and holes (or receptor sites) within the lattice. In response to this we intentionally introduce impurities to the silicon, we call this doping. The doping process can produce n-type or p-type silicon. n-type silicon has a higher concentration of electrons within the lattice, and p-type silicon has a higher concentration of holes. For a silicon detector, these two types of silicon are grown within the same bulk material to create a p-n junction. Without applying an external bias, the interface between the n-type and p-type silicon will set up an electric field region that is at a steady-state of charge distribution, as in no current* will flow through it without outside influence. This region is known as the depletion region. We can then apply an external reverse bias to the material to widen the depletion region. Reverse biasing means that we connect the negative lead to the p-type side of the junction and the positive lead to the n-type side this draws holes from the p-type silicon into the n-type, and conduction electrons from the n-type into the p-type (39).

The goal then is to fully deplete the silicon wafer, so that the full thickness of the wafer is in a steady state and observed current results from incoming charged particles interacting with the material rather than from the material itself. The detector may also be over-depleted by operating it at a potential difference that is higher than that required to fully deplete it. Different impurity densities within the detector can impact signal risetimes. Nab is sensitive to pixel dependent risetime differences as they will impact the TOF shift (see Fig. 2.3). Slightly over-depleting a silicon detector can reduce the effect of different impurity densities within the silicon, so the goal is to operate the Nab detectors in such a configuration.

*There are some potential sources of current even within the depletion region, notably, electron hole pairs can be created due to thermal excitations within the material. This phenomenon is discussed in more detail in Ch. 4.

2.5.2 Thickness

The Nab experiment currently (2025) utilizes two 2 mm thick detectors. This thickness was selected because it will fully stop the maximum energy electrons that are expected from the neutron decay. The endpoint energy for the decay electrons is ~ 782 keV. The stopping distance for 800 keV electrons in silicon is ~ 1.75 mm based on their CSDA range (48).

The Nab detectors are susceptible to failure by a number of modes. They may become contaminated, break during handling, or be damaged in situ by high voltage discharges. Sometimes these failure modes can be addressed with repairs. For example, a wire bond broken during handling can be fixed with the appropriate tools and expertise. However, many of these failure modes require replacement of the detector. Controls are actively implemented to prevent loss of detectors, and a bank of detector candidates is maintained to avoid delays in data-taking. A subset of the detectors in reserve are 1.5 mm thick. Manufacturing challenges with 2 mm thick detectors make it difficult to obtain candidates that meet the performance requirements of Nab, so 1.5 mm thick detectors may be implemented in the future. Initial simulation work by the collaboration shows that not fully stopping the most energetic electrons may not have a noticeable impact on the data set. This will be further investigated in the future.

2.5.3 Segmentation

The Nab detectors are segmented into 127 hexagonal “pixels.” Figure 2.9 shows the segmentation geometry.

Each pixel is read out independently. The hexagonal shape of the pixels is primarily because it is an efficient way to fill the space without gaps. An additional bonus is that at any given point on the detector you can touch only three different pixels at once. This means that charge sharing effects between pixels are limited to sets of three.

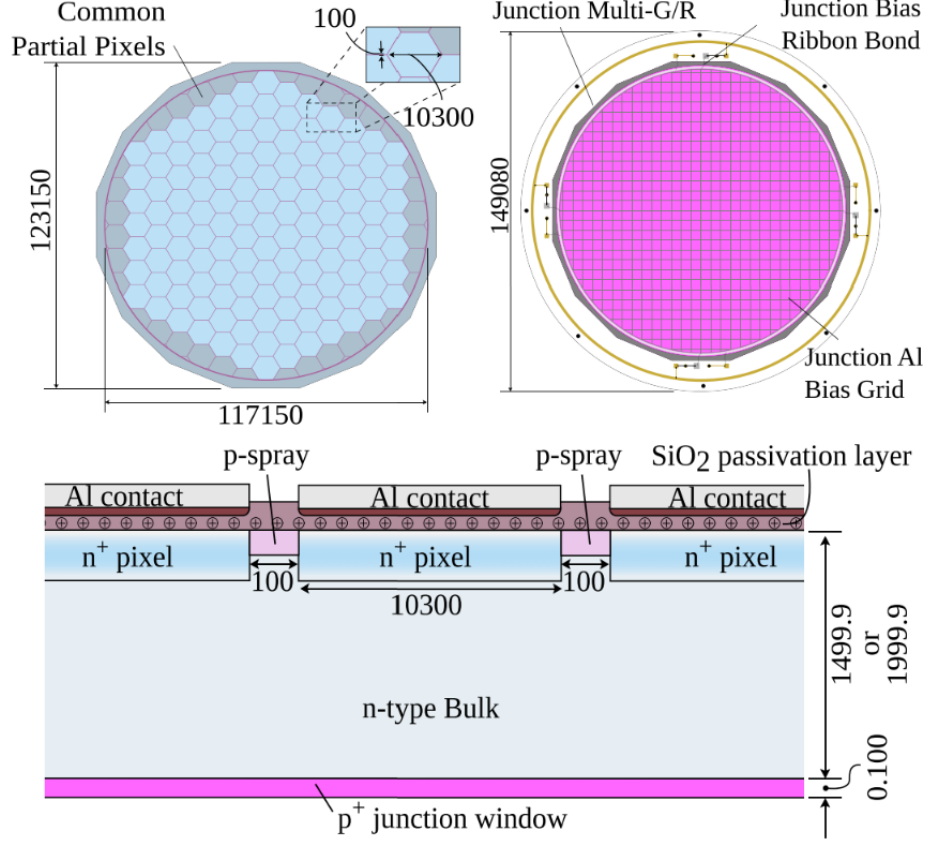


Figure 2.9: The Nab silicon detector geometry (34). The top left shows the overall segmentation on the ohmic side of the detector (back). The top right shows the aluminum bias grid on the front of the detector. The bottom shows a cross section of the detector where the aluminum contacts on the back of the detector (top in the cross section) that correspond to each pixel can be observed. The pixels are isolated by 100 microns of p-spray. Note that all measurements are in microns.

The segmentation of the detector is designed to make identifying decay electron and proton pairs possible since Nab detects these events in coincidence. The DAQ logic uses geometry and pulse shape discrimination to label candidate coincidence events during data-taking (46). The decay rates within the spectrometer are such that pileup of coincident events on a single pixel is not a major concern. Since the decay products are guided by magnetic field lines to either detector, corresponding events will typically appear within a ring of pixels of each other on the same or opposite detectors.

2.5.4 “The Sandwich”

A few factors led to the design of what is termed here “The Sandwich.”

1. The detector has to be within the ultra-high vacuum of the magnet’s bore. The FET cards (labelled FET assembly in Fig. 2.11) are not clean enough to be in the ultra-high vacuum volume, so they are in a designated rough vacuum volume. So, part of The Sandwich is a copper vacuum flange which is sealed with indium (Fig. 2.10(a)).
2. The pins on the FET pogo pin board (labelled in Fig. 2.11) are in a different pattern than the contacts on the back of the detector, so the Rogers board (Fig. 2.10(b) and 2.12) is need to transition between the two.
3. The frit plate (Fig. 2.10(c)) helps protect the Rogers board pogo pins from getting damaged when the detector is not installed.
4. The armor back cover and armor (Fig. 2.10(d) and (e)) serve a duel purpose. They interface between the detector and the rest of the stack, and they protect the detector on its journey between the lab that houses the positive pressure hood where the detector is installed and the FNPB where the rest of the detector system generally stays.

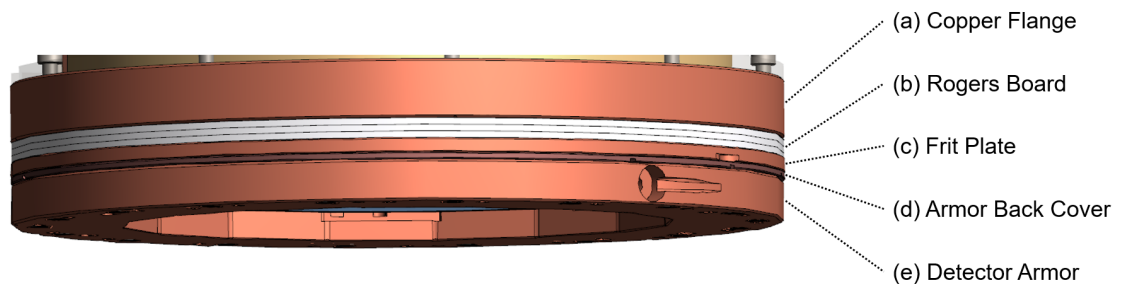


Figure 2.10: The stack of disks that lead up to the detector within the ultra-high vacuum termed “The Sandwich.”

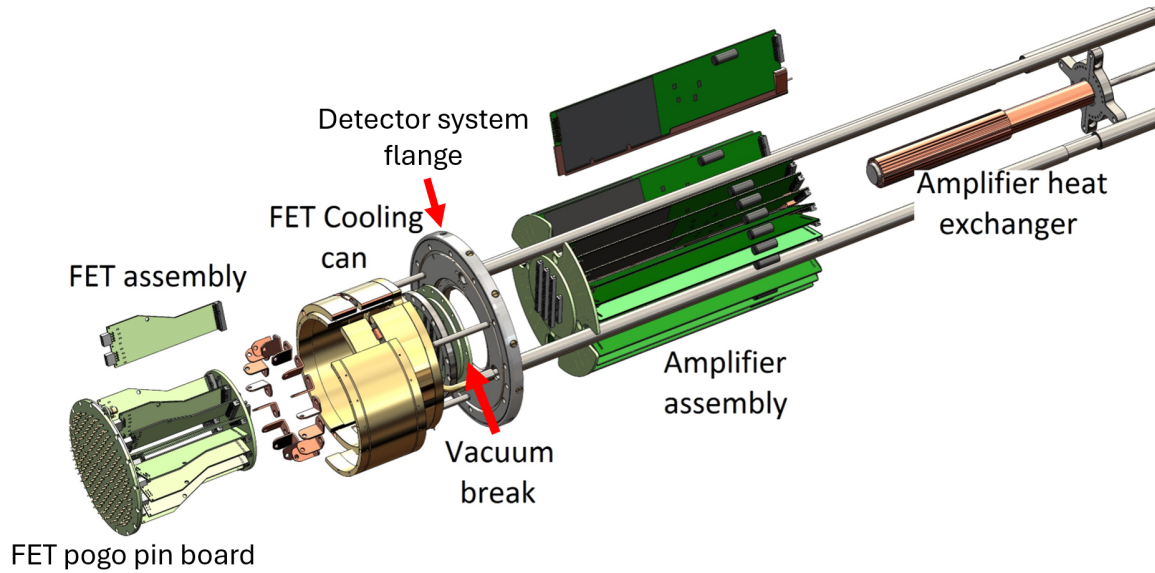


Figure 2.11: Exploded diagram of the detector electronics. The labelled vacuum break is between the FET volume which is maintained at a rough vacuum and the preamplifier volume which is in air.

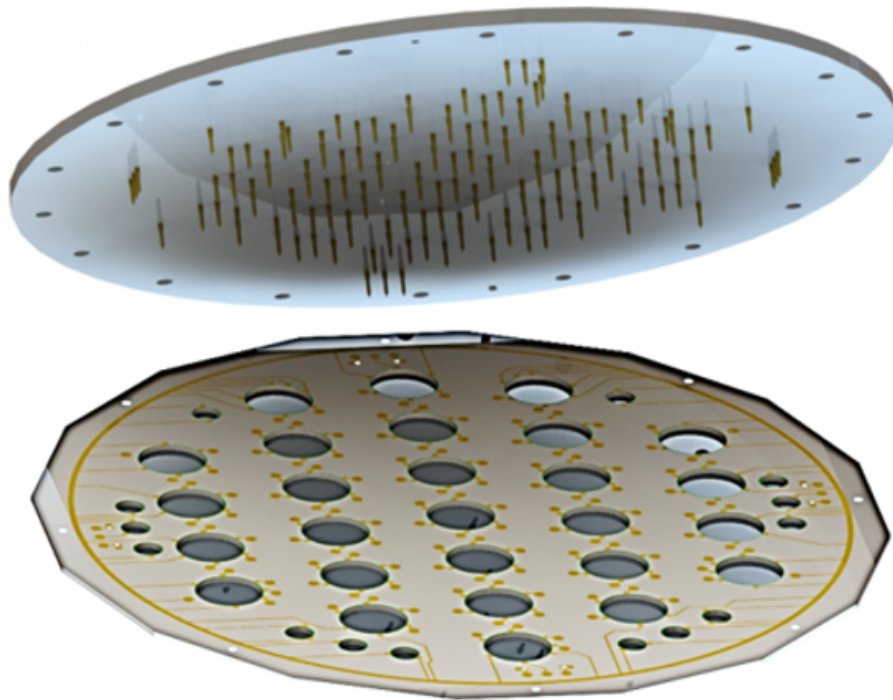


Figure 2.12: The Rogers board (top) and the ohmic face of a detector (bottom). The Rogers boards pogo pins make electrical contact with the gold plated circles on the back of the detector.

2.5.5 Detector Armor

The detector armor has gone through a couple upgrades over the last five years. The first upgrade was to account for the difference in thermal contraction of the copper armor and the ceramic back plate of the detector. The most recent upgrade is was to introduce three new features.

1. A clocking feature and alignment pins to make installing the armor and detector assembly more foolproof. (We're all fools sometimes!)
2. A slot for the witness plate to be mounted in.
3. A slot and clamp for a Lakeshore PT-111 temperature sensor to be installed in.

The witness plate (Fig. 2.13(a)) was added in response to concerns that arose during commissioning that a contaminant was being introduced to the face of the detector and effectively forming an unexpected deadlayer that shifted the

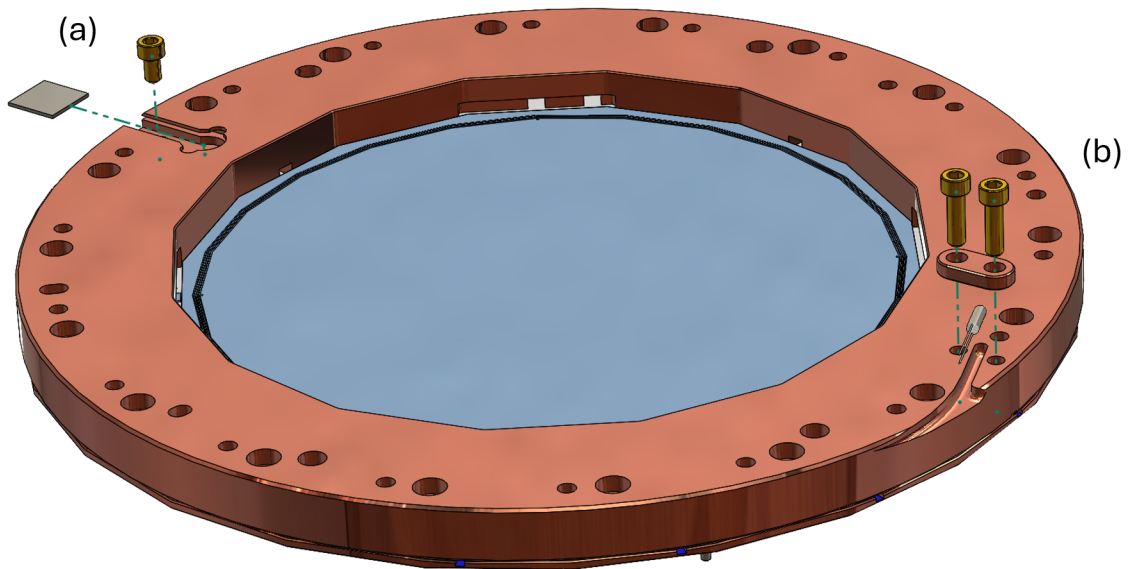


Figure 2.13: Detector armor with new features for (a) the witness plate and (b) temperature monitoring.

average measured proton energy down. The witness plate is a removable, 1 cm³ square silicon wafer. Its size makes it compatible with the ellipsometry instruments that are available onsite at the ORNL Center for Nanophase Materials Sciences (CNMS) which will be used for characterizing any future depositions on the silicon wafer.

The new temperature sensor feature (Fig. 2.13(b)) was added to test a model of temperature sensor for ultra-high vacuum compatibility. The Lakeshore PT-111 model was selected due to its ultra-high vacuum compatible materials, and the precision that it can achieve within the magnetic field environment.

Chapter 3

Nab Detector Cooling System

3.1 Motivation and Challenges for Cooling the Nab Detectors

Energy resolution, timing resolution, and detection efficiency are partially influenced by the temperature stability of two main components: (1) the detector and (2) the amplifying electronics:

1. With detector temperatures of 150 K or less, the signal-to-noise ratio is sufficient for seeing proton signals. Temperature stability is necessary to maintain a consistent detector response to incoming charged particles.
2. Similarly, the BF862 N-channel junction field-effect transistors (FETs) used for initial signal amplification must be kept at a relatively constant temperature since their gain varies with temperature. They must also be cooled to mitigate the heat load from the amplifying electronics on the detector.

Hence, the detectors and a portion of the accompanying front-end electronics must both be actively cooled. A recirculating, gaseous-helium-based cooling system has been designed and implemented to accomplish this. The low specific heat of helium offers fine control over system temperatures, and its low boiling point circumvents

some of the complications that can arise with cryogenic liquid-based cooling. Details of the design and performance of this system will be discussed below.

The two main goals for the Nab detector cooling system are to cool both detectors to below 150 K and to achieve ± 0.5 K stability.

Cooling the detectors to below 150 K reduces noise due to thermally excited electron-hole pairs in the silicon since this process is positively correlated to temperature. As Knoll tells us, “the probability per unit time that an electron-hole pair is thermally generated is given by”:

$$p(T) = CT^{3/2}e^{-\frac{E_g}{2kT}}, \quad (3.1)$$

where T is absolute temperature, E_g is bandgap energy, k is the Boltzmann constant, and C is a proportionality constant characteristic of the material (39). The observable associated with this is detector leakage current which decreases as the detector is cooled.

Electron-hole pair creation energy varies with temperature (35). This temperature dependence means that changes in temperature can lead to different *measured* energies for incident particles of the same energy. The observable here is a shift of the energy peak measured by the detector. This is studied with a 207-Bi source in Chapter 4. The mobility of charge in silicon is also temperature dependent. This directly affects rise times of signals (35). For Nab to meet its precision goals, the uncertainty on particle arrival times must be understood to ± 0.3 ns.

The detectors are located at the upper and lower ends of the 7 m tall Nab spectrometer and there is limited floor space near the detectors. The cooling system had to be designed around these spatial constraints (see Fig. 3.1). So, the bulk of the cooling equipment was installed on the more spacious beamline enclosure “roof” that is roughly level with the middle of the magnet, and cold helium is delivered to each detector via long vacuum-insulated transfer lines.

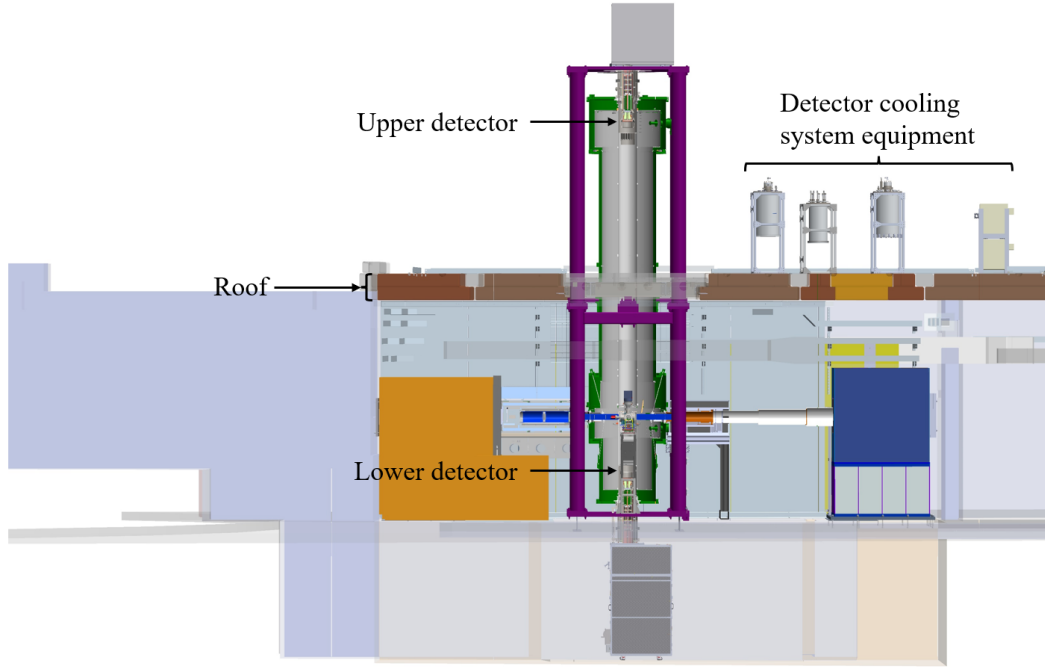


Figure 3.1: This schematic shows the locations of the detectors relative to the placement of the detector cooling system equipment.

The detectors are operated at high voltage. In particular, for the measurement of a the upper detector is floating at -30 kV (this has been discussed in Section 2.4.1). For safety, access to the detectors must be contained within Faraday cages. Thus, the insulated helium lines must traverse a high voltage break to reach the detector system. To do this, we designed specialty components that are electrically and thermally insulated as discussed in Section 3.2.

Data collection for Nab proceeds for months at a time. Therefore, the cooling system must be able to operate continuously for these long periods. So, the cost of helium gas and the logistics of providing a constant supply to the system motivated a closed-loop that recirculates the coolant.

Since Nab is a high precision experiment, it is also crucial to minimize introducing any noise to the detectors which could obscure proton signals. In early tests with LN_2 as the coolant, disruptively high levels of noise were observed in the detectors (11).

Noise due to physical shaking of the cooling lines and hence microphonics is minimized by using helium gas instead of liquid nitrogen.

We are able to achieve cost-effective helium circulation by implementing two double diaphragm process pumps which must be operated above the freezing temperature of water instead of utilizing much more expensive pumps which are capable of circulating media at cryogenic temperatures. We recover some of the cooling power that is lost by warming the gas on each cycle with off the shelf counter flow heat exchangers *. This is discussed in Section 3.2.

3.2 Nab detector cooling system design

The Nab detector cooling system consists of two independent, helium gas recirculating, closed loops. One loop is for the upper detector system and one is for the lower detector system. The two loops are nearly identical with the only difference being in the geometry of the transfer line routes.

Within each loop, a KNF Neuberger N1400.1.2 double diaphragm process pump circulates the helium gas (Fig. 3.2(a)). With respect to the piping and instrumentation diagram shown in Appendix A, the direction of flow is right to left across the KNF pump (P-001). Just downstream of the outlet of the KNF pump, an MKS GE250A mass flow controller † is used to precisely control the flow rate of the helium gas. The flow rate can be changed to make adjustments to the temperature of helium gas. After the flow controller, the gas enters a counter flow heat exchanger that is housed in a vacuum vessel (“Tardigrade,” Fig. 3.2(b), Fig. 3.3(b)).

In the counter flow heat exchanger (CFHX) the gas is pre-cooled by thermal contact with cold gas that is returning from the detector system to the KNF pump in the other leg of the CFHX. The gas then exits the vacuum vessel that houses the CFHX via a 6’ long vacuum-insulated transfer line and enters a separate vacuum

*<https://www.mcmaster.com/8546T11/>

†<https://www.mks.com/f/ge250a-ge300a-mass-flow-controller>

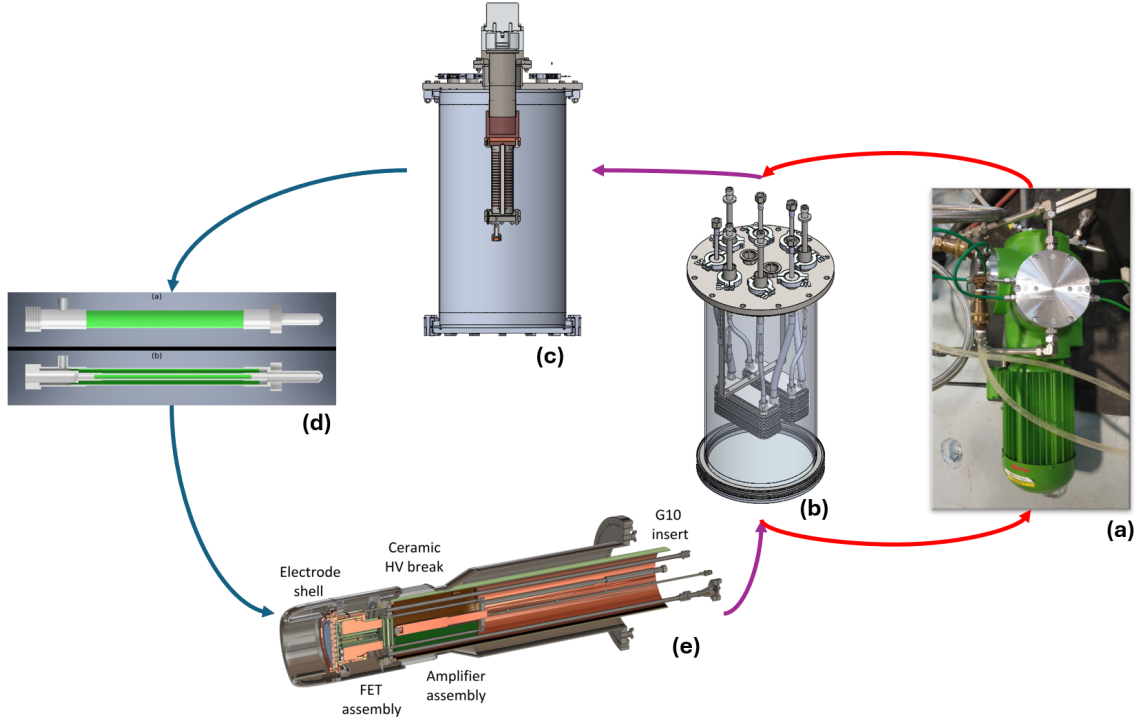


Figure 3.2: Representative flow diagram of one cooling loop (the second loop is functionally identical):(a) KNF Neuberger double diaphragm process pump, (b) Counter flow heat exchanger (“Tardigrade”); vacuum vessel and both counter flow heat exchangers are shown, only one is used in each loop, (c) Primary heat exchanger and vacuum vessel (“Cool-o-stat”), (d) Custom G-10 high voltage feed through (HVFT), (e) Nab detector system.

vessel in which a Sumitomo CH-110 cryocooler is mounted (2). The pre-cooled gas flows through the primary heat exchanger which is mounted to the cryocooler (“Cool-o-stat,” Fig. 3.2(c), Fig. 3.3(a)). See Fig. 3.3 for a view of the two vacuum vessels and the components they house.

As the gas travels through the primary heat exchanger, it passes through a series of oxygen-free high-conductivity (OFHC) 101-copper disks separated by OFHC 101-copper spacers (Fig. 3.4). The arrangement of plates in the primary heat exchanger maximizes the path length through the heat exchanger and the turbulence of the helium flow, increasing the cooling efficiency of the cold head. Helium exits the heat

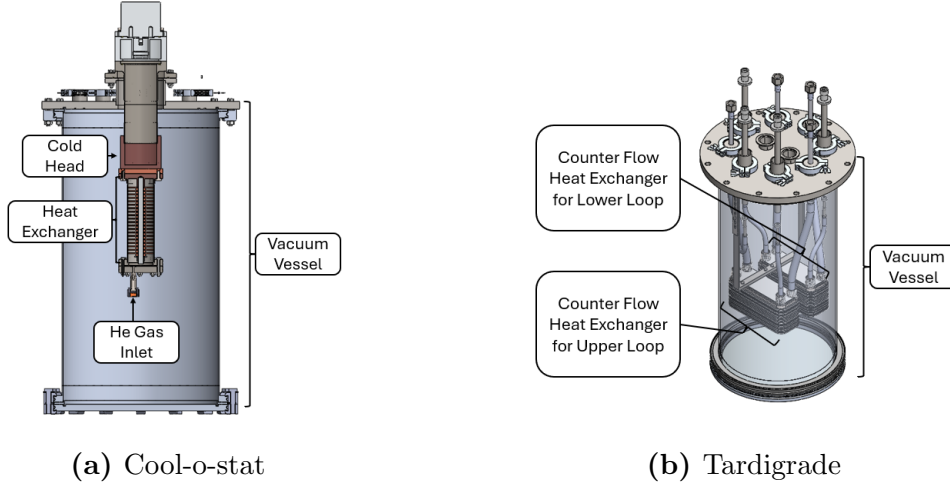


Figure 3.3: (a) A cut view of the vacuum vessel that houses the cold head and the primary heat exchanger which is mounted to it (“Cool-o-stat”); (b) A view of the vacuum vessel with transparency to show the CFHXs for both of the cooling loops that are housed within (“Tardigrade”).

exchanger at sub-100 K temperatures. This is the coldest point for the helium gas in the system (typically 40 to 50 K).

Before it exits the lines within the Cool-o-stat vacuum vessel, the gas passes over an in-line cartridge heater and an in-line platinum resistance temperature detector (RTD) (these can be seen in Fig. 3.8). These components form the essential constituents of a proportional–integral–derivative (PID) feedback loop, which can be used to regulate and stabilize the temperature of the helium coolant. The PID loop itself is controlled by a Lakeshore 336 Controller[‡] which operates by monitoring the RTD and adjusting the power output of the cartridge heater. The helium is then carried to the detector system by a long vacuum-insulated transfer line (38’ for the upper detector and 47’ for the lower detector).

The transfer line mates with the specialty component that goes across the high voltage break which we have termed the G-10 High Voltage Feed Through (HVFT) (Fig. 3.2(d), 3.5, and 3.6(a)). These custom HVFTs were designed and fabricated to transport the gas into the high voltage cage, across the 30 kV potential drop between

[‡]<https://shop.lakeshore.com/temperature-products/temperature-controllers/336.html>

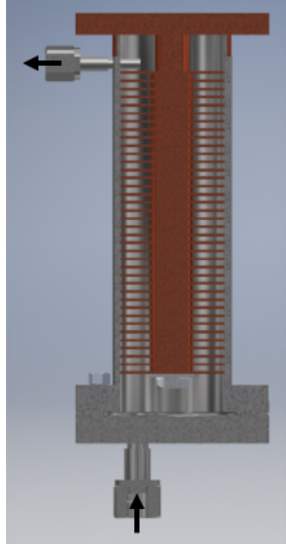


Figure 3.4: This is the primary heat exchanger. It was custom-built for this detector system. It contains 37 OFHC 101-copper disks separated by OFHC 101-copper spacers. A through hole in the center of the disks and spacers allows them to be stacked over the rod that is concentric with the cylinder that forms the outer shell of the heat exchanger. The disks each contain an additional 1/4" hole that is offset from the center for gas to pass through and neighboring disks are rotated 180° out of phase. Gas enters through the bottom of the heat exchanger.

the inner and outer cage. To maintain an electrical break across the inner and outer high voltage cages, G-10 was used for both the outer vacuum jacketing and the inner transfer line of the feed through. The G-10 transfer line and vacuum jacketing were epoxied to 3" Linde style Cryofab bayonets. Within the inner high voltage cage, the HVFT mates with the detector mount by means of an additional custom bayonet-style connector.

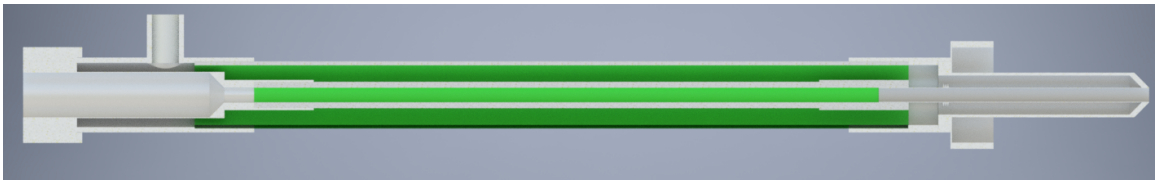


Figure 3.5: Cross section of a CAD model of a Nab HVFT.

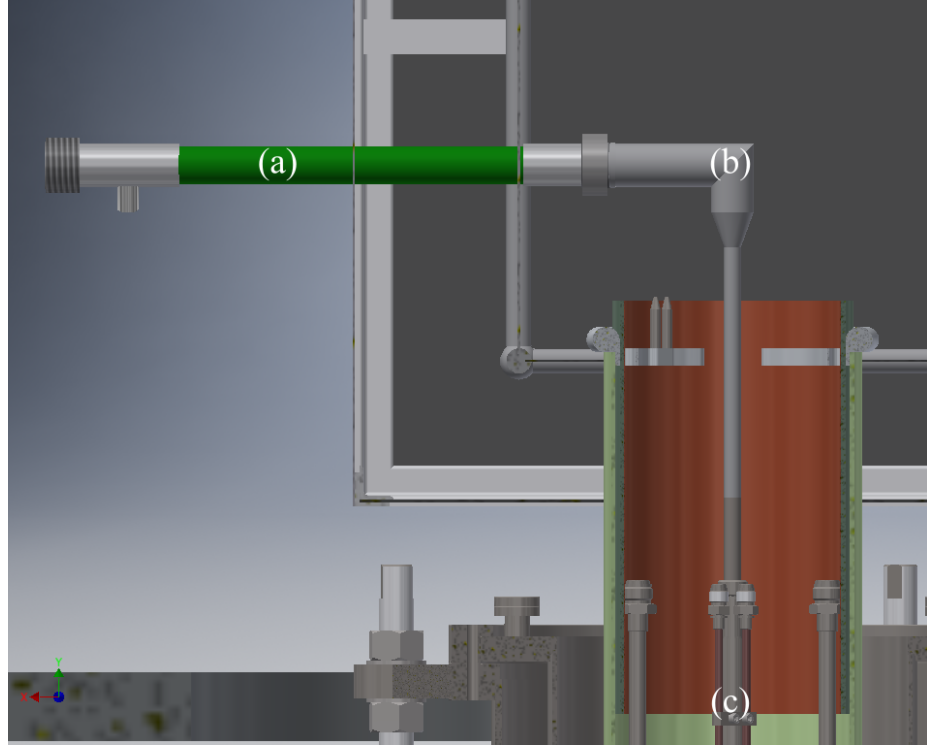


Figure 3.6: CAD model of the connections between (a) the HVFT, (b) the custom connector, (c) and the detector system cooling lines.

This custom bayonet is vacuum-jacketed and it has a right-angle in it which necks down to a lance (Fig. 3.6(b)) that feeds the gas into the 1/4" inner diameter vacuum-jacketed stainless steel line that is part of the detector system (Fig. 3.6(c)). The line in the detector system goes through a vacuum break into the FET can. The FET volume is maintained at a vacuum level around a few 10^{-4} Torr. Thus, no vacuum jacketing is required for the cooling line in this volume. The cooling line wraps around within the FET volume roughly 1.5 times forming the "Ring" (Fig. 3.7(a)). The shroud assembly (Fig. 3.7(c)) functions as a heat exchanger between the helium gas and the detector and FET cards. The FET volume is directly behind the detector, which is where the cold helium dissipates the heat load on the detector. The gas then exits the FET volume to an identical 1/4" id stainless line, then cryogenic elbow, G-10 HVFT, and goes to a long vacuum-jacketed return transfer line (39' for the upper detector and 48' for the lower detector). The return line goes to the vacuum

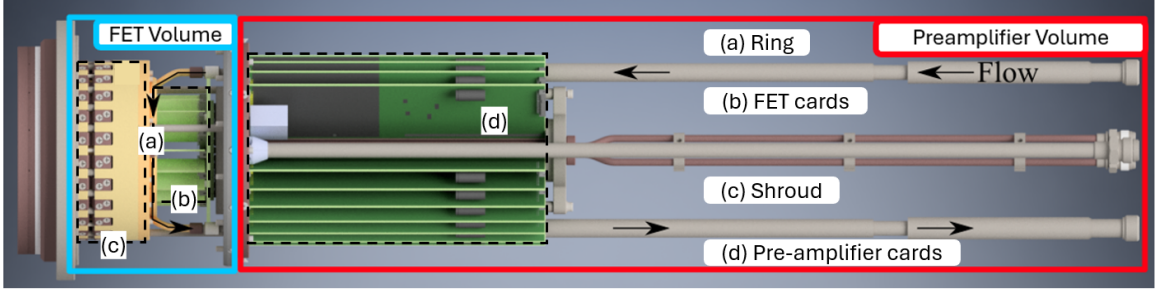


Figure 3.7: A 3D model of the inner components of a Nab detector system. The pre-amplifier volume is maintained at room temperature and 1 atm. Helium gas enters the mount in the upper line and travels downstream through the mount as indicated by the arrows. The FET volume is evacuated to $\sim 10^{-4}$ Torr. The cooled helium gas circulates around the ring (a).

vessel that houses the CFHX (Fig. 3.2(a) and 3.3(b)). Here the still somewhat cold gas comes into thermal contact with the warm gas leaving the KNF pump in the opposite leg of the CFHX. This warms the helium up to above 273 K before it enters the KNF pump where the cycle through the loop repeats.

3.3 Temperature Sensor Locations

The Nab detector cooling system is instrumented with several temperature sensors. There are two in-line platinum RTDs in each loop. The approximate locations of the sensors within the Cool-o-stat assembly are shown in Fig. 3.8. One is at the inlet to the primary heat exchanger to monitor the temperature of the pre-cooled gas. The second in-line platinum RTD is used to monitor the temperature of the helium leaving the primary heat exchanger that is mounted to the cold head. Each cold head has two temperature sensors mounted to the interface plate that is between it and the primary heat exchanger (Fig. 3.8). During the commissioning of this system, temperature monitoring for the detector system itself was inconsistent because the detector system was undergoing commissioning in parallel. Thus, different temperature sensor locations are used in the upper and lower mounts to benchmark performance. We cannot put a temperature sensor directly on the surface of the silicon detector, so

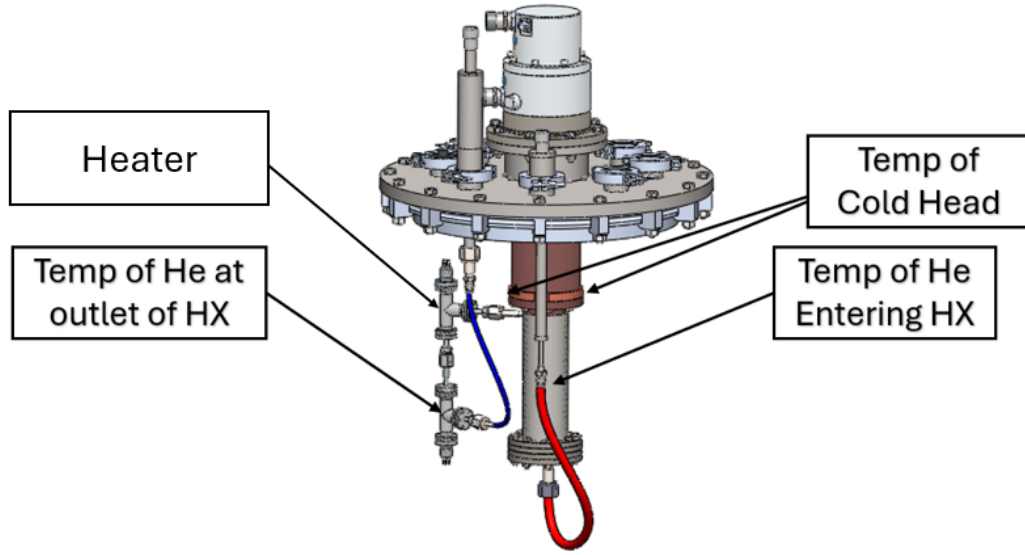


Figure 3.8: A view of the cold head and custom heat exchanger inside the Cool-o-stat with labels for the approximate locations of temperature sensors and the in-line heater.

the temperature in the FET volume for the upper detector and the temperature on the Ring for the lower detector (approximate locations shown in Fig. 3.9) are used to benchmark the performance of the system.

3.4 Performance and Discussion

The figures of merit for the Nab detector cooling system are its ability to operate continuously for a beam cycle, temperature stability, and detector temperatures achieved. The performance of the Nab detector cooling system during the first simultaneous cooldown of the upper and lower detector systems which started June of 2023 and ran through November 2023 is presented here in terms of these figures of merit. They are followed with a discussion of heat load calculations for the system. The heat load calculations use data from a more recent cooldown where performance of the system was further optimized.

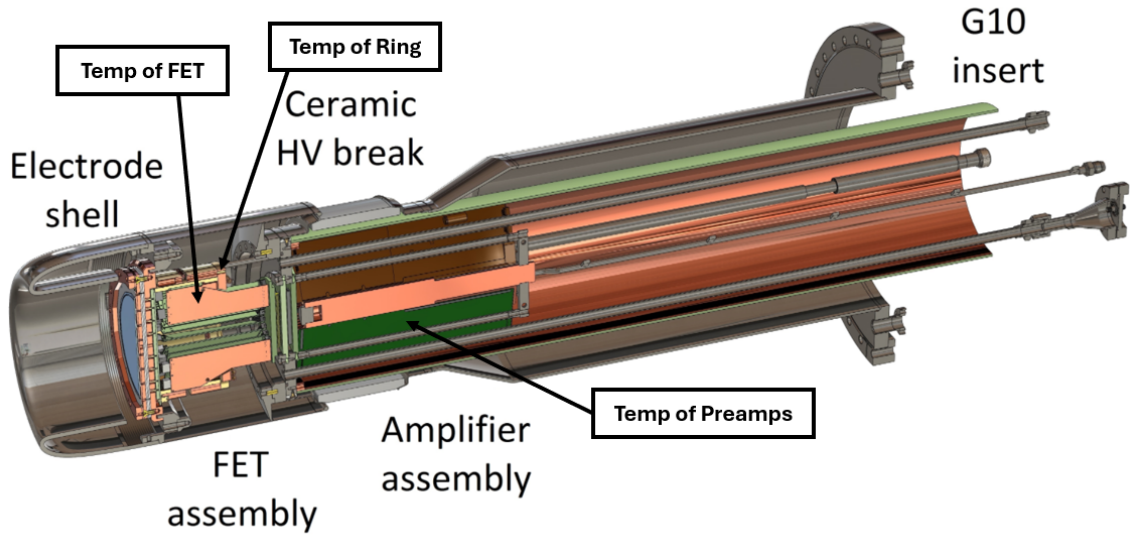


Figure 3.9: A cut view of the detector system with labels for the approximate locations of temperature sensors.

Continuous operation. The only interruption in operation during the commissioning period described above was to repair a KNF pump diaphragm rupture in the lower loop. The resulting downtime was roughly two days. In the future, downtime from similar failures can be reduced by heat curing the thread-lock on the diaphragm retaining plate. Furthermore, we now have a third circulation pump that we can swap into the system to avoid longer outages due to pump failure.

It is important to understand the performance of the KNF Neuberger double diaphragm process pumps to optimize the performance of the cooling system. The rubber diaphragms in the heads of each pump wear out over time. The best solution to this is to replace the diaphragms routinely. Another factor that can increase the likelihood of a diaphragm rupture is operating the system with the inlet pressure of the circulation pump well-above or well-below atmospheric pressure. Either of these operation modes significantly decrease the lifetime of the diaphragms and reed valves within the pump heads. Finally, the circulation pumps will get very hot if they are

not actively cooled. We use chilled water to cool them during operation. This is two-fold in its benefits to the system. It lowers the amount of wear on the diaphragms and reed valves, and it also reduces the contribution of the pumps to the heat load on the system. In summary, by periodically replacing the diaphragms, by running the system so that the pump inlet pressure is approximately equal to atmospheric pressure, and by actively cooling the circulation pumps, we can run the system for full beam cycles (approximately 3 to 6 months) uninterrupted.

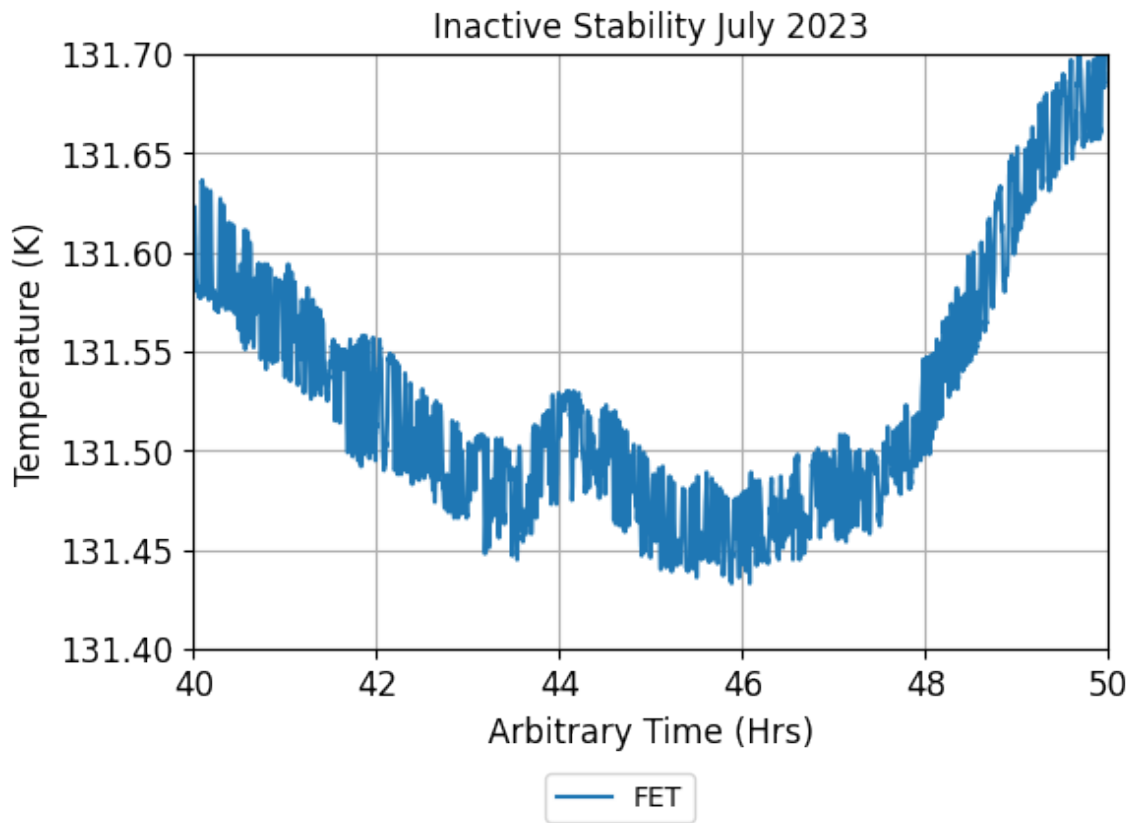


Figure 3.10: This plot shows the temperature of the upper detector FET volume over a 10 hour period during an inactive period—overnight—while no changes were being made to the detector configuration.

Inactive stability. The system is capable of achieving ± 0.2 K inactive stability over a ten hour period (see Fig. 3.10). Inactive stability refers to the temperature stability during a period where the in-line heater is off, the flow rate is constant, and the state of the detector is stable. Under these conditions, the temperature at

the FET in the upper detector system varied by less than 0.2 K over a 10 hour long period. The temperature of the detector is sensitive to the amount of power being supplied to the FETs. In addition, active changes in the experiment hall conditions and in the power being supplied to the detector electronics did lead to larger than 0.2 K variations in the temperature. The design goal is to achieve ± 0.5 K active temperature stabilization, so if we can control external factors we will be able to achieve better than this.

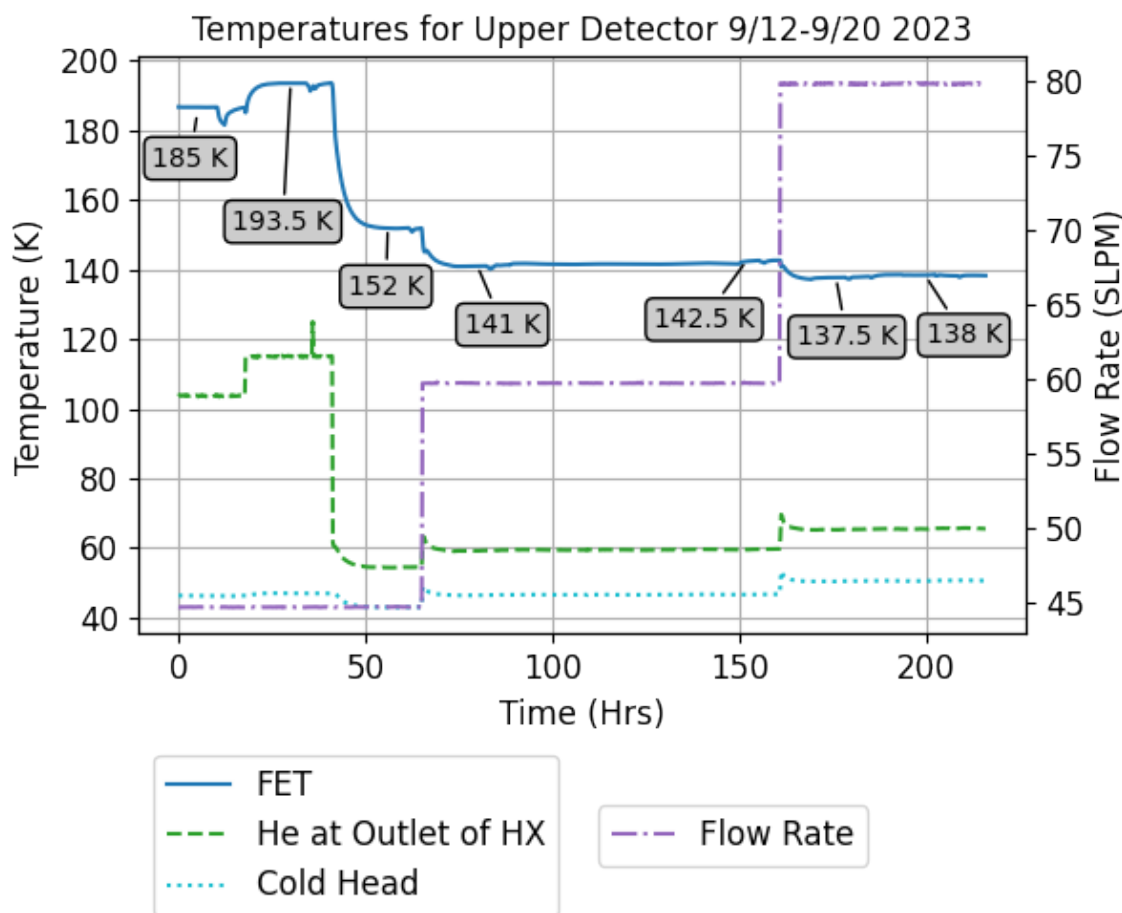


Figure 3.11: This plot demonstrates the dynamic capabilities of the system. Each stabilization temperature for the upper FET volume is explicitly labeled (grey outlined text). The temperature sensor and flow rate line colors and styles are represented in the key below the plot. The smaller changes in temperature at a constant flow rate were achieved with the in-line heater.

Active stability. With a combination of controlling the flow rate of the helium and the settings on the in-line heater and PID loop, this system is capable of achieving stabilization for the full range of temperatures that it can access. Target temperatures are accessed by dynamically tuning the flow rate and heater settings. It is demonstrated in Fig. 3.11 that the system is capable of both fine and coarse tuning. This dynamic range enables future studies of temperature effects on the detector performance which are important to understand to reach the precision goals for Nab.

Temperatures. As discussed in Section 4, ongoing commissioning configurations have led to us using two different temperature sensor locations to benchmark performance in the upper and lower cooling loops. The FET temperature is used for the upper loop and the “Ring” temperature is used for the lower loop. During the June to November 2023 cooldown, the FET temperature in the upper detector system reached 129 K, and the “Ring 2” temperature for the lower detector system reached 129.4 K (See Fig. 3.12 and Fig. 3.13). This meets the goal for the cooling system of reaching temperatures below 150 K. This cooldown was an element of Nab’s commissioning data taking. Results from this commissioning effort are shared in (9).

The table below summarizes the temperatures reached in the June to November 2023 cooldown. The values that are used for benchmarking are bolded. (Note: “heat exchanger” is abbreviated with “HX” in the table.)

Table 3.1: Temperatures at different positions in the system during Nab’s commissioning.

Sensor Position	Preamplifier Volume	FET Volume or Ring 2	Outlet of Primary HX	Cold Head
Upper	312.9 K	129 K	60.3 K	46.7 K
Lower	308.5 K	129.4 K	73.0 K	50.4 K

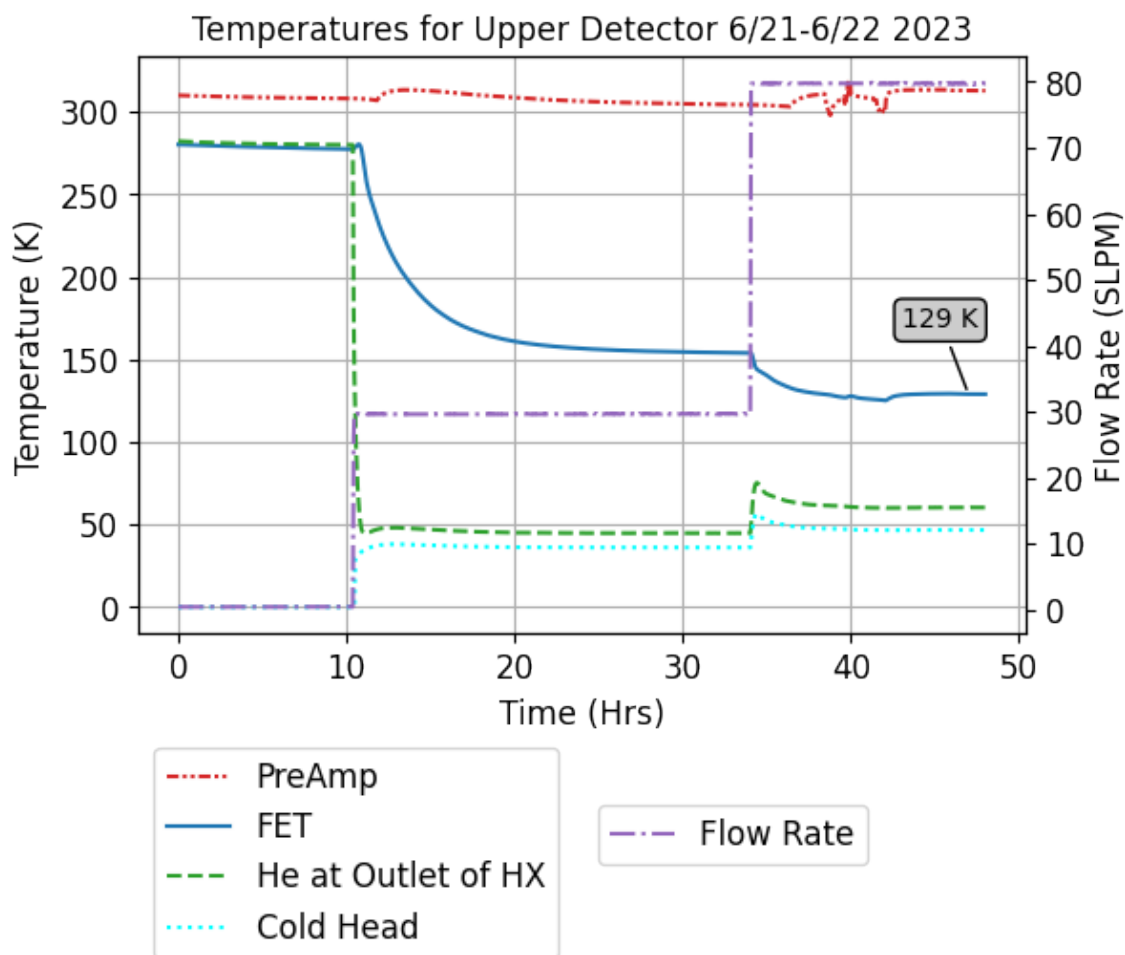


Figure 3.12: This plot shows the cooling system performance with the upper detector system at the beginning of the cooldown in June 2023. The temperature sensor and flow rate line colors and styles are represented in the key below the plot. Near the 10 hour mark, the cooldown was started. Around the 34 hour mark, the flow rate was changed from 30 SLPM to 80 SLPM. This pushed the FET volume temperature from just above 150 K to 129 K.

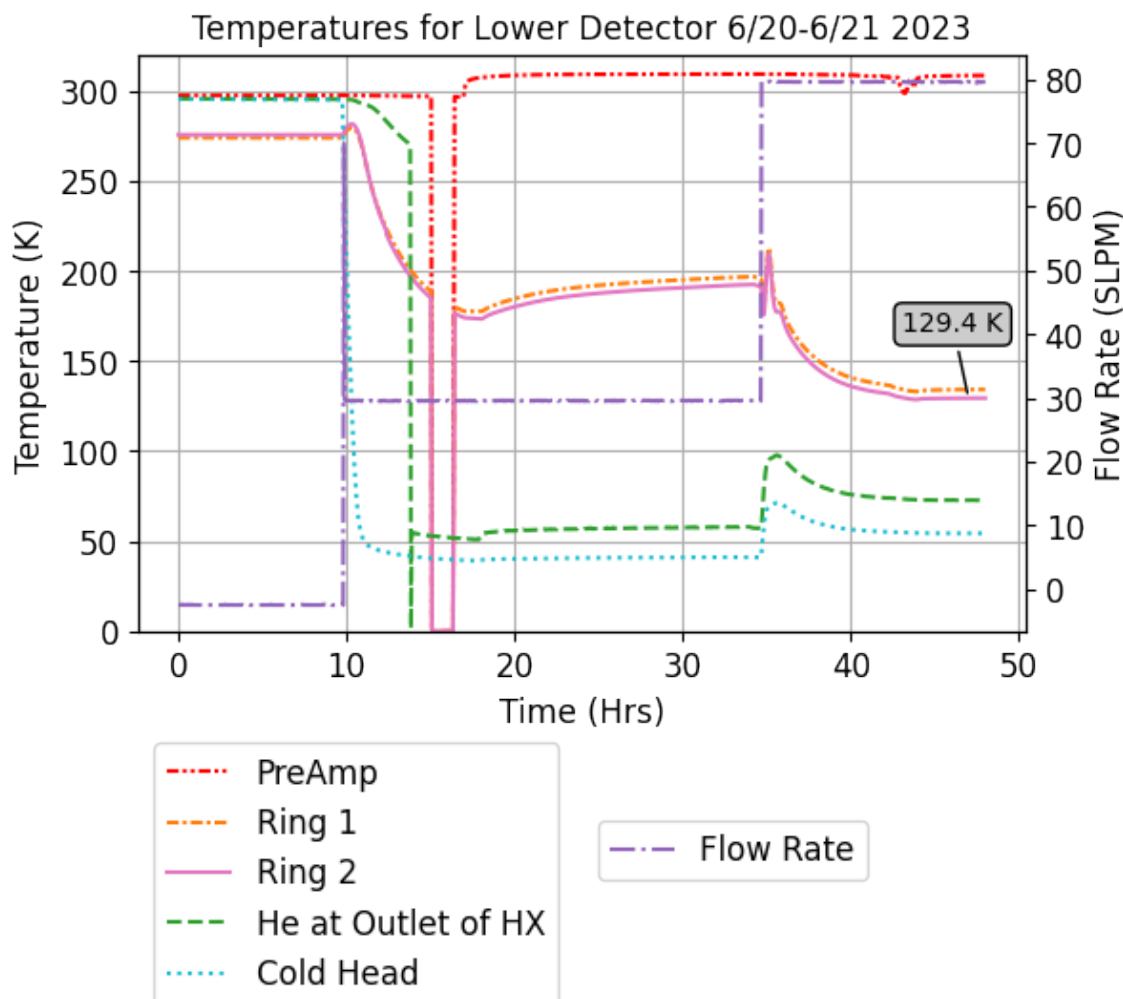


Figure 3.13: This plot shows the cooling system performance with the lower detector system at the beginning of the cooldown in June 2023. The temperature sensor and flow rate line colors and styles are represented in the key below the plot. Near the 10 hour mark, the cooldown was started. Around the 15 hour mark there was an interruption in temperature data being collected, but it was restored around the 17 hour mark. Around the 34 hour mark, the flow rate was changed from 30 SLPM to 80 SLPM. This pushed the ring temperature down from close to 200 K to 129.4 K.

It is notable that the performance of this cooling system is improved by pumping on all insulation vacua in situ. During the tests discussed in Section 3.5, the insulation vacuum for the long return transfer line from the detector system back to the Tardigrade for each loop was not being actively pumped on. With all insulation vacua connected to turbo pumps, sharing of turbo pumps for separate volumes was done where possible. The coldest temperature for the lower loop was lowered from 129.4 K to about 115 K, and the upper loop was lowered from 129 K to about 100 K.

3.5 Heat Loads

During the design-phase of the Nab detector cooling system, a series of engineering calculations were done to predict the detector system heat load. To make these estimates, a few assumptions were made: 1) all thermal connections are perfect, 2) radiative cooling from the bore of the magnetic spectrometer is neglected, and 3) heat from the preamplifier assembly is rejected via dry nitrogen or air circulation and the temperature at the cryo feed through is 300 K. With these assumptions and with attributing 3.2 W to the FET electronic heat load, the heat load from the detector system was estimated to be 32.12 W for each loop.

When actively pumping on all of the insulation vacua that are part of the detector cooling system, we are able to achieve colder detector temperatures. Here, we will refer to the values from running the lower cooling loop with the detector system in the room-temperature magnetic spectrometer to make estimates of the heat loads absorbed by the system in practice. To do this, we assume that the heat load from the transfer lines is 0.68 W/m, and that the heat load from each Linde bayonet connection is 2.163 W as specified by Cryofab (4). In practice, the heat loads may vary depending on the vacuum achieved in the insulation volume of the transfer lines. We used the following expression to balance the heat loads around the loop and come up with the heat dissipated by the cold head and an approximate heat load for the

detector system:

$$W = \dot{m}c\Delta T, \quad (3.2)$$

where W is heat, $\dot{m}$ is the flow rate, c is specific heat of helium which is assumed to remain relatively constant over the temperature range of interest, and ΔT is the difference in temperature across the component under consideration. Using Eq. 3.2, the heat removed from the system by the cold head is ~ 128 W, and the heat load of the detector system is ~ 48 W.

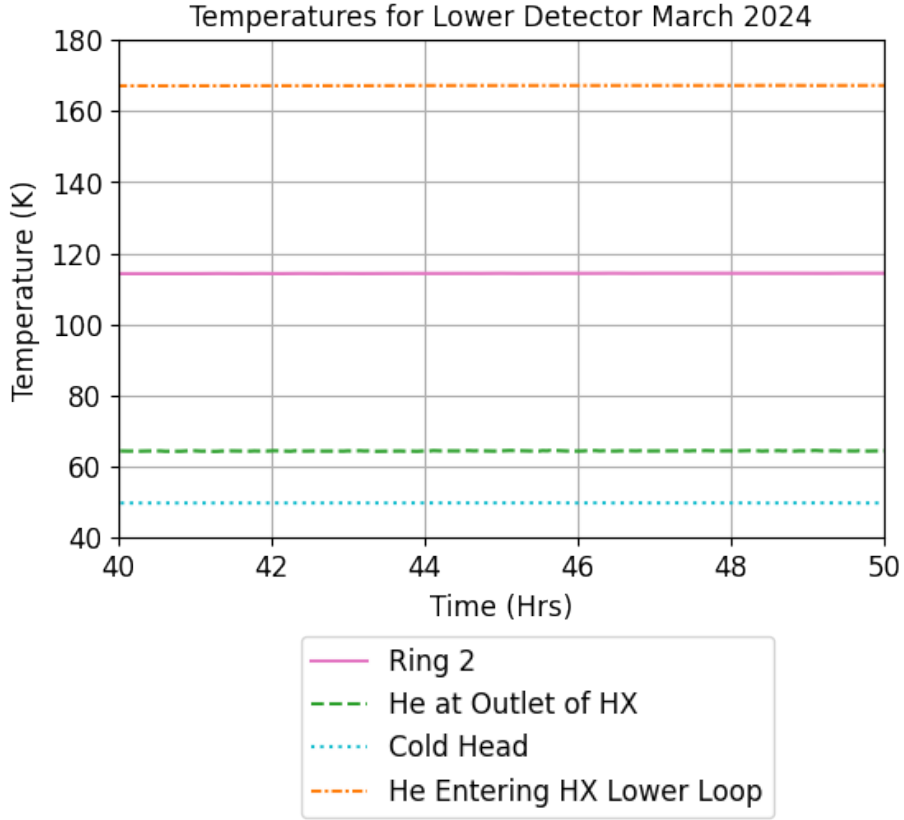


Figure 3.14: This plot shows the temperatures used for the heat load calculations. The temperature sensor and flow rate line colors and styles are represented in the key below the plot. The temperatures are lower than those in the performance section because post the commissioning run with both detectors we found that by actively pumping on all the insulation vacua the system could achieve significantly improved performance.

The heat removed by the cold head was calculated by using the difference in the temperature of the helium entering the HX and the helium leaving the HX (see Fig. 3.14). For the detector system heat load, the calculation was more involved. The heat loads from Cryofab for the transfer lines and Linde bayonets were used to extrapolate from the temperature of the helium leaving the HX to the temperature that the gas “should” be just before it enters the detector mount. The difference in the “Ring 2” detector system temperature and the estimated temperature of gas entering the detector mount was then used in Eq. 3.2 to determine the approximate heat load of the detector system to be 48 W.

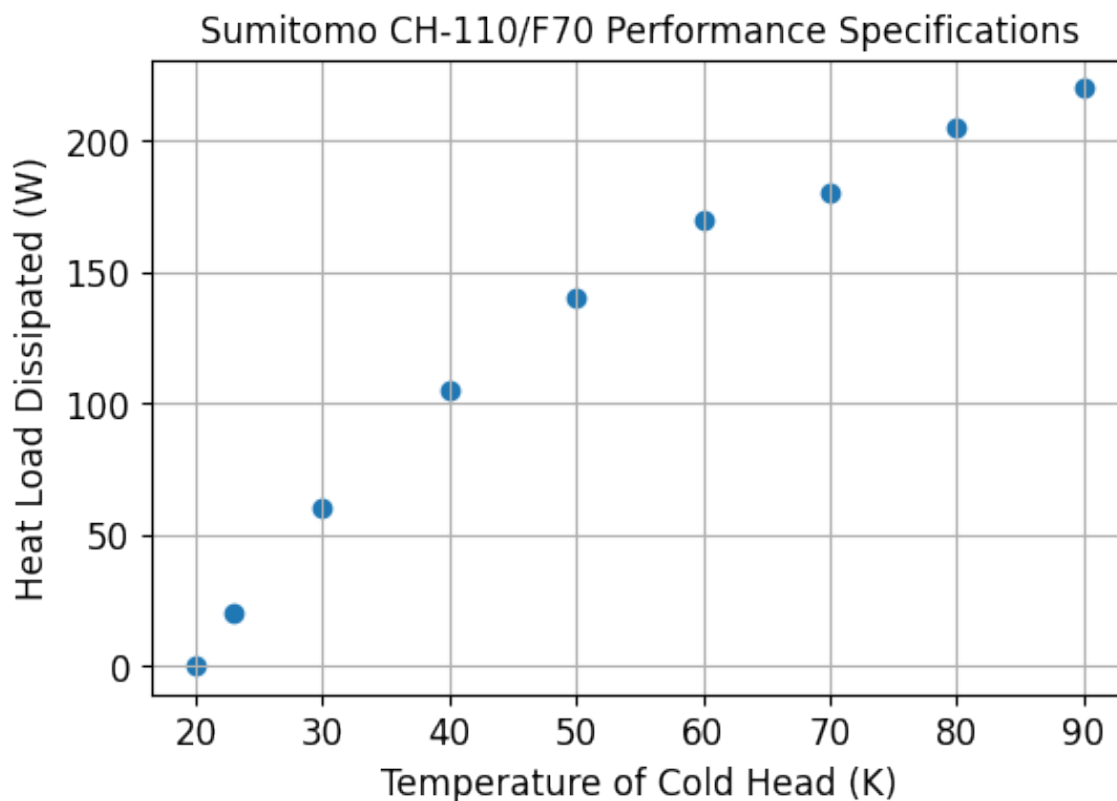


Figure 3.15: These specifications were provided by Sumitomo (2).

The cooling power curve provided by the Sumitomo CH-110 Cryocooler is shown in Fig. 3.15. The cold head was at ~ 50 K for the calculations above (see Fig. 3.14). At this temperature, the cold head should be able to remove 140 W of heat from the

system. Comparing this to the 128 W that is removed from the helium as it passes through the heat exchanger indicates that the cool-o-stat assembly has slightly better than 90% efficiency. At roughly 48 W, the heat load that is calculated for the detector system is $\sim 50\%$ higher than the 32 W that was initially estimated. The radiative coupling between the room temperature bore and the detector system will have some contribution to the heat load. Using thermal view factors, and approximating the detector as a disk concentric with a cylinder that represents the bore of the magnet, the heat load that the ΔT between the room temperature bore and cold bore will impose on the detector is ~ 2 W. Since the Nab experiment runs with the bore cold, the 48 W heat load can be adjusted to 46 W which is $\sim 44\%$ higher than the initial estimate. This may be due to thermal connections in the system with efficiencies that are not readily known as well as thermal coupling between the preamplifying electronics and the FETs that is not accounted for.

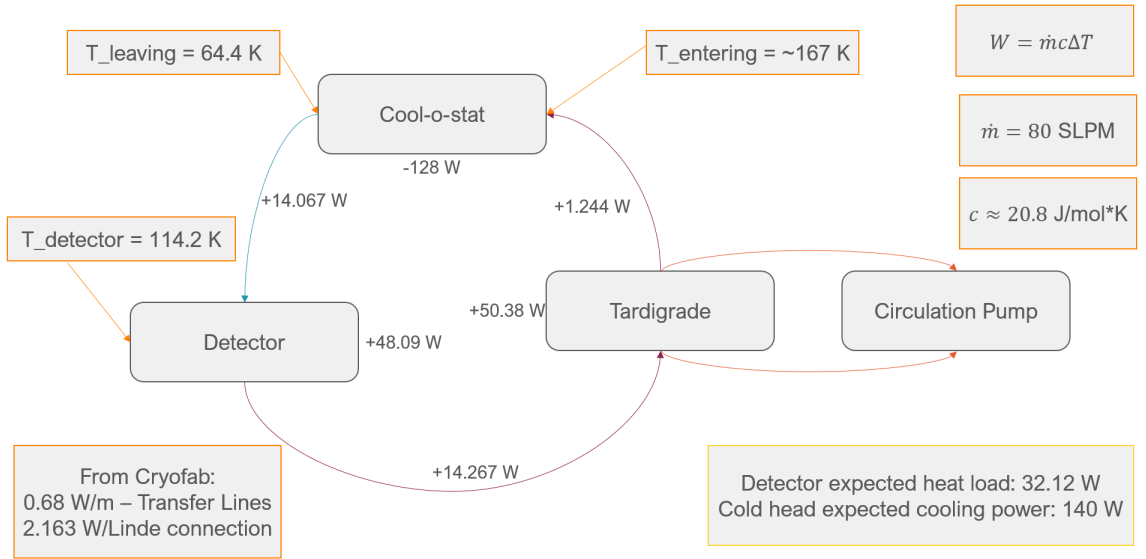


Figure 3.16: This diagram shows the approximate heat loads calculated using temperatures shown in Fig. 3.14.

3.6 Long Term Stability

The long term stability of the system is subject to all components of the system operating as expected, upkeep and troubleshooting are required proactively to maintain this. A small leak in the system, or failure of a circulation pump can easily cause a loss in efficiency and inconsistency in the stability of the detector temperature.

The plot in Fig. 3.17 shows the stability that was achieved with the cooling system for the upper detector in November of 2024 while the system was operating as expected. Over the five day period that is shown the temperature of the armor (which is the closest to the detector temperature) was maintained at 129.014 ± 0.401 K.

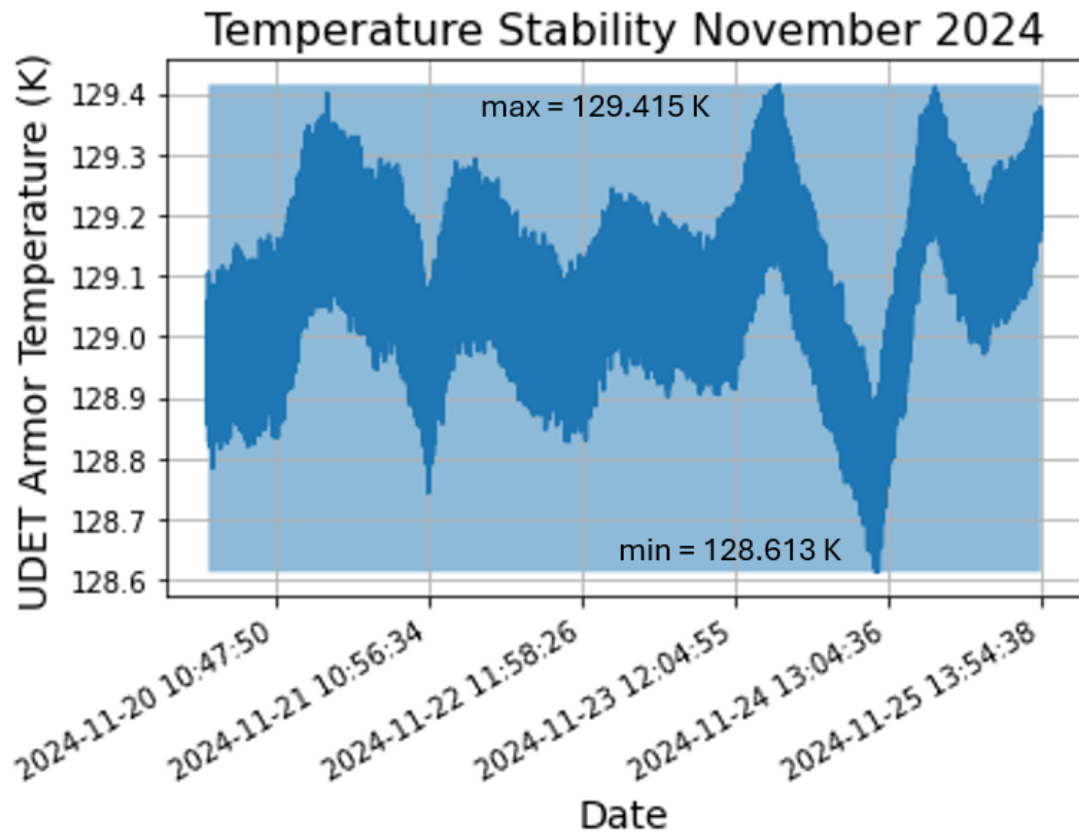


Figure 3.17: Temperature stability achieved for the upper detector over a period of five days.

Chapter 4

Temperature-Dependent Detector Studies and Analysis

There are two consequences of temperature variation that require detector temperature stability in the Nab Experiment.

1. Detector gain is sensitive to changes in ehp creation energy with temperature.
2. Signal rise times vary as charge mobility changes with temperature.

These were introduced briefly in Section 3.1, but this chapter will provide further detail especially for (1) as it has been the main focus of the temperature dependent studies so far. The 0.5 K stability design goal for the cooling system comes from a conservative calculation to determine what temperature variation will restrict detector gain shift to less than 1×10^{-4} (7). Inputs for this calculation came from values published in literature on the temperature dependence of ehp creation energy in silicon.

4.1 Electron-Hole Pair Creation Energy

The energy gap, or band gap, between the valence and the conductance bands in silicon increases with decreasing temperature (35; 53). The band gap temperature

dependence in silicon is represented by:

$$E_g(T) = E_g(0) + \frac{aT^2}{T + b}, \quad (4.1)$$

where $E_g(0) = 1.1692$ eV, $a = (4.9 \pm 0.2) \times 10^{-4}$ eV, and $b = 655 \pm 40$ K (35). In practice, the energy required to create an electron-hole pair, ϵ_{ph} , in semiconductors (like silicon) is greater than E_g .

Canali et al. showed a linear relationship between ϵ_{ph} and E_g , but their fit parameters did not match the behavior observed by Pehl et al. (15; 49?).

Several experiments have been conducted to investigate the relationship between ϵ_{ph} and temperature (14; 16; 38; 49; 53). A high level summary of the results of these experiments are shown in Fig. 4.1.

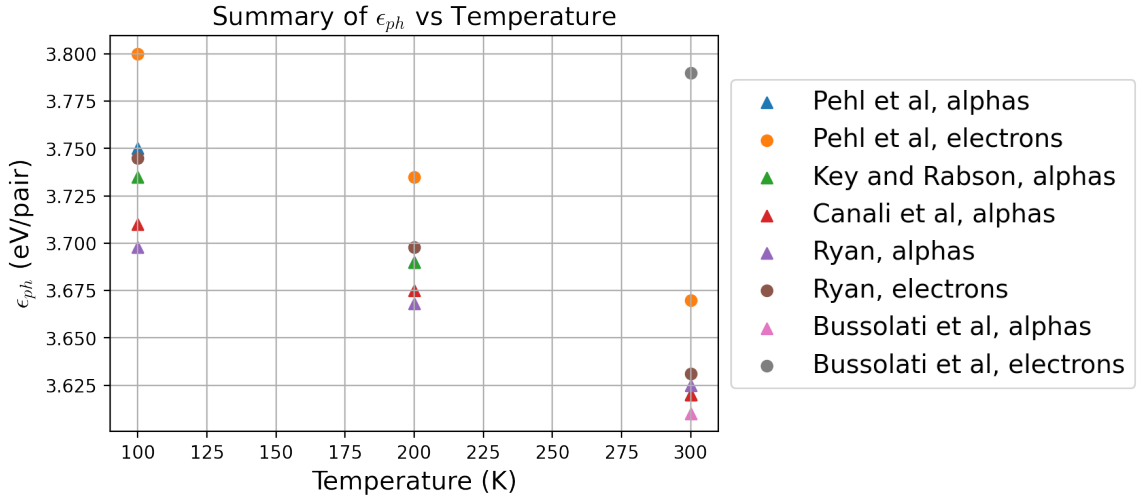


Figure 4.1: Summary of temperature dependent electron hole pair creation energies in silicon from literature (14; 16; 38; 49; 53).

The collective literature points to an approximately linear relationship between ϵ_{ph} and temperature. So, using the 3 points represented in the summary plot for each (excluding Bussolati et al.'s work since they only provided data at 300 K), linear fits were made for the data sets represented in Fig. 4.1. The slopes of these fits are summarized in Table 4.1.

Table 4.1: Approximate slopes of ϵ_{ph} vs. temperature taken from the summary plot in Fig. 4.1.

Author(s)	Particle Type	Slope (eV/K)
Pehl et al.	alphas	-0.000650
Pehl et al.	electrons	-0.000650
Ryan	alphas	-0.000365
Ryan	electrons	-0.000570
Key and Rabson	alphas	-0.000575
Canali et al.	alphas	-0.000450

Pehl et al. (49) and Ryan (53) performed high precision measurements, so their results will be used for making estimates of temperature stability requirements for Nab. Pehl et al. used a lithium-drifted silicon detector to make measurements for gammas, electrons, and alphas over the temperature range 90 to 300 K. A carefully selected step pulser and a three terminal calibration capacitor were used to generate a known charge pulse which enabled the precise, absolute measurement of ϵ_{ph} (49). Ryan used two ~ 2 mm thick, high purity silicon guard ring detectors with a ~ 10 nm gold surface barrier with different resistivities to measure electrons and alphas over the temperature range 100 to 250 K. They used the same careful electronics chain as Pehl et al. to make an absolute measurement of ϵ_{ph} . Pehl et al. provides the most-referenced work on this subject and the Ryan measurement used detectors that are more similar to the Nab detectors than those used by Pehl et al.

The normal operating temperature for the Nab detectors still needs to be determined, but for the sake of these calculations I will assume that the operating temperature of the detectors is 120 K. This is well within the capabilities of the existing helium gas detector cooling system and offers the reduced noise benefits that come with colder detectors without being so cold that it will lead to freeze out in the FETs. Gain shift per K can be determined by taking the ratio of the slope of ϵ_{ph} vs. T to the approximate ϵ_{ph} that corresponds to the standard data-taking temperature. The needed values were obtained by making linear fits to the relevant data shown in Fig. 4.1. To make a conservative estimate of the temperature stability

requirements, the slope is taken from Pehl et al.'s data since it is larger than Ryan's, and the ϵ_{ph} is taken from Ryan's results since it is smaller than Pehl et al.'s and in the denominator. The values of ϵ_{ph} for electrons are used because they are higher than that for the alphas and will therefore yield a more conservative constraint on temperature stability. This results in the following:

$$\text{gain shift/K} = \frac{m_{\text{Pehl}}}{\epsilon_{\text{Ryan}}} = \frac{0.00065}{3.72} = 0.000172/\text{K}. \quad (4.2)$$

Using this gain shift per Kelvin, and the 1×10^{-4} allowable gain shift yields:

$$0.000172/\text{K} \times T < 0.0001 \longrightarrow \boxed{T < 0.588 \text{ K}}. \quad (4.3)$$

The detector temperature must be maintained with a stability of ± 0.588 K in order to constrain the gain shift to the needed level. It is then reasonable to truncate this value to 0.5 K since this will be an even more conservative restriction. The detector cooling system was shown in Section 3.6 to achieve ± 0.401 K.

4.2 The Anatomy of a Waveform

A waveform, also referred to as a pulse or a signal, is a depiction of the energy collected by the data acquisition system (DAQ) with respect to time. Each waveform consists of 7000 time bins. The DAQ logic attempts to align the start time, or t_0 , of the waveform with the $n = 3500$ time bin. This logic is not perfect, so generally when making quality cuts on the data we look at a window around t_0 of $3450 < t_0 < 3510$ since the majority of real signals fall in this window. Each time bin is 4 ns wide. The DAQ saves energies in units of ADC. So, before applying an energy calibration,

waveforms are displayed as 1d histograms with energies in ADC binned into 4 ns wide time bins. See Fig. 4.2 for an example waveform.

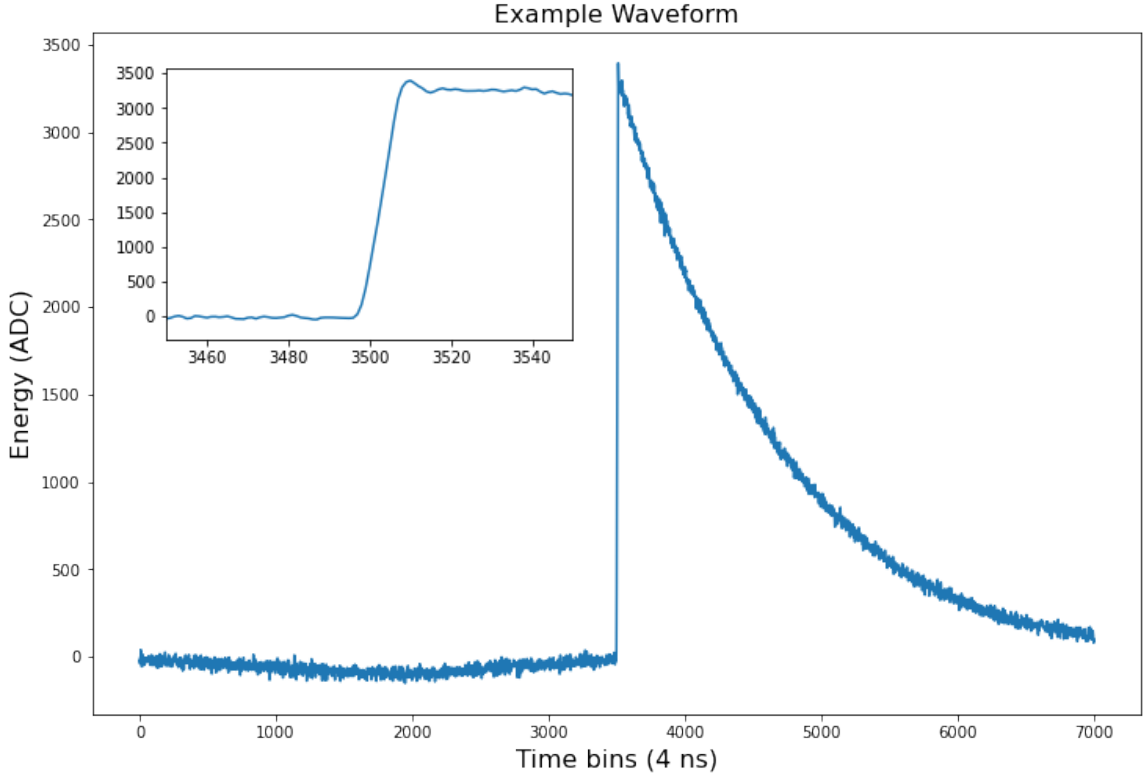


Figure 4.2: This is an example of a waveform from the Nab spectrometer. The inset plot shows a zoomed in segment of the waveform around where the peak is.

The rise time of the waveform can be correlated with the charge collection time for electron-hole pairs in the silicon detector. Charge collection time is related to mobility. Which is the speed at which electrons and holes move through silicon when an electric field is applied. Electron and hole mobilities are not identical, so their behaviors need to be treated independently. The electron/hole mobility in silicon is temperature-dependent.

The energy of a waveform is typically obtained by convolving it with a trapezoidal function and then taking the height of the resultant “trapezoid” as the energy of the waveform. For Nab data, this process is done during post data collection analysis.

The “determineEnergyTiming” function from the pyNab repository (45), is used to obtain energies for the analysis presented here.

4.3 Analysis for September 2023 Source Studies

These studies focus on the temperature dependent shift of the 975.7 keV peak from a radioactive 207-Bi source since this peak was the strongest in this dataset.

4.3.1 Setup

This study investigates the temperature-dependent behavior of the Nab detectors. Data was taken in the Nab spectrometer after the summer 2023 beam cycle while the magnet was cold. The upper detector (“Manitoba”) was used in a multi-year long detector characterization campaign at The University of Manitoba. It had relatively low leakage current compared to other candidate detectors and it was reading energy deposition from protons as expected. After being installed in the Nab spectrometer, it seemed like it developed a mysterious deadlayer which led to a reduction in the position of the proton energy peak. The lower detector (“Spot”) had a rather high leakage current. As a result, “Spot” could not be biased past -50 V. The nominal operating detector bias for the Nab detectors at the time that this study took place was -200 V, so I focused on data taken at that bias voltage. The short radioactive source insertion system (SRSIS) was used to insert 207-Bi into the spectrometer. Position, bias, and temperature scans were performed. A summary of the data analyzed is provided in Table 4.2. Because “Spot” was underdepleted for the entirety of this study, I focused on analyzing the data taken with “Manitoba.” During the data-taking period for this study, the detector electronics were unstable. This required the electronics to be power cycled multiple times each day. The power cycling resulted in thermal fluctuations.

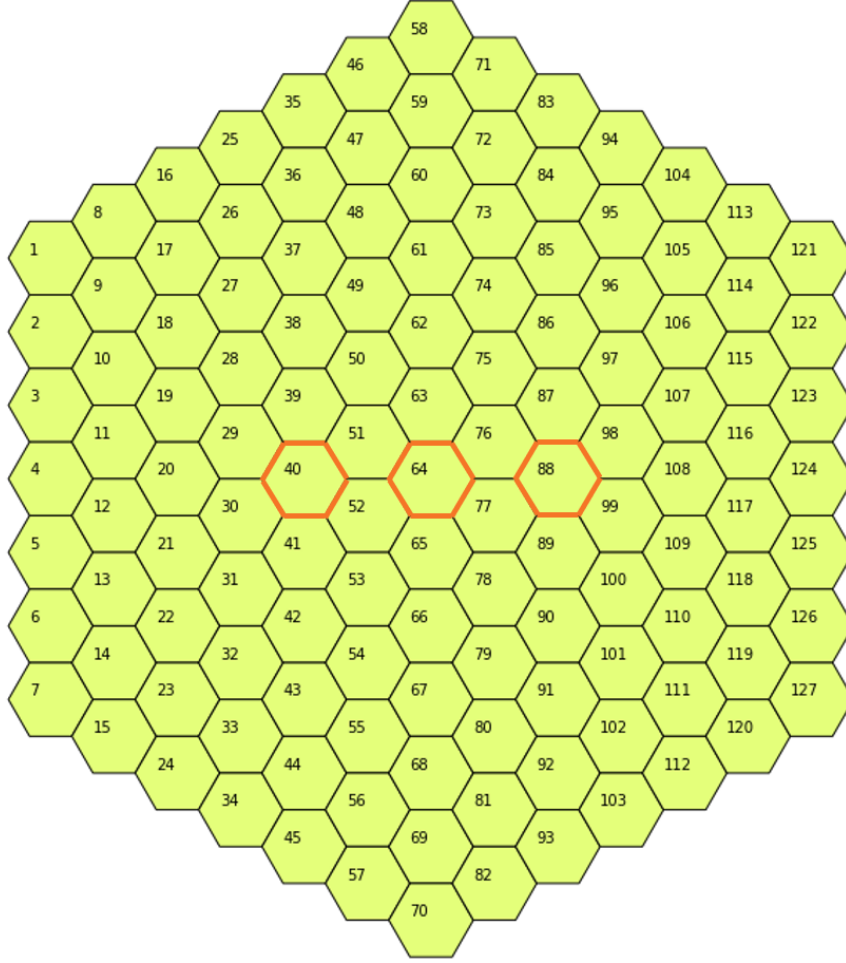


Figure 4.3: The three pixels that were studied are outlined in orange (pixels 40, 64, and 88). The upper detector during this study was “Manitoba.”

The 207-Bi source was positioned within the Nab spectrometer with the SRSIS. The SRSIS employs a linear telescopic transfer arm that is manually actuated with a rotary drive, so positions are given in terms of degrees. The three positions that were studied here are: 315, +2.5, and +35 degrees (with 315 degrees corresponding to 7 full revolutions of the rotary drive dial plus 315 degrees, and the +n degrees corresponding to values above the 8th full revolution). They correspond to the source being aligned with pixels: 40, 64, and 88 respectively (Fig. 4.3).

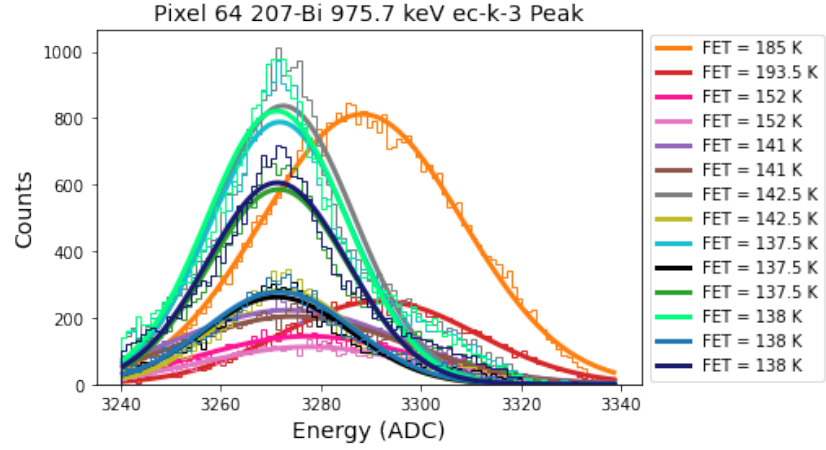
Table 4.2: September 2023 summary of 207-Bi runs. The upper detector FET volume is abbreviated to “UFET.”

UFET Temperature (K)	Runs for Pixel 40	Runs for Pixel 64	Runs for Pixel 88
185	4219	4214	4218
193.5	4240	4233	4232
152	4253	4248, 4252	-
141	-	4258, 4266	4264
142.5	-	4274, 4282	4283, 4285
137.5	-	4292, 4296, 4302	4297, 4301
138	4327, 4331	4316, 4320, 4326	4321, 4325

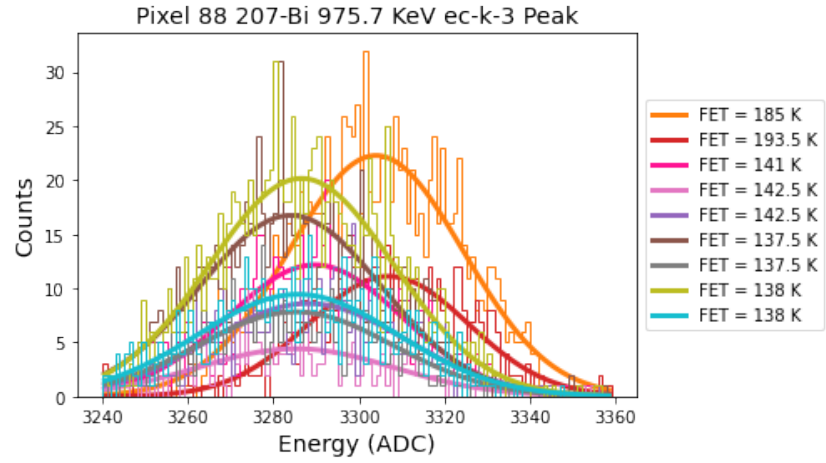
4.3.2 Analysis and Discussion for September 2023 Data

In Fig. 4.4, the gaussian’s means at higher temperatures (193.5 K and 185 K) are visibly higher than the means of the gaussian fits at lower temperatures. This follows the expected trend displayed in Fig. 4.5. The plot shows that as temperature increases, the energy required to promote an electron-hole pair from the valence band to the conductance band decreases. So, at higher temperatures, incoming particles with the same amount of energy will excite more electron-hole pairs. This will induce a higher current that will result in a higher energy being recorded by the DAQ. As temperatures decrease and the ϵ_{ph} increases, less electron-hole pairs will be excited, leading to the DAQ recording a lower energy for the incoming particle. Note that in Fig. 4.4 some of the temperatures are repeated this is because each gaussian is determined for a single data run (shown in Table 4.2), and in some cases there were multiple runs at the same temperature.

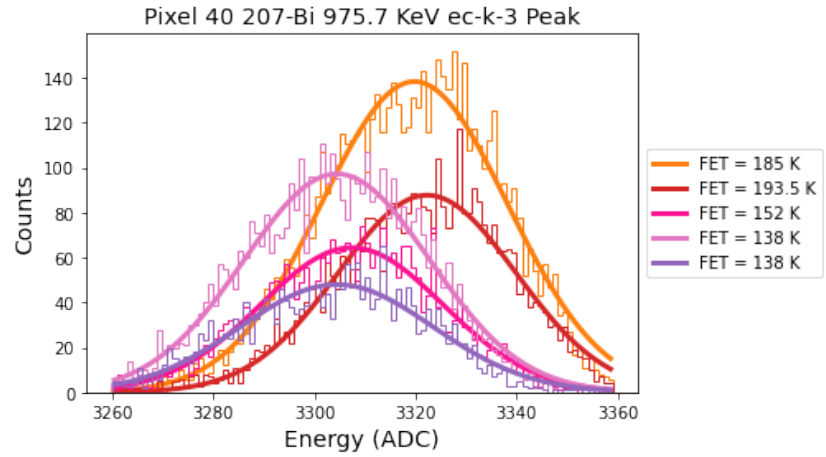
For this study, the pixels were not gain matched. This is what leads to the vertical separation between the mean energies for each pixel. The slope of the means versus temperature averaged to 0.11 ± 0.01 keV/K. This is utilizing the $1 \text{ ADC} = 0.3 \text{ keV}$, an approximate conversion rate from the Nab calibration team.



(a)



(b)



(c)

Figure 4.4: (a) Pixel 64, (b) Pixel 88, (c) Pixel 44

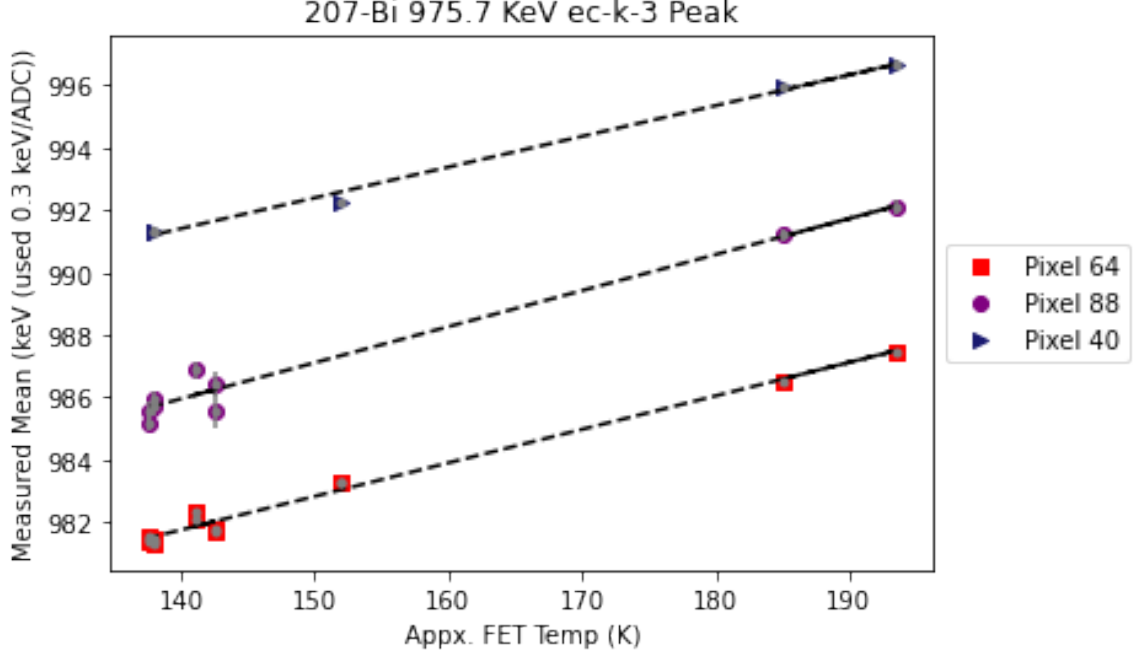


Figure 4.5: Means extracted from gaussians vs. temperature.

The slope of 0.11 keV/K can be used to calculate a restriction on temperature variation with a similar method as the one performed with values from literature in Section 4.1. Doing this calculation yields a temperature variation limit of 0.893 K. This is higher than the 0.588 K calculated above, and greater than the 0.5 K specification that the detector cooling system was designed to meet. So, this study shows that the 0.5 K limit on temperature variation is a safe specification to continue operating with.

The summary obtained from literature shows a wide spread in ϵ_{ph} values. Some of this variation could be due to the uniqueness of each silicon detector that results from the fabrication process. This is evidence that it is worthwhile to perform a temperature scan with each new detector that is implemented to ensure that it does not exceed the gain shift limitations.

4.4 Analysis for May 2025 Source Studies

Two new detectors were installed in the Nab spectrometer in early 2025 for the spring data-taking campaign. The detector electronics went through a system redesign between the September 2023 data set and this one. The transition boards between the FET volume and the preamplifier volume were revised, new cables to power the electronics chain were implemented, and the grounding scheme was scrutinized. The updated detector electronics were much more stable. They no longer required the daily power cycling that was necessary during the 2023 campaign. Similar to the analysis presented in Section 4.3, this study also focuses on the temperature dependent shift of the 975.7 keV peak from a radioactive 207-Bi source.

4.4.1 Setup

For this measurement, the full radioactive source insertion system (RSIS) was used. This system has more versatility and can cover more of the area of the detector than the SRSIS which was used in the September 2023 campaign. The RSIS source holder is able to accommodate five sources. During this study, there were two 207-Bi sources, two cadmium sources, and one tin source installed. Each detector was operated at five different temperatures for this study. The range of temperatures achieved for the upper detector were 115 K to 152 K (corresponding runs are shown in Table 4.3) and for the lower detector were 135 K to 152 K (corresponding runs are shown in Table 4.4). Both detectors were biased to -300 V. The nominal operating detector bias for the Nab experiment is currently (2025) -300 V.

4.4.2 Plots and Discussion for May 2025 Data

The 975.7 keV peak was fit with a gaussian distribution at each temperature and for each of the pixels in the upper detector (“Goop!”)(Fig. 4.6). The means of these gaussian fits were then plotted against the temperatures (Fig. 4.7) and a linear fit was

Table 4.3: Summary of 207-Bi runs from May 2025 used for analysis of upper detector behavior (“Goop!”).

UDET Temperature (K)	Runs for Pixel 65	Runs for Pixel 109	Runs for Pixel 97
115	7823	7824	7826
120	7839	7841	7842
125	7782	7701	7693
138	7787	7788	7790
152	7810	7811	7812

Table 4.4: Summary of 207-Bi runs from May 2025 used for analysis of lower detector behavior (“VALENTINE”).

LDET Temperature (K)	Runs for Pixel 1019	Runs for Pixel 1022	Runs for Pixel 1063	Runs for Pixel 1066
135	7826	7824	7827	7823
136	7693	7701	7697	7782
138	7790	7788	7791	7787
143	7842	7841	7843	7839
152	7812	7811	7813	7810

made to the points. The slopes of these fits are represented alongside the median value of the means for the given pixel in Table 4.5. The conversion is still $1 \text{ ADC} \approx 0.3 \text{ keV}$. However, since the energy units fall out in the math, units of ADC have been retained in the table.

Table 4.5: May 2025 Summary of Slopes of Mean vs Temperature Plots for Upper Detector (“Goop!”).

UDET Pixel	Slope (ADC/K)	Median Value (ADC)
65	0.1706	3115.418
109	0.2129	3096.751
97	0.2183	3098.993

To obtain an average limit on the variation of temperature for upper detector (“Goop!”) pixels take:

$$\frac{1}{n} \sum_i \frac{\text{slope}_i}{\text{median value}_i} \cdot \Delta T < 1 \times 10^{-4}, \quad (4.4)$$

where n is the total number of pixels. Carrying out Eq. 4.4, yields $\Delta T < 1.547$ K. This value is significantly larger than those seen so far in Sections 4.1 and 4.3.

The same analysis was carried out for the lower detector (“VALENTINE”) (Figs. 4.8, 4.9, 4.10).

Table 4.6: May 2025 Summary of Slopes of Mean vs Temperature Plots for Lower Detector (“VALENTINE”).

LDET Pixel	Slope (ADC/K)	Median Value (ADC)
1019	0.2200	3156.390
1022	0.2541	3137.252
1063	0.2262	3128.504
1066	0.2230	3212.112

Employing Eq. 4.4 with the data from Table 4.6 yields a limit of $\Delta T < 1.368$ K. This is less than the value obtained for the upper detector, but still significantly larger than the earlier values of 0.588 K and 0.893 K.

On one hand, a larger limit on the temperature variation is desirable since that means that if the cooling system maintains the design specified 0.5 K stability the gain shift will be even further constrained than the 1×10^{-4} requirement for Nab’s precision goals.

On the other hand, this behavior is outside of the expected behavior for electron-hole pair creation energy temperature dependence based on literature. Maximizing the possible ΔT limit by tactful choices of values from literature (the opposite of what was done to obtain the 0.588 K limitation) yields 1.032 K. This is still smaller than what was observed here.

The widths of the gaussian plots for each peak are also plotted versus temperature (Figs. 4.7, 4.9, 4.10). No meaningful trend is observed.

The results of the studies for each of the three detectors that were investigated are represented in terms of gain variation assuming a 0.5 K shift in Table 4.7 since the detector cooling system is capable of achieving better than 0.5 K stability (Section 3.6).

Table 4.7: This table summarizes the gain variation that is expected for each detector assuming a 0.5 K shift.

Detector Name	Gain Variation	Statistical Uncertainty
“Manitoba”	5.44×10^{-5}	0.16×10^{-5}
“Goop!”	3.24×10^{-5}	0.21×10^{-5}
“VALENTINE”	3.66×10^{-5}	0.20×10^{-5}
Low Estimate from Literature	4.8×10^{-5}	-
High Estimate from Literature	8.6×10^{-5}	-

4.5 Future Work

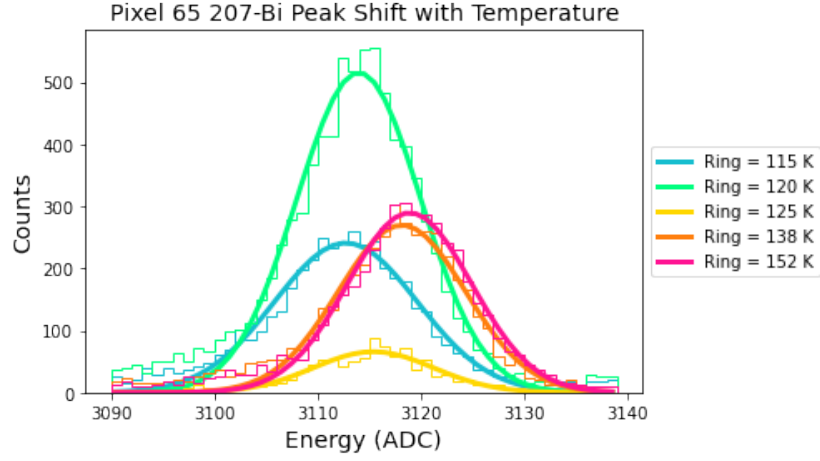
In the future, it will be interesting to pursue deeper understanding of the lower temperature dependence observed in the May 2025 data set relative to the September 2023 data set.

Leading potential sources of the differences:

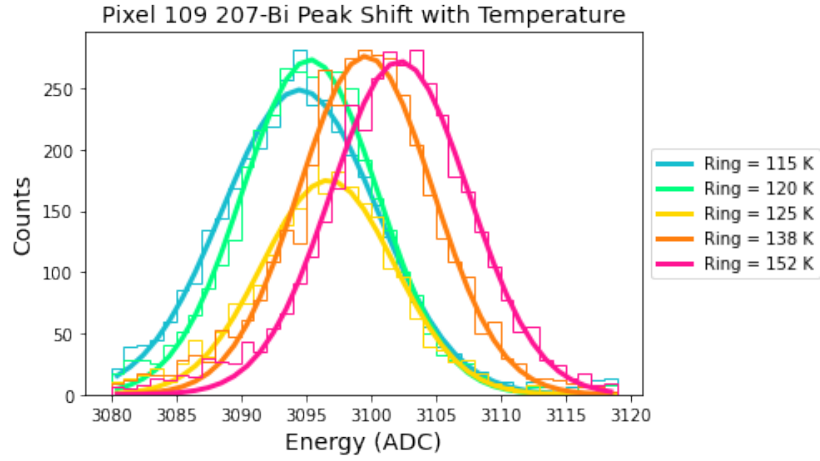
1. The September 2023 data set covered a higher and slightly larger range of temperatures.
2. The detector electronics were redesigned between the 2023 and 2025 data sets.
3. The detector bias in 2023 was lower at -200 V instead of -300 V.

For (1), it would be reasonable to go back and try fitting the subset of data that falls at 152 K and below to see if a more shallow slope is obtained. For (2), a study could be designed to probe some element of the difference that is introduced by a different set of electronics. This is especially possible during the current running mode of Nab because starting in Fall 2025 the detector positions have been swapped within the spectrometer. This means that it would be possible to run a temperature scan with a source and look at whether the resulting slope is more detector dependent or electronics dependent. For (3), this is also something that a future study could easily be designed to address by running detector bias scans in conjunction with a temperature scan.

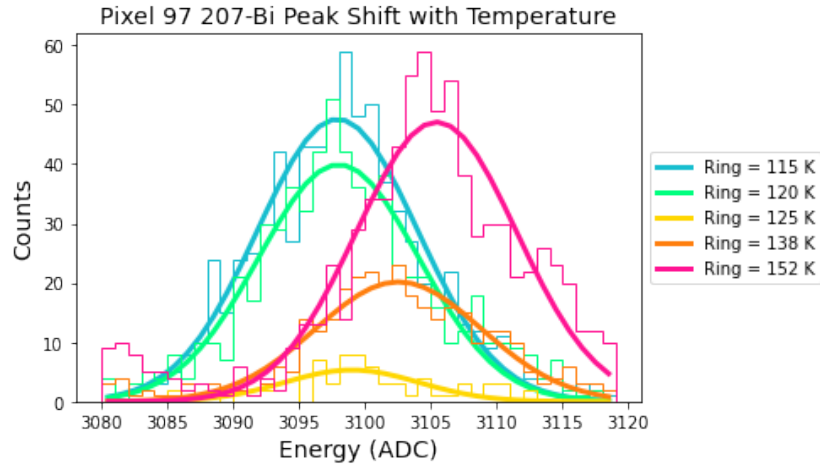
Another area that needs more work is the temperature dependence of timing in the detector. With the current data set, we can look at rise times. However, in order to interpret the meaning of the temperature dependence of rise times on the timing of the decay proton and electron signals dedicated timing studies to understand their implications are needed.



(a)



(b)



(c)

Figure 4.6: Gaussian fits to 207-Bi peak: (a) Pixel 65, (b) Pixel 109, (c) Pixel 97. The solid continuous lines correspond to the gaussian fits and the jagged thin lines are the histogrammed data.

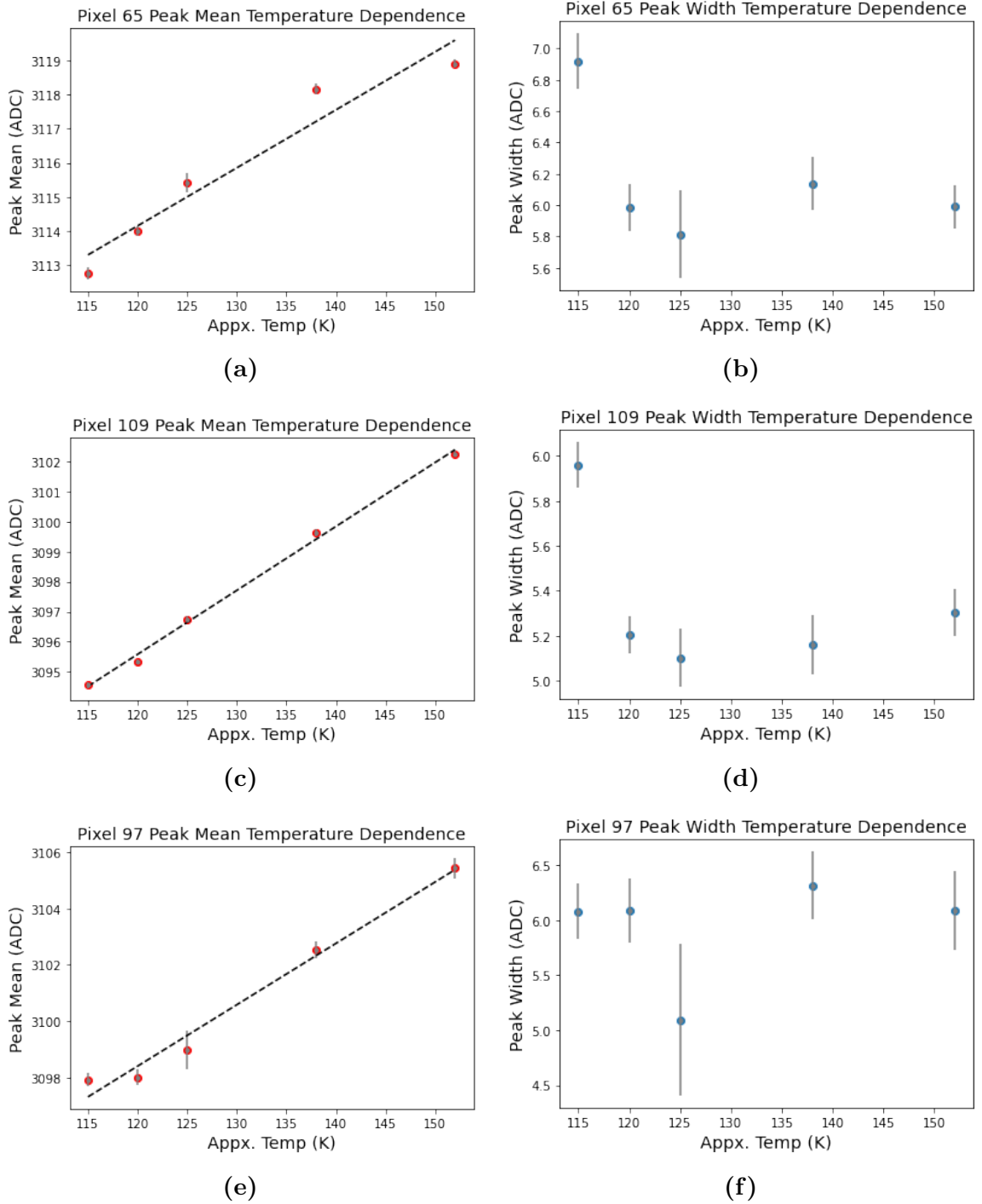
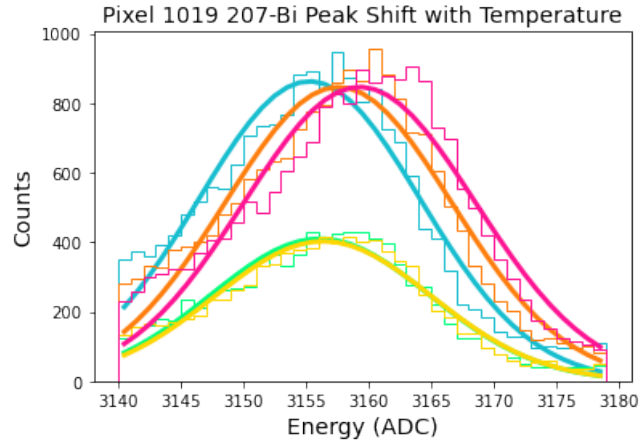
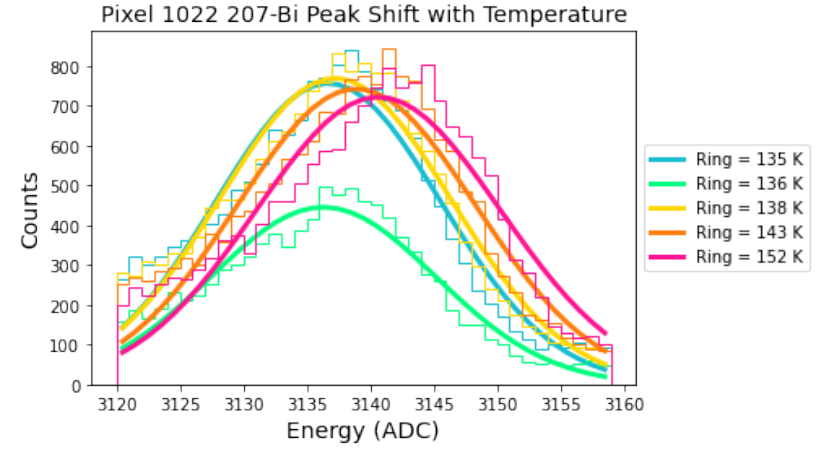


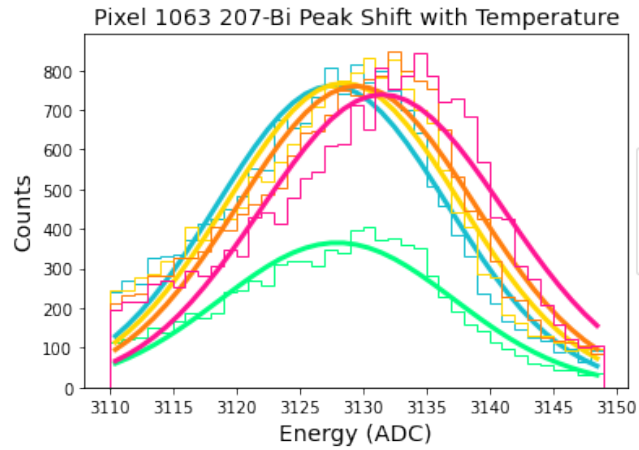
Figure 4.7: Results are shown for pixel 65 (top), pixel 109 (middle), and pixel 97 (bottom) of the upper detector ("Goop!"). Red points give the gaussian means at each temperature, and blue points give the gaussian widths. The error bars correspond to statistical uncertainty provided by the fit.



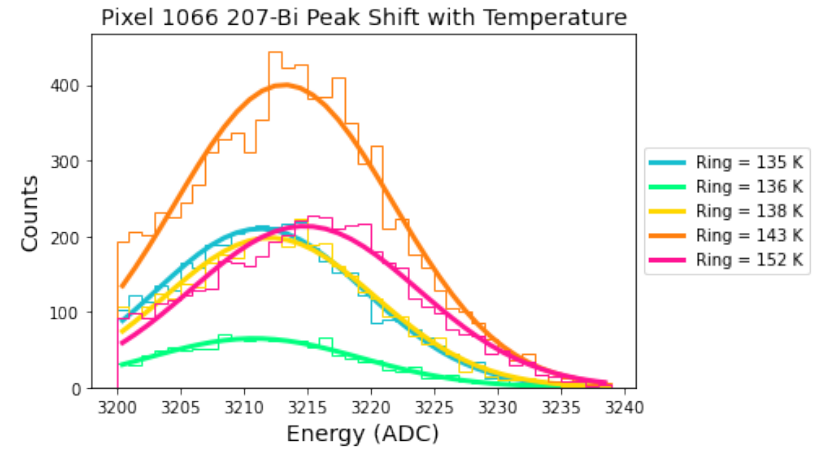
(a)



(b)



(c)



(d)

Figure 4.8: Gaussian fits to 207-Bi peak: (a) Pixel 1019, (b) Pixel 1022, (c) Pixel 1063, (d) Pixel 1066. The solid continuous lines correspond to the gaussian fits and the jagged thin lines are the histogrammed data.

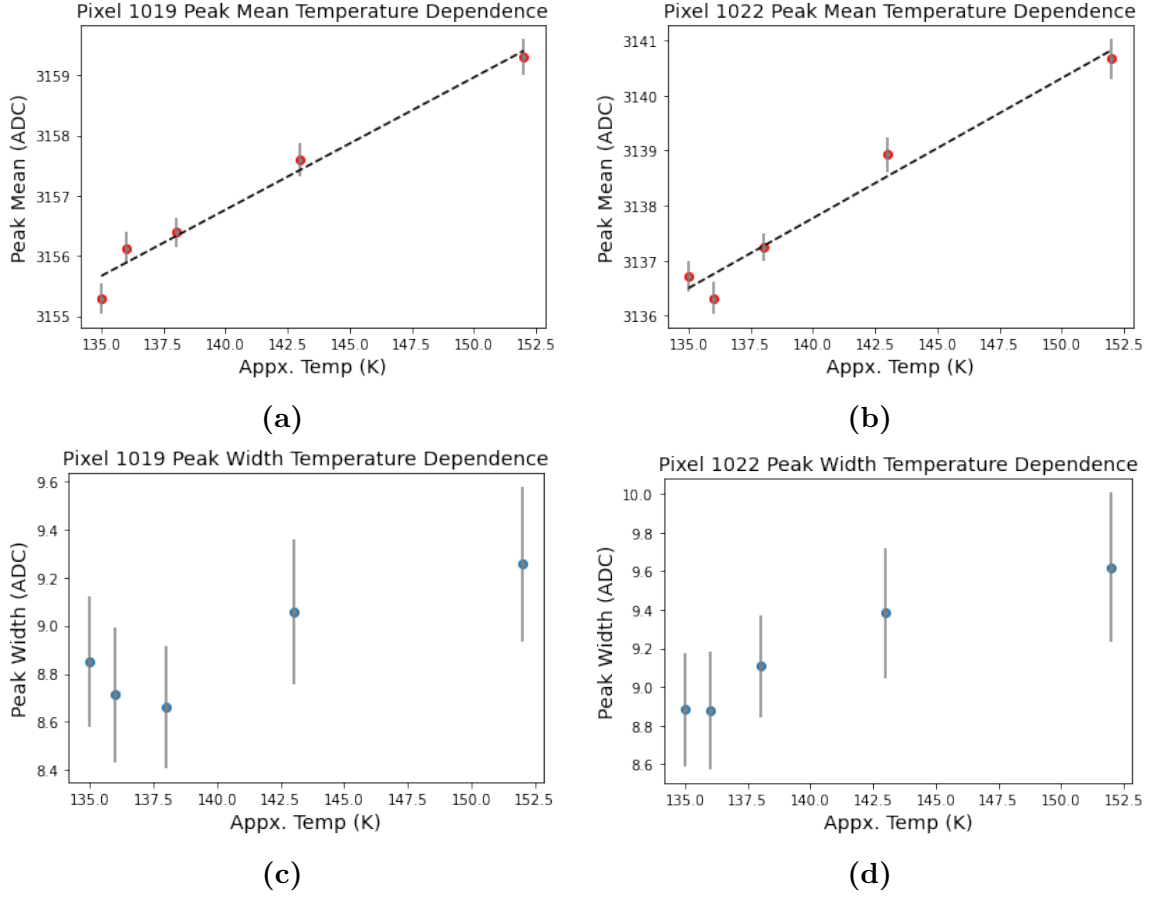
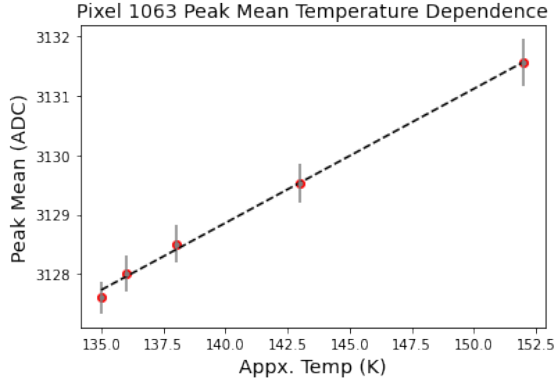
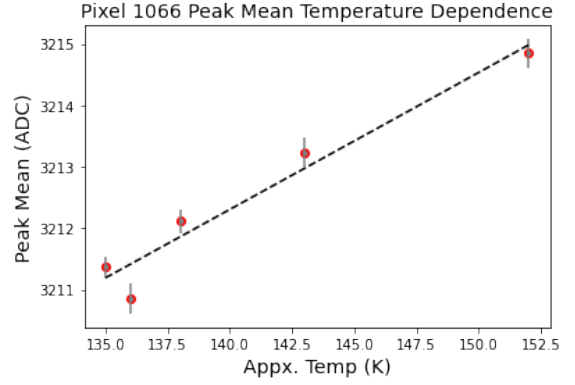


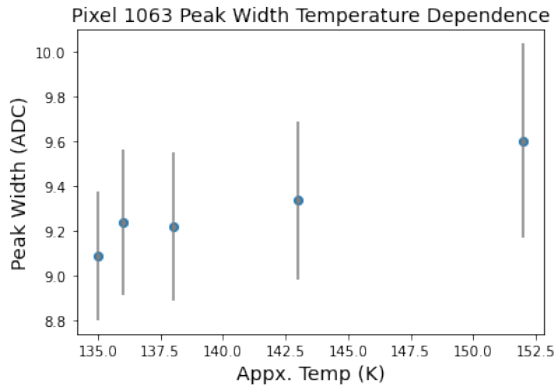
Figure 4.9: Results are shown for pixel 1019 (left) and pixel 1022 (right) of the lower detector (“VALENTINE”). Red points give the gaussian means at each temperature, and blue points give the gaussian widths. The error bars correspond to statistical uncertainty provided by the fit.



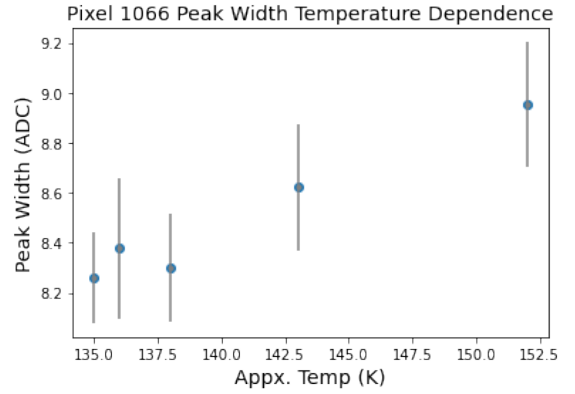
(a)



(b)



(c)



(d)

Figure 4.10: Results are shown for pixel 1063 (left) and pixel 1066 (right) of the lower detector (“VALENTINE”). Red points give the gaussian means at each temperature, and blue points give the gaussian widths. The error bars correspond to statistical uncertainty provided by the fit.

Chapter 5

Nab Detector Thermal Profile

It is important to understand the temperature gradient across the surface of the detector because if the range exceeds the 0.5 K temperature stability requirement then a pixel by pixel correction will be necessary to account for the temperature induced variation in gain.

The thermal profile of the detector was modeled by John Ramsey using Ansys software (see Fig. 5.1). In this model, the total temperature gradient across the detector face is very small (0.03 K). However, thermal modeling is often unreliable due to the empirical nature of thermodynamics—especially in this detector subsystem which has many components (Section 2.5).

The model provides an approximate shape for the thermal gradient on the detector. One might naively assume that the detector will be coolest along the outer edge in line with the cooling Ring which the helium flows through (Fig. 5.3). However, this is not the case because the system is designed to distribute the cooling power evenly over the back face of the detector. So, it turns out that the hot spots on the detector take the shape of the circular openings in the ceramic plating on the back of the detector. These openings allow for

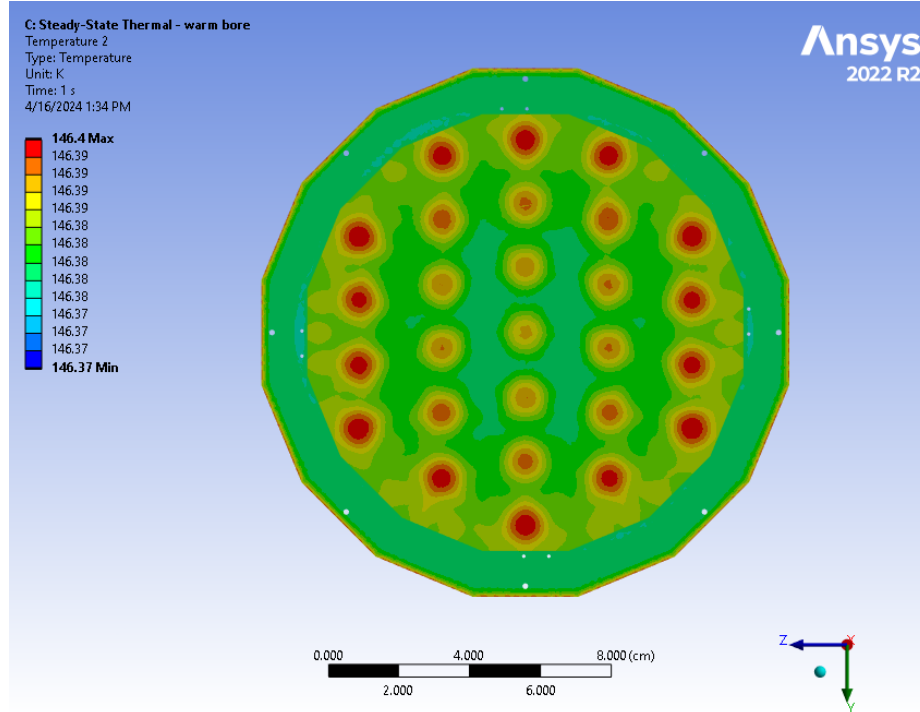


Figure 5.1: This is the heat map of the detector face produced by John Ramsey in Ansys (50).

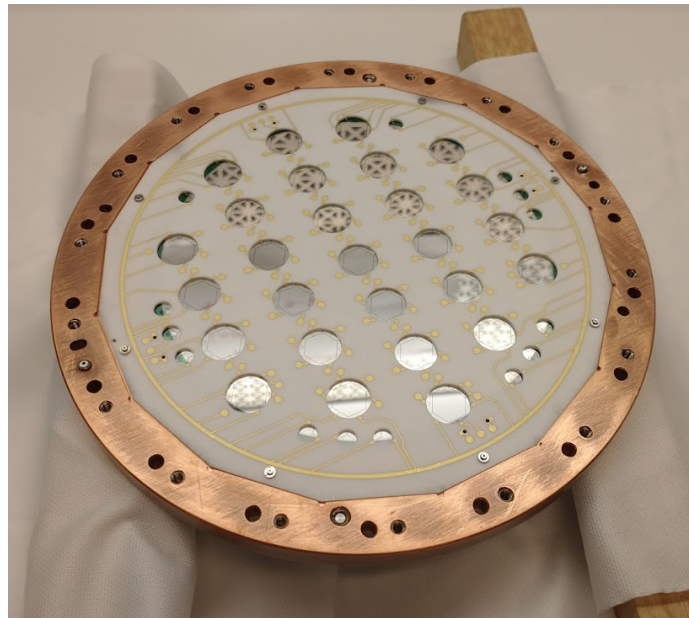


Figure 5.2: The back face of the detector is protected by a ceramic backing plate which has holes in it for the electronics to connect to the detector via wire bonds. The wired bonds go from the ohmic face of the silicon to the gold electrical contacts that are visible on the surface of the ceramic.

wire-bonds between the back face of the detector and the electrical contacts on the ceramic for the Rogers board pogo pins to make contact (see Figs. 2.12 and 5.2). The ceramic insulates the portion of the detector that it is covering and leaves the detector susceptible to heat from the electronics in the openings.

5.1 Initial Mini-Chamber Thermal Profile Measurement

This measurement was performed in a vacuum vessel referred to as the “Mini-Chamber” that was initially designed for electronics testing. The “Mini-Chamber” encapsulates the detector and FETs in the same volume. It is effectively a metal cylinder with one end closed off by a blank flange, and the other with the appropriate adapter to mount the detector system flange (Fig. 5.3). For the initial thermal profile measurement, three calibrated silicon diode temperature sensors were implemented (“T1”, “T2”, and “T3”). The sensor leads were 36 AWG phosphor bronze wires with polyimide insulation from Lakeshore Cryotronics. The diodes were affixed to the face of the “Dummy” detector using Lakeshore Cryotronics’ VGE-7031 varnish*. The “Dummy” detector is a 1.5 mm thick detector that was deemed defective by the manufacturer. The sensors were placed with tweezers, and placement was determined by comparing positions on the detector face to positions on the thermal map by eye (Figs. 5.1 and 5.5). After the sensors were placed, they were left to cure under a hood (maintained at positive pressure) for more than 24 hours. The temperature sensor cables were thermally anchored by securing inch-long sections of each cable to the detector armor with kapton tape (Fig. 5.4). Thermal anchoring is the process of increasing the thermal contact between two surfaces. Thermally coupling the temperature sensor leads to the detector armor decreases the heat load from the leads on the temperature sensor to ensure accurate temperature readings.

*<https://www.lakeshore.com/products/categories/overview/temperature-products/cryogenic-accessories/varnish>

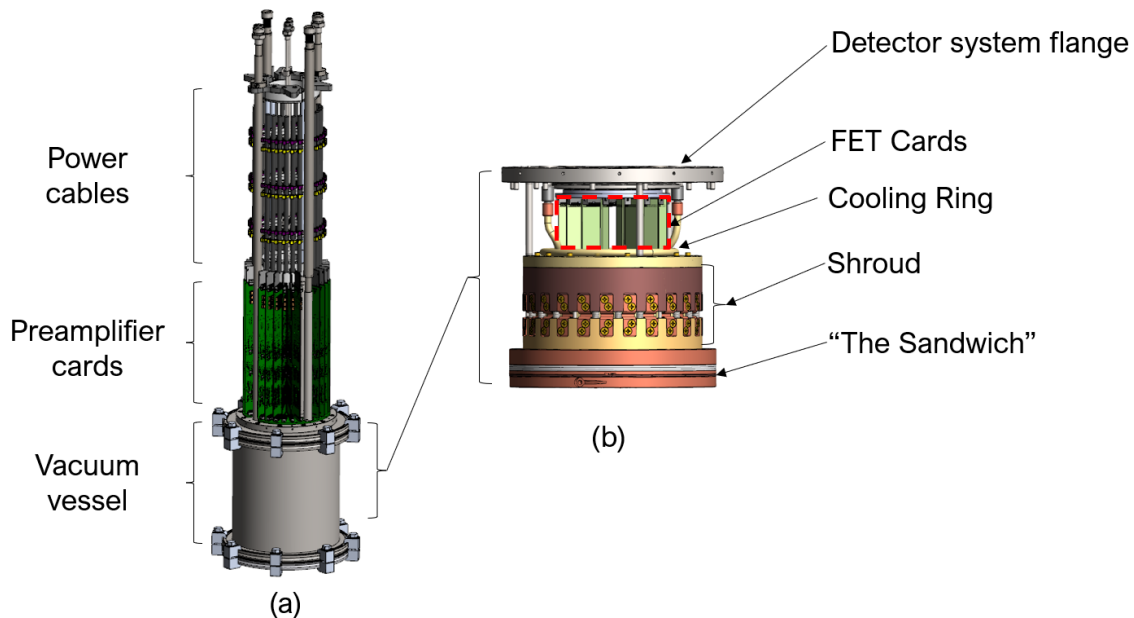


Figure 5.3: This is the Mini-Chamber set up. (a) Shows the vacuum vessel, the preamplifier cards in air, and the power cables that supply power to the preamplifiers and the FETs further down the electronics chain. (b) Shows what is contained inside the vacuum vessel. This includes the FET cards, the cooling Ring, the Shroud, and “The Sandwich” of plates and boards that lead up to the detector. The detector system flange is also labelled for reference.

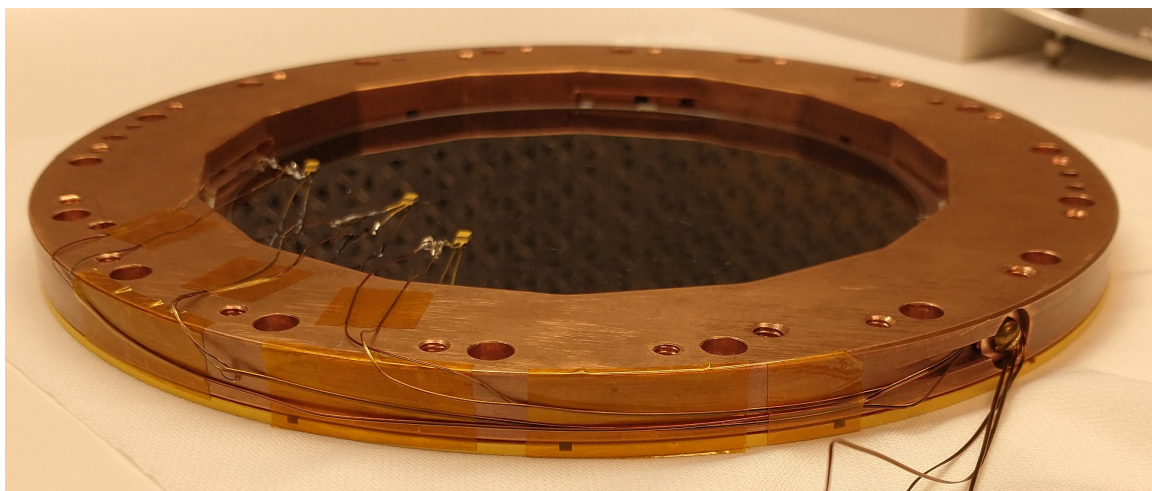


Figure 5.4: This picture shows where the cables are thermally anchored to the detector armor by kapton tape.

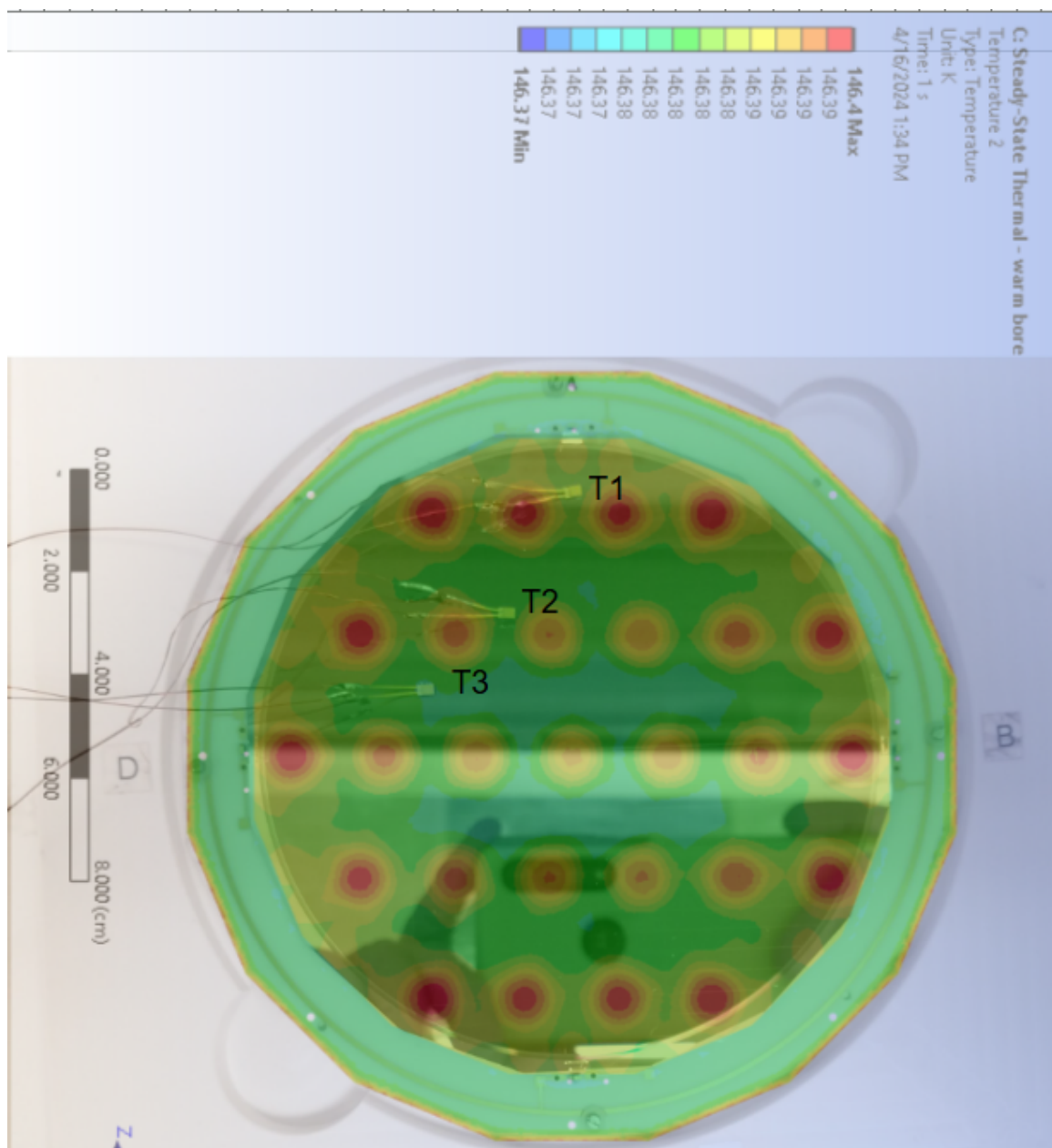


Figure 5.5: This is the heat map of the detector face produced by John Ramsey in Ansys superimposed over the “Dummy” detector with the initial three temperature sensors on it.

After the varnish cured, a clocking error was observed. The printout of the heat map (Fig. 5.1) was 90° out of phase with the orientation of the detector during sensor placement such that the temperature sensor positions were rotated 90° counterclockwise from their intended positions. Actual sensor positions relative to the thermal map are shown in Fig. 5.5. Due to this clocking error, none of the temperature sensors were placed on a detector hot spot (shown in red in Figs. 5.1 and 5.5). The full temperature range across the face of the detector is not captured in this initial measurement (Section 5.1.2).

5.1.1 Thermal Radiation Shield for the Mini-Chamber



Figure 5.6: This is the thermal radiation shield that was implemented in the Mini-Chamber during the initial thermal profile measurement.

The thermal boundary conditions in the Mini-Chamber are different than those in the Nab spectrometer. The Mini-Chamber is much smaller, so the walls of the chamber which are roughly room temperature are closer to the detector face than the walls in the spectrometer. In addition, when installed in the spectrometer, the shiny surface of the HV electrode (described in Section 2.4.1) serves somewhat as a radiation shield. When installed in the spectrometer, the detector system is nested inside a radiation shield, such that the inner wall of the spectrometer is the third layer away from the detector. To mitigate radiative heat loads from the inner walls of the Mini-Chamber, a radiation shield was constructed out of shim material (Fig. 5.6). The shim material was shaped by hand and is held together by stainless steel wires. Wires were also used to create standoffs to center the radiation shield in the Mini-Chamber so that it did not touch the warm wall of the chamber at more than the point contacts formed by the wire standoffs.

5.1.2 Results of the Initial Thermal Profile Measurement

Table 5.1: Initial thermal profile measurement results. Three of the columns are designated to the difference in temperature between $T1$, $T2$, $T3$, and the armor, T_a .

Flow rate (SLPM)	T_a (K)	$T1$ (K)	$T1-T_a$ (K)	$T2$ (K)	$T2-T_a$ (K)	$T3$ (K)	$T3-T_a$ (K)	Range (K)
60	114	116.30	2.30	116.36	2.36	116.26	2.26	0.10
80	109	112.5	3.25	112.33	3.33	112.21	3.21	0.12
30	140	142.18	2.18	142.22	2.22	142.15	2.15	0.7
100	109	112.04	3.04	112.14	3.14	112.01	3.01	0.13

It is of note that, during this initial thermal profile measurement, the detector armor temperature was monitored by an uncalibrated platinum RTD sensor. The level of precision provided by this sensor is not as fine as the precision provided by the calibrated silicon diode sensors that were affixed to the face of the “Dummy” detector. The maximum temperature range across the measured points on the face of the detector was 0.13 K which is less than the 0.5 K requirement. The smallest

range across the measured points on the detector face was achieved when the detector armor was around 140 K. This is very close to the temperature condition that was modeled in Ansys by John Ramsey. In general, at lower armor temperatures, the temperature range is larger.

Since the detector armor temperature is going to be the main detector temperature monitored during running conditions, it is also beneficial to look at how the temperatures on the face of the detector vary in comparison to the armor temperature. The offset between the armor temperature (T_a) and the surface temperature ($T1$, $T2$, or $T3$) is different at different temperatures and under different helium flow rate conditions.

At the end of this test (once the temperature data were recorded), the feasibility of biasing the detector with temperature sensors affixed to its front surface was investigated. The “Dummy” was successfully biased, suggesting that it is possible to perform tests which require the detector to be “on” in the future.

5.2 Final Thermal Profile Measurement

For this measurement, a fourth temperature sensor was affixed to a modeled hot spot (See Fig. 5.7). In the previous test hardware from one of the two existing detector systems was used. However, for this test, since both of the existing detector systems were installed in the spectrometer for the Nab data-taking campaign, hardware from the new third detector system was implemented. This was the first measurement performed with the new detector system, and at the time that this measurement was completed the cables to power the detector electronics had not yet been acquired.

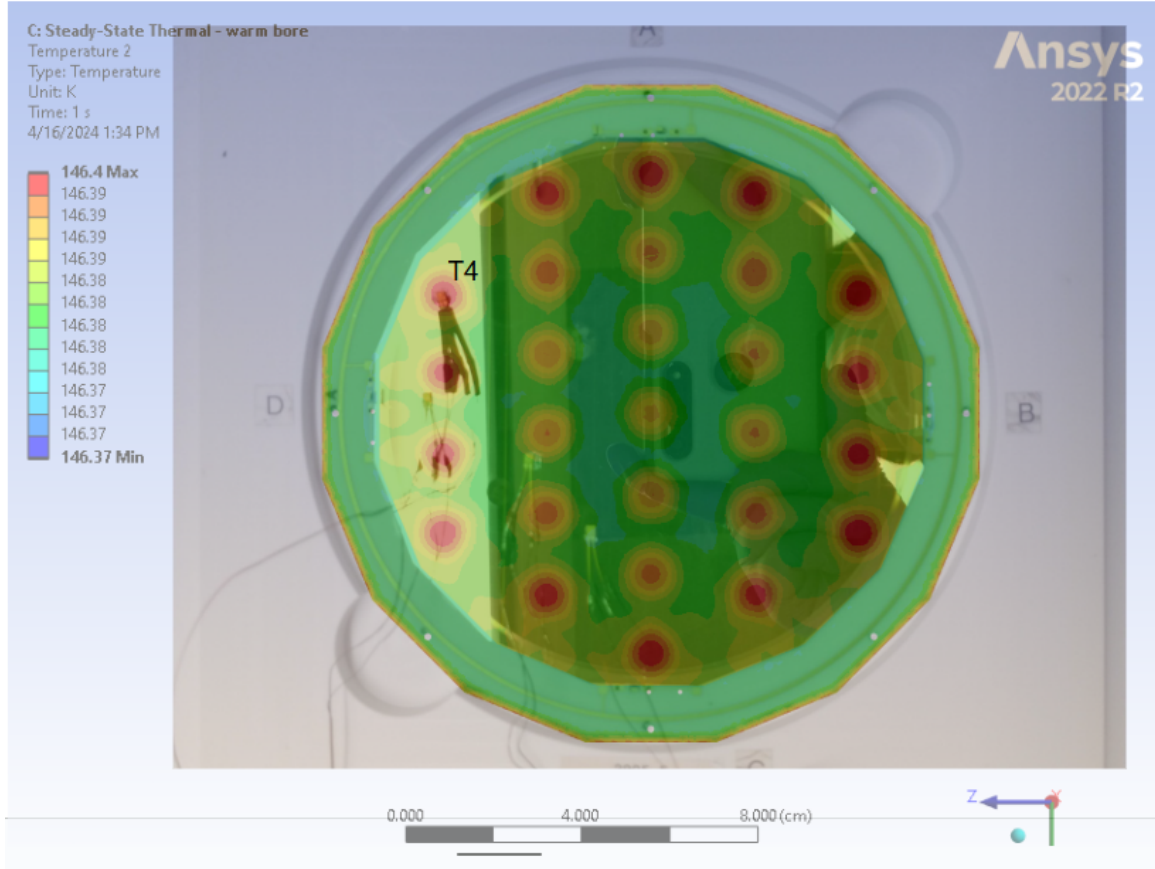


Figure 5.7: This picture shows the position of the fourth temperature sensor (“T4”) which was affixed to a hot spot of the “Dummy” detector for the final thermal profile measurement.

5.2.1 FET Pogo Pin Board Nichrome Wire Heater

A nichrome wire[†] heater was implemented in place of the detector electronics to provide the heat load for the final thermal profile measurement (Fig. 5.8). In order to provide a heat load that matches that of the electronics as closely as possible:

1. The heat needs to reach the detector primarily by conduction through the pogo pins that contact the back face.
2. The maximum heat load from the FET cards was modeled to be ~ 5.6 W, so the wire heater should be operated at a few values up to that threshold to test

[†]<https://shop.lakeshore.com/default/temperature-products/cryogenic-accessories/cryogenic-wire/nichrome-heater-wire.html>

if there is a large difference in the shape of the thermal profile with varying heat loads.

3. The heater needs to be able to operate in rough vacuum and at low temperatures (around 100 K).

Careful decisions were made to address each of these factors. For (1), an older version of the FET pogo pin board that had been retired was converted into a heater board for this test. By heating the FET pogo pin board with a nichrome wire, the heat load position mimics that of the FET cards (the closest part of the electronics chain to the detector) as closely as possible. For (2), the nichrome wire heater was connected to a variable voltage power supply, so that the heat load could be manually adjusted throughout the test. For (3), nichrome wire was selected as the heater over something less vacuum compatible like a pad heater which might be adhered to the surface with non-vacuum compatible adhesive. The nichrome wire was adhered to the board with DP-190 epoxy which has been shown to handle thermal cycling without cracking by the manufacturer[‡]. While DP-190 is not rated for use in vacuum by the manufacturers, it has been observed to be compatible with rough vacuum across multiple applications within the Nab collaboration.

5.2.2 Calibrated Platinum RTD for the Final Thermal Profile Measurement

A new, calibrated, Lakeshore PT-111, platinum RTD was used to monitor the armor temperature throughout the final thermal profile measurement. This was the first test of the new PT-111 sensor for monitoring the detector armor temperature (the new armor design which is discussed in Sec. 2.5.5 was used in this test). The uncertainty of the calibrated PT-111 was given as ± 24 mK (@ 300 K) and ± 11 mK (@ 100 K).

[‡]<https://multimedia.3m.com/mws/media/1235570O/dp190-scotch-weld-technical-data-sheet.pdf>

5.2.3 Cooling Considerations for the Final Thermal Profile Measurement

The lower cooling loop of the helium gas recirculating detector cooling system was used to cool the “Dummy” detector in the Mini-Chamber for this test (this is the same as for the initial thermal profile measurement). The G-10 HVFTs were not used due to space constraints during this test (they were used in the initial thermal profile measurement). This reduced the heat load on the system. The bayonets that are usually used for the lower detector cooling system were used. However, the part on the third detector system that the bayonets interface with allow for $\sim 16''$ more engagement between the lance of the bayonet and the mating part than the current (2025) lower detector system. This also reduced the heat load on the system. These differences led to significantly lower temperatures being achieved in the final thermal profile measurement.

In order to compare the two measurements and validate the use of the FET board heater in place of the electronics as the heat load for the system in the final measurement, the in-line heater (“Cool-o-stat heater”) was employed to raise the temperature of the gas while operating the cooling system with a helium gas flow rate of 100 SLPM. This setting was also chosen as the one to use for benchmarking because during the initial thermal profile measurement this was the setting at which the largest temperature range on the face of the detector (0.13 K) was observed.

5.2.4 Results of Final Thermal Profile Measurement

Throughout this test, $T_4 > T_1 > T_2 > T_3$, as expected from the Ansys model (Figs. 5.1, 5.5, and 5.7). The largest range observed on the face of the detector at any given time was 0.17 K (Fig. 5.9). This is comfortably below the 0.5 K limit.

The difference between T_1 and T_3 with the helium flow rate set to 100 SLPM was the maximum observed range in the initial measurement (Table 5.1). In the final measurement, with the helium flow rate set to 100 SLPM and the Cool-o-stat heater

at 13 W, $T1 = 115.093$ K and $T3 = 114.968$ K. So, $T1 - T3 = 0.125$ K. Rounding to the same number of significant figures that were recorded for the initial measurement, the difference is 0.13 K. This matches what was observed in the initial measurement, so using the FET board heater seems to produce the same results as using the detector electronics to provide a heat load to the system.

The values for each temperature sensor at each setting that was tested are recorded in Table 5.2. The offsets between each temperature sensor on the face of the detector and the armor temperature sensor are summarized for these same settings in Table 5.3. Overall, the armor temperature offset seems to be smaller at the higher flow rate.

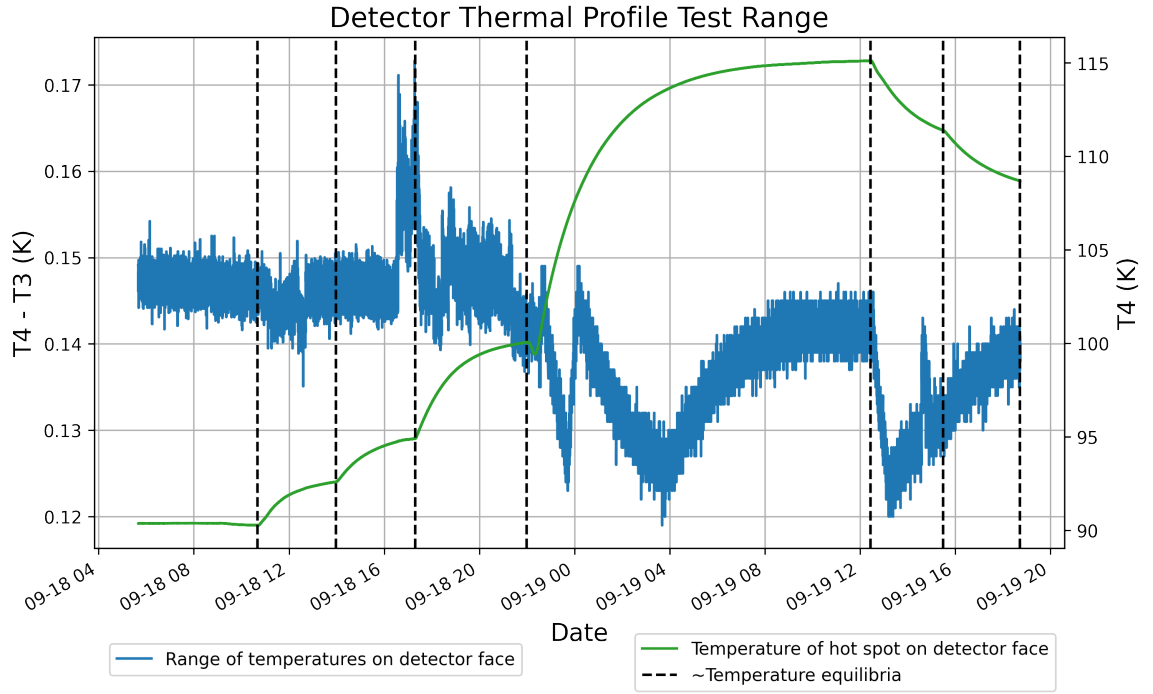


Figure 5.9: Plot of temperatures during final thermal profile measurement. The fuzzy blue line represents the temperature range measured on the face of the detector ($T4 - T3$; left-axis). The smooth green line represents the Temperature of the hot spot on the detector ($T4$; right-axis). The dashed, black, vertical lines indicate the positions at which temperatures reached a rough equilibrium for each setting.

Table 5.2: Final thermal profile measurement temperature ranges.

Flow rate (SLPM)	FET board heater (W)	Cool-o-stat heater (W)	T_4 (K)	T_1 (K)	T_2 (K)	T_3 (K)	Range T_4-T_3 (K)
60	0	0	90.284	90.244	90.188	90.140	0.14
60	1.44	0	92.604	92.557	92.519	92.458	0.15
60	2.78	0	94.917	94.852	94.803	94.756	0.16
60	5.51	0	100.060	100.022	99.972	99.918	0.14
100	5.51	13	115.11	115.093	115.030	114.968	0.14
100	2.78	13	111.382	111.361	111.305	111.252	0.13
100	1.52	13	108.685	108.644	108.601	108.544	0.14

Table 5.3: Final thermal profile measurement temperature offset between detector face and armor (with all sensors calibrated).

Flow rate (SLPM)	FET board heater (W)	Cool-o-stat heater (W)	T_4-T_a (K)	T_1-T_a (K)	T_2-T_a (K)	T_3-T_a (K)
60	0	0	4.017	3.976	3.920	3.873
60	1.44	0	4.018	3.971	3.933	3.872
60	2.78	0	4.000	3.933	3.885	3.837
60	5.51	0	4.160	4.122	4.073	4.019
100	5.51	13	3.612	3.595	3.532	3.470
100	2.78	13	3.366	3.345	3.289	3.236
100	1.52	13	3.326	3.305	3.242	3.185

Chapter 6

Systematic Uncertainty in the Electron Neutrino Correlation Coefficient Due to Proton Detection Efficiency

Protons of different energies are detected with different efficiencies. This causes energy dependence of proton detection efficiency which leads to a deformation in the shape of the Nab tear drop. The initial commissioning data set for Nab was taken in 2023 (Figs. 6.1 and 6.2)(30). The detectors for the 2023 commissioning campaign were “Manitoba,” positioned at the upper end of the spectrometer, and “Spot” at the lower end. The proton peak in “Manitoba” was centered around ~ 10 keV (Fig. 6.2). This is significantly lower than the ~ 20 keV simulated mean proton energy and the mean proton energy observed with “Manitoba” during characterization studies at the University of Manitoba proton source (44). The “Manitoba” detector is thought to have been contaminated at some point between the characterization studies and the 2023 commissioning run at the SNS.

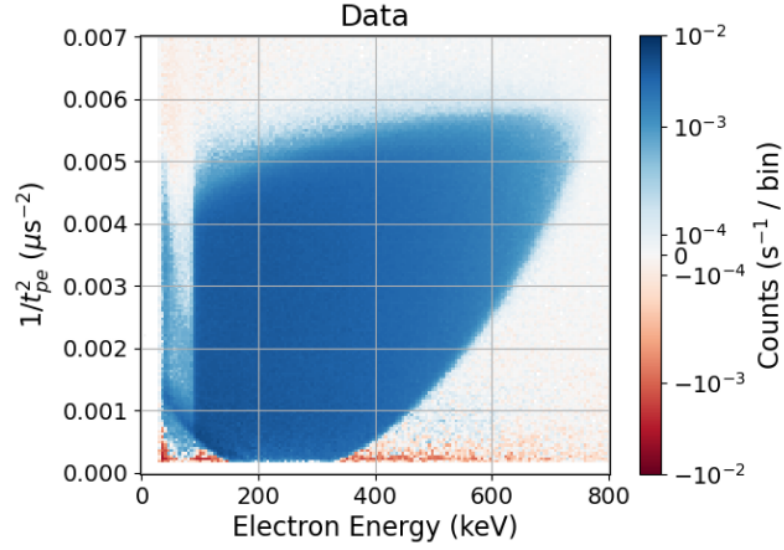


Figure 6.1: The tear drop measured in the Nab apparatus for the commissioning run in 2023 (30).

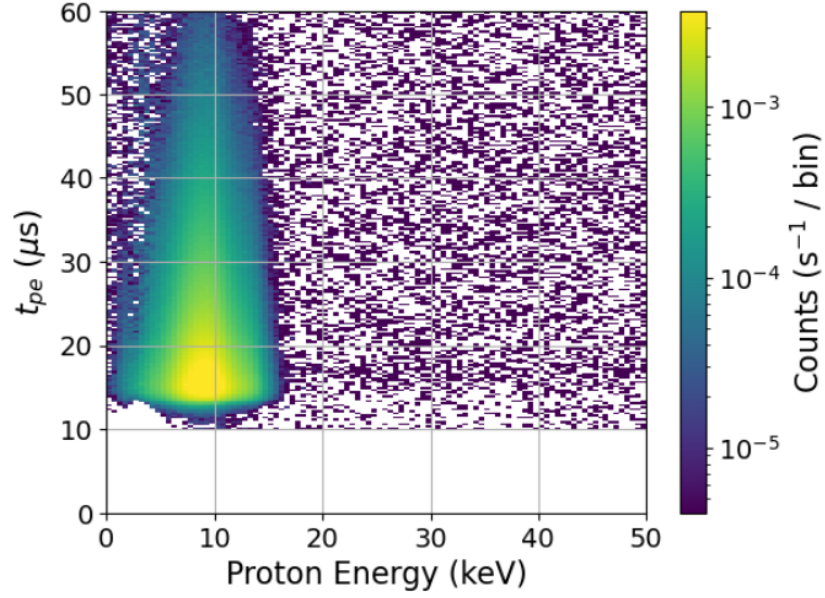


Figure 6.2: The proton energy distribution for the 2023 commissioning run. The proton energy peak is centered ~ 10 keV (about half of the expected energy) (30).

The contamination led to the creation of a dead layer on the face of the detector that absorbed a portion of the energy of incoming decay particles and displaced the proton peak. The suppression of the proton peak impacts the detector response. This calls for two paths of action:

1. Study the impacts of the suppressed proton peak by performing simulations, analyzing observed data, and comparing the results to validate the conclusions drawn from each.
2. Troubleshoot the detector contamination to prevent proton peak suppression in the future.

Pursuant of (2), between the 2023 and 2024 campaigns, new detector candidates

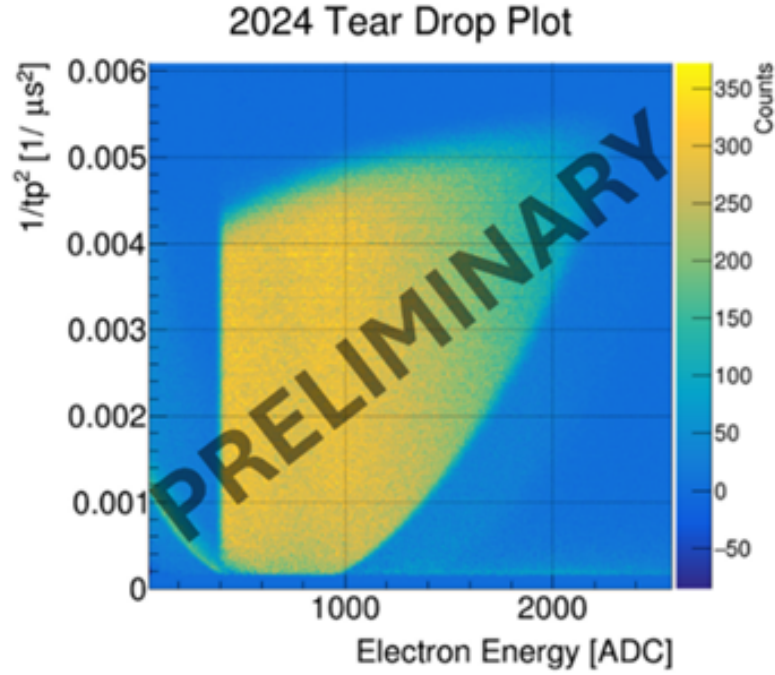


Figure 6.3: The tear drop measured in the Nab apparatus for the commissioning run in 2024 (20). With more operable pixels, more stable electronics, and a higher energy proton peak, the edges of the tear drop are more defined than in 2023.

for production data-taking were selected. For the 2024 campaign (Fig. 6.3), “Goop!” and “VALENTINE” were installed as the upper and lower detectors respectively. There is ongoing work to understand the source of contamination, and improvement of procedures up to this point have eliminated potential contamination risks to the detector. The proton peak for the 2024 data set was observed at ~ 18 keV (Fig. 6.4). The lack of obvious contamination indicated a successful installation.

During the spring 2025 data-taking campaign (which utilized the same detectors, in the same positions as the 2024 campaign), the proton peak was observed at ~ 14 keV. This time the reduced energy is suspected to have been caused by high voltage breakdowns which resulted in a non-uniform deposit on the detector. Some pixels will therefore display more suppressed proton signals than others, so pursuing (1) is critical for Nab to reach its precision goals.

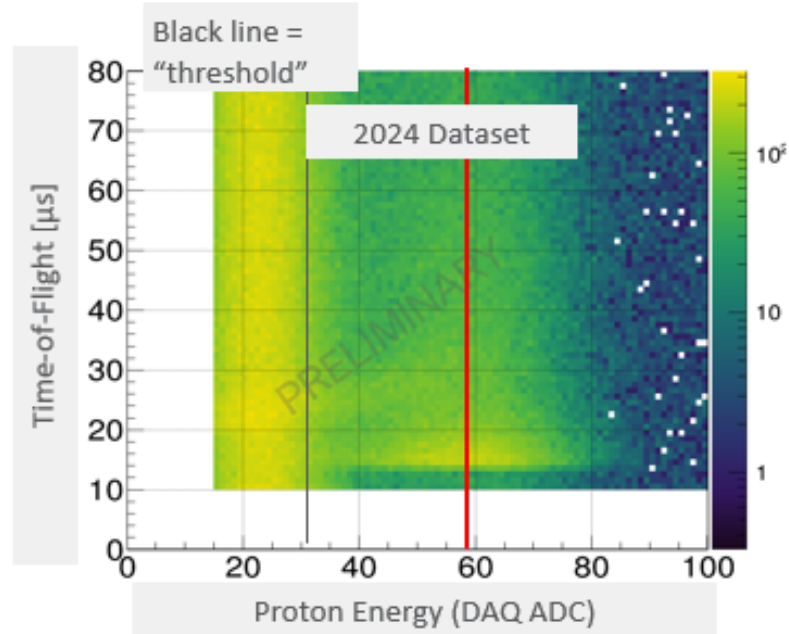


Figure 6.4: The proton energy distribution for the 2024 commissioning run. The proton peak center is given by the red line. The peak is near 60 ADC ≈ 18 keV, much more in line with the expectation (20).

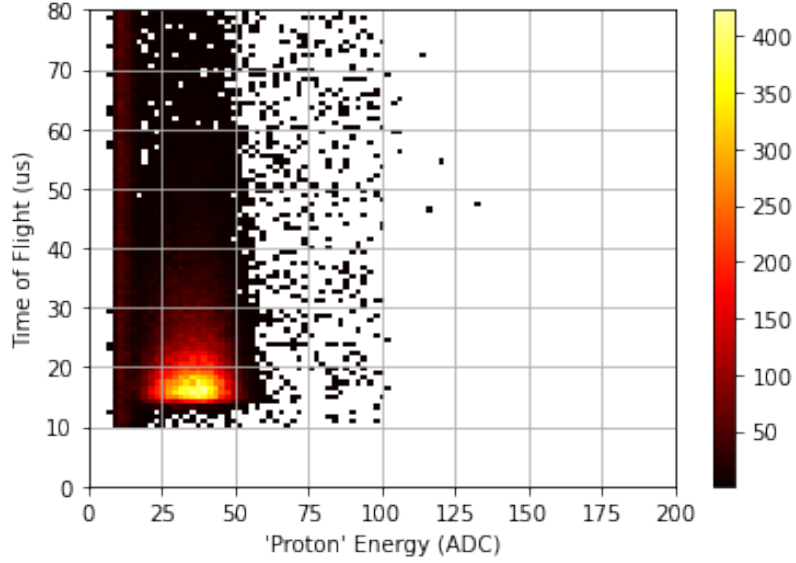


Figure 6.5: Proton energy spectrum for Run 7244 in spring 2025. The peak falls near 47 ADC $\approx$ 14 keV for the full spring 2025 data set, but in this run it is about 40 ADC $\approx$ 12 keV.

6.1 Method

This section will focus on the energy dependence of the proton detection efficiency for the spring 2025 data set. Results from simulations will be referenced and used as a baseline of comparison for the potential method that is presented here for determining the proton detection efficiency from observed decay proton signals (32). For this estimate of the proton detection efficiency, the following assumptions were made:

- Channeling effects (28) are neglected.
- Protons that fall outside of a gaussian shape (in a straggling tail) are neglected.
- The length of the proton flight paths are assumed to be the same as each other, and are estimated using the proton TOF.
- Rough estimates for proton energies using TOF averages are made.
- Back-scattered protons are negligible for proton TOFs $< 40 \mu\text{s}$.

- No background subtractions were made.
- A constant gain is assumed with a conversion rate of $1 \text{ ADC} = 0.3 \text{ keV}$.

The procedure is briefly summarized here and described in more detail in Section 6.2.

1. Select proton events that are identified by the DAQ as coincidence events (protons that are paired with an electron) and run the trapezoidal filter on the waveforms to extract their energies.
2. Loop over the pixels in the upper detector, and form histograms of the proton signals for each to determine which pixels have well-separated proton and noise peaks (Fig. 6.6).
3. Select a pixel that displays well-separated peaks (for pixels with overlapping noise and proton peaks some adjustments to the following steps may be needed).
4. Use the difference between the coincident proton and electron's timestamps as an estimate for the TOF, and sort the proton events into four $5 \mu\text{s}$ wide bins.
5. Within each TOF bin, histogram the proton energies.
6. Set the lower threshold and make a gaussian fit to the resultant proton peak (Fig. 6.10).
7. Use the threshold along with the gaussian mean and width to calculate a z-score for each plot.
8. With the z-score, determine the fraction of area that is in the tail of the gaussian below the threshold (Eq. 6.4) (42; 41).
9. Plot the average proton hit energy (the gaussian means) versus $1/\text{TOF}^2$ (use the central values of the TOF bins as an estimate) (Fig. 6.11).

10. To make a rough mapping from $1/\text{TOF}^2$ to initial proton energy, treat the lowest TOF bin center as the TOF that corresponds to the highest energy protons (751 eV). Then, use the classical expression $L = \text{TOF} \cdot \sqrt{2E/m}$, where L is the length of the flight path, E is kinetic energy, and m is mass to estimate L . Pretend like L is the same for all protons and using a different form of the same expression solve for E for each point.
11. Plot the average proton hit energy versus the rough estimate for the initial proton energy (Fig. 6.12) and compare to simulation (Fig. 6.8a).
12. Estimate the proton detection efficiency for each initial energy by subtracting the value found in (8) from (1). This estimate neglects effects from channeling and straggling.
13. Plot the approximate proton detection efficiency versus the rough estimate of initial proton energy (Fig 6.13) and make a linear fit to the data. Compare to Fig. 6.8b.
14. Use the slope from (13) and the fit from the parametric study (7) to estimate the contribution that the energy dependence of the proton detection efficiency will have on $\Delta a/a$. Compare to Fig. 6.9.

6.2 Analysis and Discussion

The spring 2025 data-taking cycle was split into two different running modes. One for production data-taking and one for systematic studies. In production data-taking mode, detector biases were set to -300 V, the Nab magnet was at full field, the high voltage electrode was biased to -29 kV, the E×B electrode (described in Section 2.4.2) was off, and the majority of the upper detector pixel thresholds were set to 15 ADC. The run analyzed here (run 7244) was in the production data-taking mode with the

exception that the $E \times B$ electrode was biased to -10 V. This study is not sensitive to a small bias from the $E \times B$ electrode.

The initial focus on a pixel that displays a distinct noise pedestal and proton peak is intended to avoid effects from the noise peak overlapping with the proton peak to validate the general approach. After data cuts to only look at protons that were flagged as part of a coincidence event by the DAQ, thirty-four pixels were observed by eye to have distinct peaks. Pixel 51 (Fig. 6.6) was selected because its peaks were among the cleaner of the set of pixels with distinct peaks and it is near the center of the detector (Fig. 6.7).

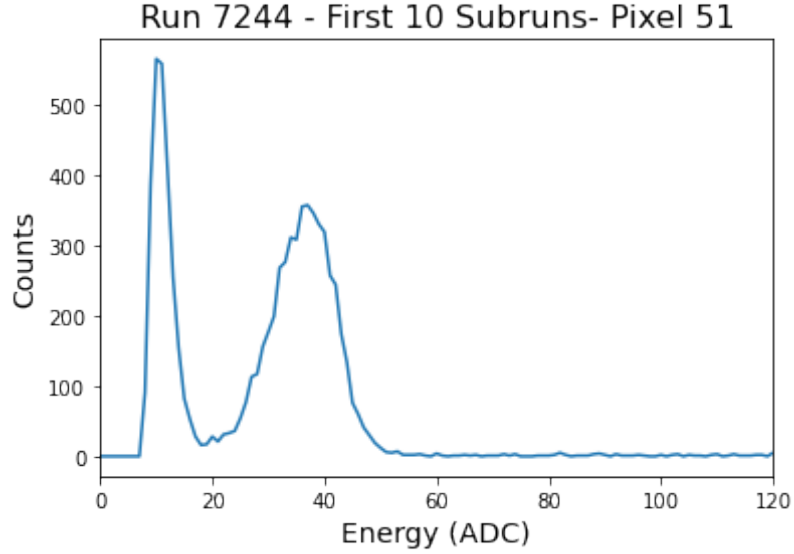


Figure 6.6: Proton events on pixel 51 from the first 10 subruns of run 7244. The peak around 10 ADC is noise, and the peak just below 40 ADC is the proton peak.

Initial proton energy refers to the energy of the proton just after decay and before it traverses the spectrometer to the upper detector. The average proton hit energy in keV and the initial proton energy in eV can be expressed as:

$$E_{p,\text{hit}} = 14.02 + 7.506 \times 10^{-4} \cdot E_{p,i} + 9.909 \times 10^{-9} \cdot E_{p,i}^2, \quad (6.1)$$

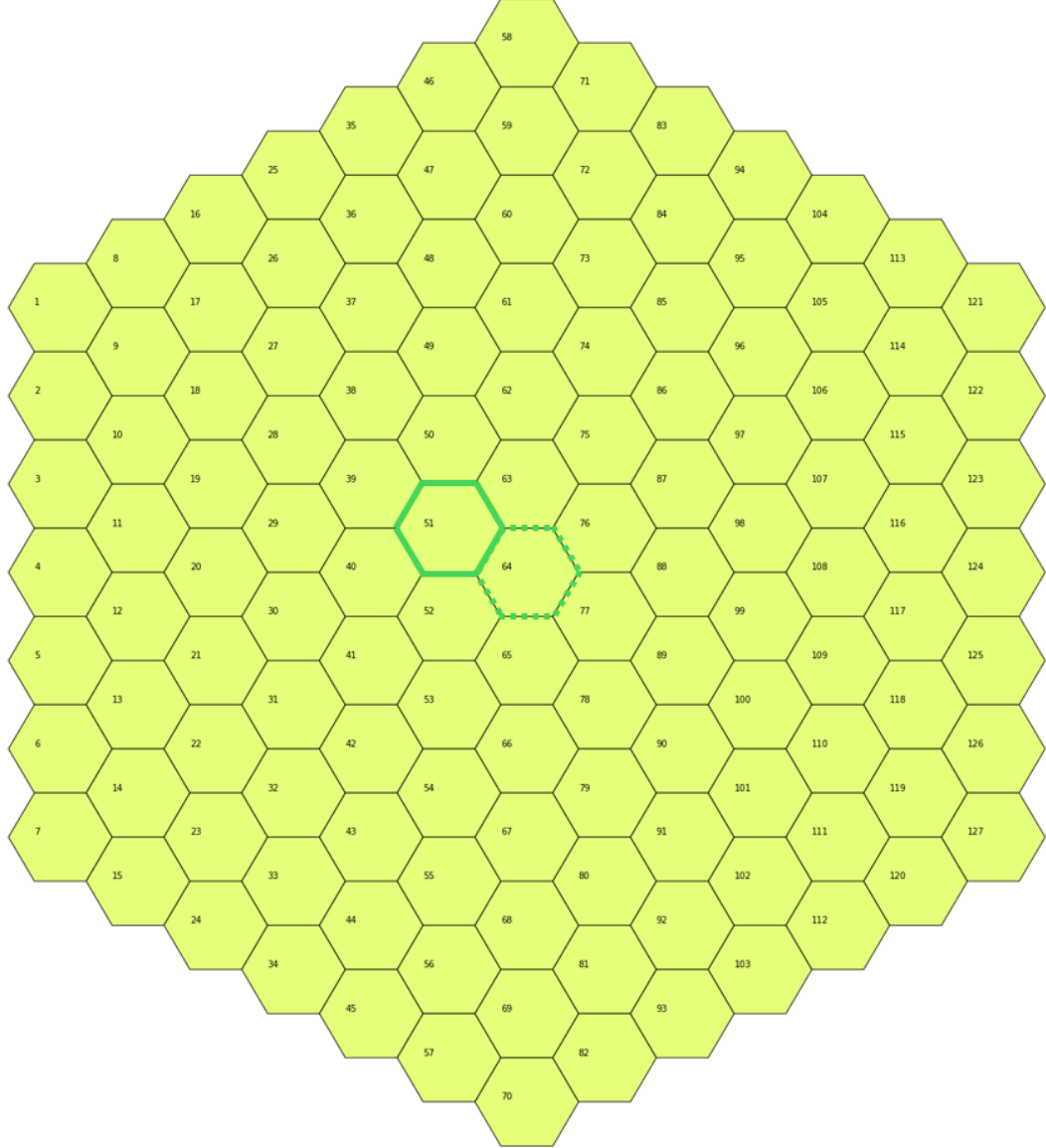
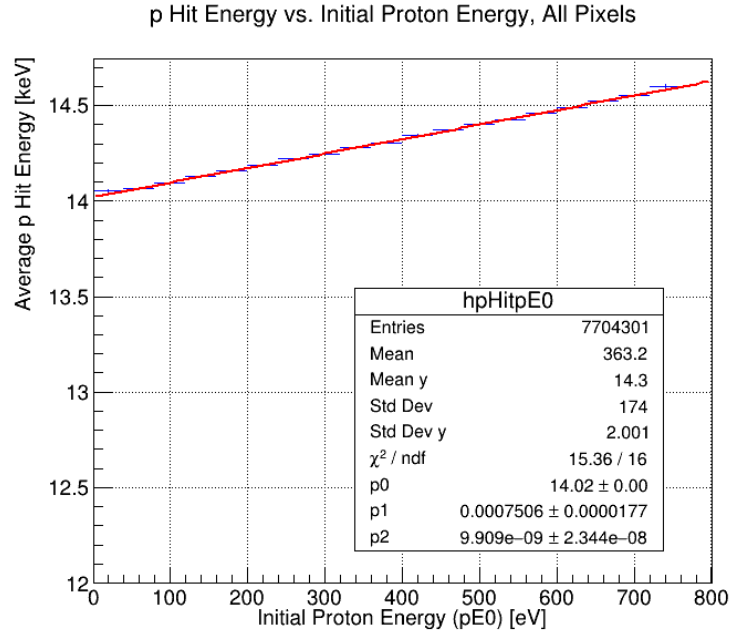
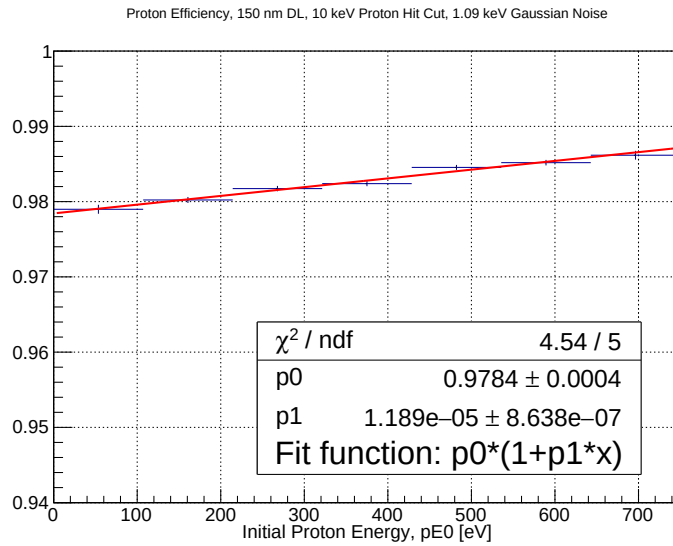


Figure 6.7: Pixel 51 is outlined in a solid green hexagon and the central pixel (pixel 64) is outlined in a dashed hexagon of the same color.

where $E_{p,\text{hit}}$ is average proton hit energy, $E_{p,i}$ is initial proton energy, and the expression relating them is provided by the fit to simulated data (Fig. 6.8a) (32). Since the squared term's contribution in the fit is small in comparison to the linear term, the relationship between the average proton hit energy and the initial proton energy can be approximated as linear.



(a)



(b)

Figure 6.8: (a) Simulated average proton energy versus initial proton energy is shown. The plot is fit with a degree 2 polynomial. The squared term's coefficient (p2) is small compared to the linear term's coefficient (p1). (b) The simulated proton detection efficiency versus initial proton energy for a detector with a deadlayer of 150 nm (as might be introduced by a contaminant), a 10 keV threshold, and gaussian noise centered at 1.09 keV. A linear fit to the data was performed and the parameters are labelled on the plot (32).

The proton detection efficiency simulation that was run with the most statistics investigated a 150 nm deadlayer and a 1.09 keV gaussian noise peak (32). A linear fit was applied to the results to extract the energy dependent detection efficiency. The slope from the linear fit in Fig. 6.8b is $\sim 1.163 \times 10^{-5} \pm 8.451 \times 10^{-7} \text{ eV}^{-1}$.

This slope is then related to the relative uncertainty on a via the parametric study of this effect (7). The parametric study resulted in a plot of a versus the detection efficiency and the linear fit to that plot was:

$$a = -3.53 \times 10^{-7} \cdot c_1 - 0.1029, \quad (6.2)$$

where c_1 is the detection efficiency in ppm/keV. Utilizing Eq. 6.2, the simulated relative uncertainty on a is $\Delta a/a \approx 3.99 \times 10^{-2} \pm 2.90 \times 10^{-3}$ for a threshold of 10 keV. This was the highest threshold that was modelled, and is the one which the following analysis will use for initial comparison. A summary of the results from simulation are shown in Fig. 6.9. The results show that as the threshold is lowered, the relative uncertainty on a decreases.

In order to extract $\Delta a/a$ from proton data on pixel 51, average proton hit energy versus some metric of initial proton energy must be obtained. Proton TOFs were estimated from the difference in the timestamps of the proton signal and the coincident electron signal. Then proton events were sorted into four $5\mu\text{s}$ wide TOF bins. These TOF bins are represented by separate 1d histograms of proton energy in Fig. 6.10. This bin size was selected because for a single run (run 7244), larger bins were needed to supply enough statistics to fit a gaussian distribution to the proton peak. The expression used for the fit was:

$$f(x) = A \cdot e^{-(x-\mu)^2/2\sigma^2}. \quad (6.3)$$

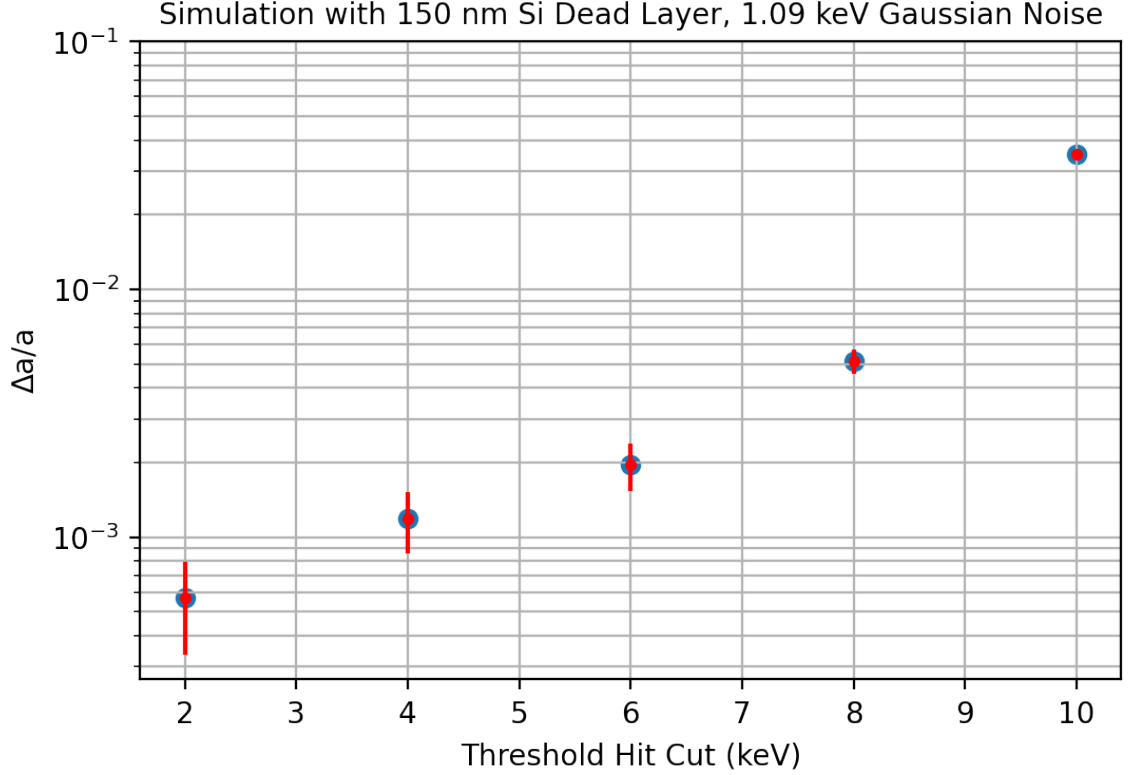


Figure 6.9: Simulated relationship between energy dependent detection efficiency and uncertainty on a vs. threshold energy. The highest studied threshold is 10 keV. This corresponds to the threshold that was set for the analysis presented here (32).

For the gaussian fitting (Fig. 6.10), the energy bin width was manually optimized to ensure sufficient statistics per bin and a sufficient number of bins to capture the gaussian shape.

The threshold was set to $33.33 \text{ ADC} \approx 10 \text{ keV}$, as a point of comparison with simulation (Fig. 6.9) and because the goodness of fit parameter was noticeably better with the threshold set to $\geq 30 \text{ ADC}$.

The gaussian fits were then used to make an estimate of the fraction of proton events that were missed by calculating the z-score from the fit parameters with the following expression:

$$\text{z-score} = \frac{\text{threshold} - \mu}{\sigma}, \quad (6.4)$$

where μ is the gaussian mean and σ is the gaussian width. The uncertainties that were provided by the fit for μ and σ were propagated through the z-score calculation to provide statistical error bars on the estimated efficiencies.

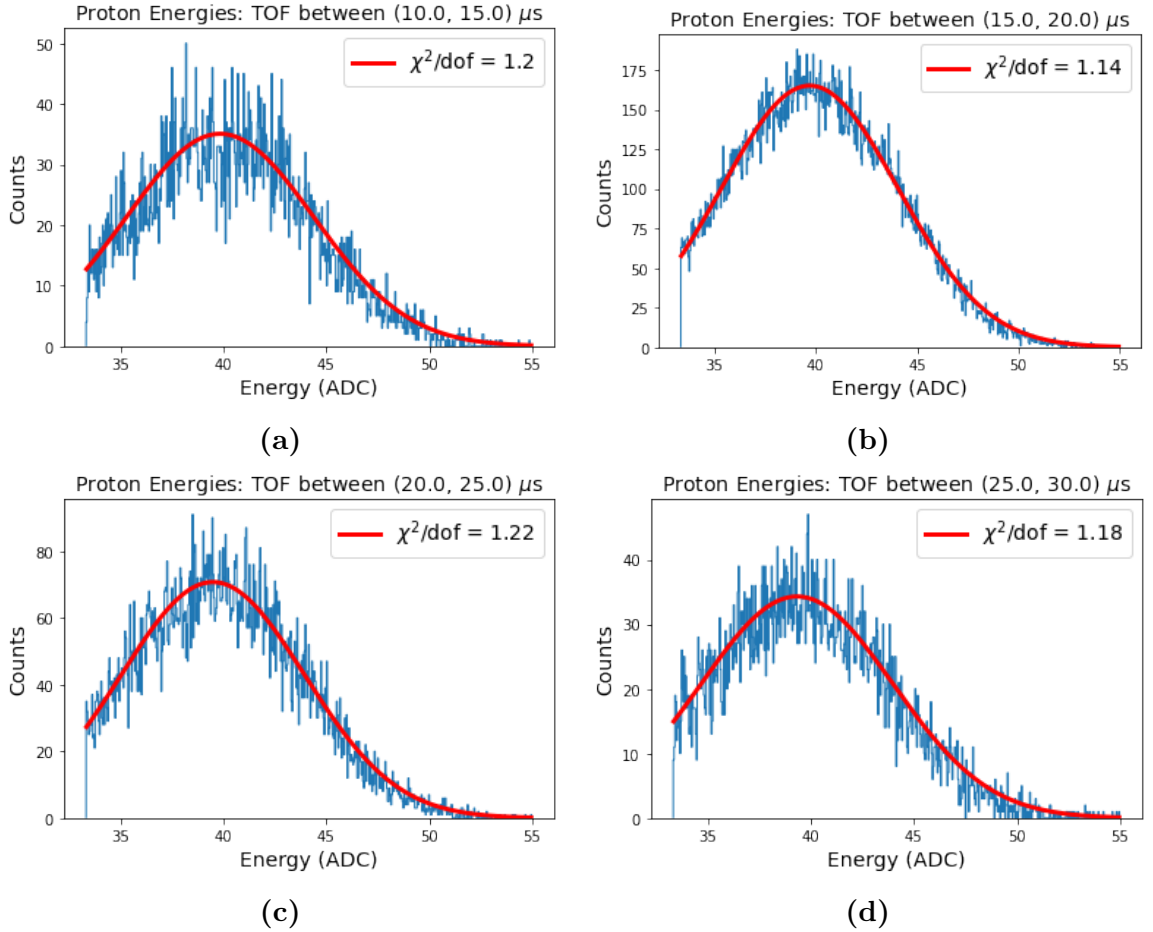


Figure 6.10: Gaussian fits to run 7244 proton peak on pixel 51. The events are split into 5 μs wide time bins, each is represented on a separate plot and fit with a gaussian curve above the 33.33 ADC $\approx$ 10 keV threshold. The TOF bin centers were 12.5 μs , 17.5 μs , 22.5 μs , and 27.5 μs . There were additional TOF bins with longer flight times, but the data set was truncated since the majority of the expected proton TOF spectrum is captured within this range.

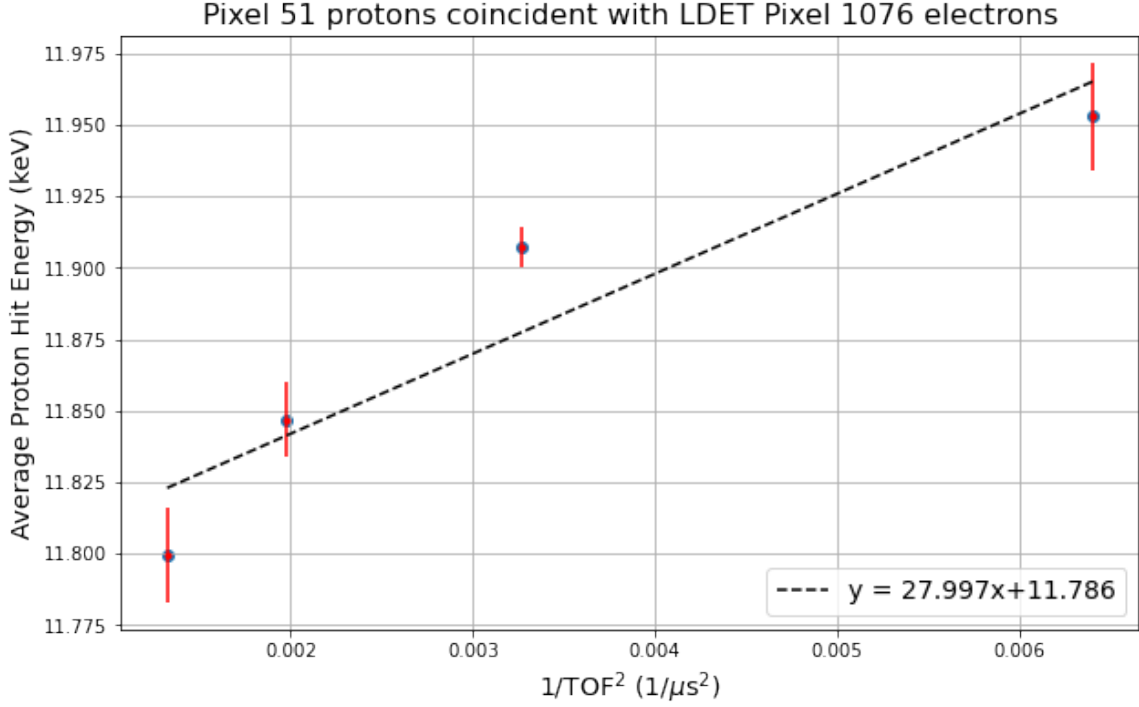


Figure 6.11: Average proton hit energies (gaussian means from Fig. 6.10) are plotted versus $1/\text{TOF}^2$ since $E_{\text{initial}} \propto 1/\text{TOF}^2$. The error bars are the uncertainties on the gaussian means provided by the fit.

In order to compare the results in Fig. 6.11 to simulation results, some mapping from $1/\text{TOF}^2$ to initial proton energy must be applied. Given $1/\text{TOF}^2$ and the flight path length, L , the initial energy can be determined kinematically. So, an estimate must be made for L . Three key assumptions are made. First, it is assumed that the lowest TOF bin center ($12.5 \mu\text{s}$) is the TOF for the highest energy protons. Second, the highest energy protons have initial energy of 751 eV. Third, the path length is the same for every proton. With these assumptions, the path length, L , was calculated to be $\sim 4.74 \text{ m}$. The initial proton energy can then be expressed as a function of $1/\text{TOF}^2$:

$$E_{\text{initial}} = \frac{m_p \cdot L^2}{2} \left(\frac{1}{\text{TOF}^2} \right), \quad (6.5)$$

where the quantity $m_p \cdot L^2/2$ is a constant. Eq. 6.5 was used to map the results in Fig. 6.11 to those shown in Fig. 6.12.

The slope of the linear fit to the equivalent plot from data (Fig. 6.12; slope = $2.4 \times 10^{-4} \pm 6.2 \times 10^{-5}$ keV/eV) is of the same magnitude as the simulated slope (Fig. 6.8a; slope = $7.506 \times 10^{-4} \pm 1.77 \times 10^{-5}$ keV/eV), but is significantly smaller (it does not fall within the stated uncertainty).

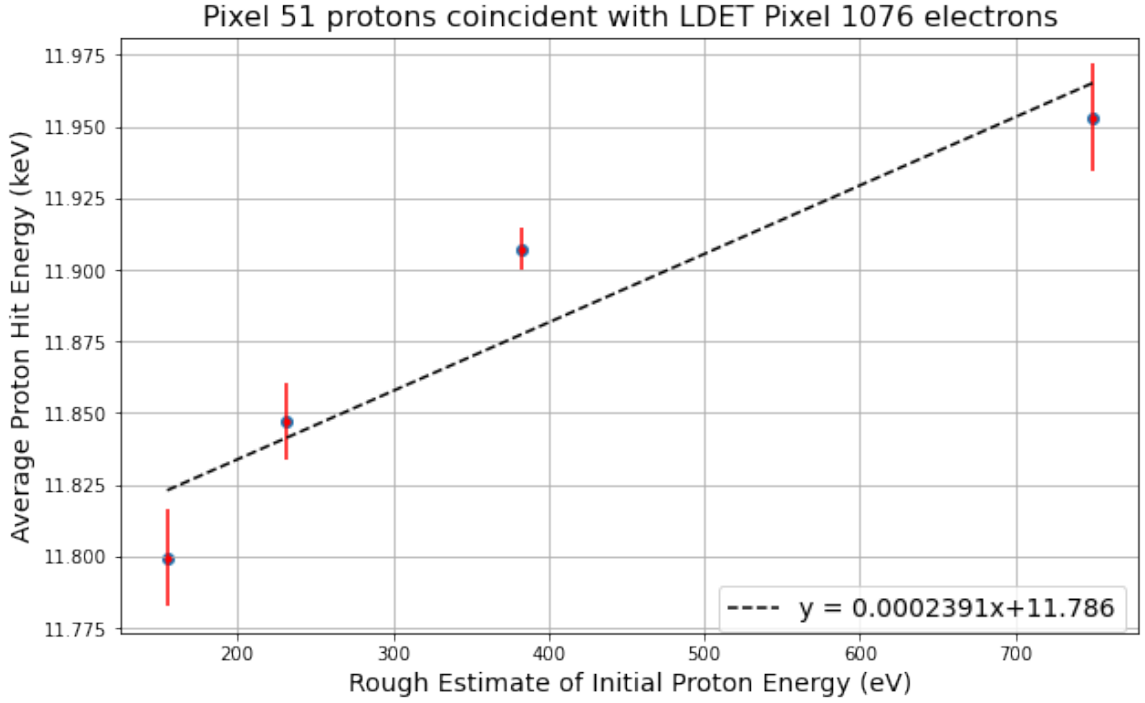


Figure 6.12: The average proton hit energy in keV is plotted versus an estimate of the initial proton energy in eV. A linear fit is made for comparison to Fig. 6.8a. The slope of the linear fit is $2.4 \times 10^{-4} \pm 6.2 \times 10^{-5}$ keV/eV.

The next step is to plot the estimated proton detection efficiencies on the y-axis in place of the average proton hit energies. This will show the dependence of the detection efficiency on proton energy. Simulation predicts that there will be a positive linear relationship between the two variables (Fig. 6.8b). The coefficient for the linear term of the fit to simulated data is $\sim 1.163 \times 10^{-5} \pm 8.451 \times 10^{-7}$ eV⁻¹.

The slope of the linear fit of the data from run 7244 on pixel 51 resulted in a slope of $2.9 \times 10^{-5} \pm 2.3 \times 10^{-5} \text{ eV}^{-1}$ (Fig. 6.13). This agrees with the slope determined from simulation within its statistical uncertainty.

The final step is to use Eq. 6.2 which requires c_1 in units of ppm/keV. In these units, the simulated and measured c_1 are $c_{1,\text{sim}} \approx 11600 \text{ ppm/keV}$ and $c_{1,\text{meas}} \approx 29020 \text{ ppm/keV}$. Putting these into Eq. 6.2 and treating the expected a as the result from Eq. 6.2 with $c_1 = 0$, yields $(\Delta a/a)_{\text{sim}} \approx 0.0399$ and $(\Delta a/a)_{\text{meas}} \approx 0.0996$. The percent difference between the central values of the simulated effect and the measured effect is then $\sim 150\%$.

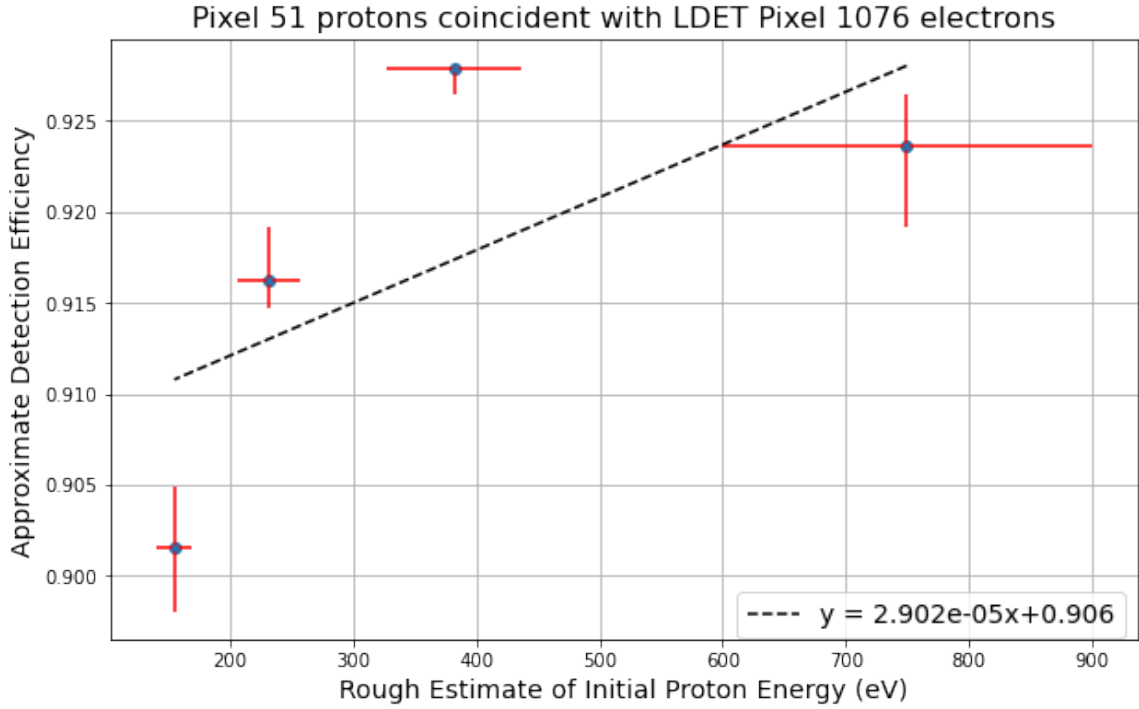


Figure 6.13: Detection efficiency estimated from gaussian fits versus the estimated initial proton energy for protons incident on pixel 51 during run 7244. The vertical error bars come from propagating the error on the gaussian fit parameters through the z-score calculation and looking up the endpoints in the z-score table (41) to determine the range of possible efficiencies. The horizontal error bars come from the width of the TOF bins. They are the variation, $\pm 2.5 \mu\text{s}$, propagated through Eq. 6.5. The linear fit yielded a slope of $2.902 \times 10^{-5} \pm 2.327 \times 10^{-5} \text{ eV}^{-1}$.

6.2.1 Future Work

The method described in this section yielded a result for the slope of the detection efficiency versus the initial proton energy that agreed with simulation within statistical uncertainty. However, agreement of the central values was poor. Disagreement of the measured detection efficiency with simulation is not an unreasonable outcome. This could suggest the presence of systematic corrections which require further study.

The statistical uncertainty on the slope for the measured data was quite large (nearly the size of the slope itself). This may be improved by analyzing more runs to increase the statistics and shortening the TOF bin width. Runs 7248, 7285, 7364, 7375, and 7376 should all be suitable for this analysis.

In the future, the range should be extended to include events with TOFs up to $\sim 40 \mu\text{s}$ (flight times longer than this are expected to include back-scattered protons). However, for pixel 51 in run 7244, the spectra between $30 \mu\text{s}$ to $35 \mu\text{s}$ and $35 \mu\text{s}$ to $40 \mu\text{s}$ fell significantly below the expected energies, so they were not included.

Another notable discrepancy was that the measured average proton hit energy versus initial energy (Fig. 6.12) had a significantly more shallow slope than the simulated slope (Fig 6.8a). If this disagreement is not resolved by background subtraction and finer TOF binning, it would be worth investigating further as it may be the result of a systematic effect.

The gaussian noise peak observed in this data set was around $10 \text{ ADC} \approx 3 \text{ keV}$ (Fig. 6.6), which is much higher than the 1.09 keV gaussian noise that was incorporated into the high statistics simulation. This is expected to have a significant impact on the comparison to the simulated results.

The $(\Delta a/a)_{\text{meas}} \approx 0.10 \pm 0.08$ result for pixel 51 is in large part due to the 10 keV threshold set in analysis. With improved background subtraction this can be reduced further into the noise pedestal.

Chapter 7

Conclusion

Nab aims to achieve the most precise measurement of the electron-neutrino correlation coefficient, $\Delta a/a \approx 1 \times 10^{-3}$, ever made. This result will be utilized to extract $\lambda = g_A/g_V$, the ratio of the axial-vector to vector weak coupling constants. The extracted λ will then be used along with recent high-precision neutron lifetime measurements to calculate V_{ud} , the first element in the Cabibbo-Kobayashi-Maskawa quark mixing matrix. The resulting precision will be competitive with the current leading results from super-allowed $0^+ \rightarrow 0^+$ decays without the need for nuclear structure corrections.

The Nab experiment uses two highly-segmented, thick, large-area silicon detectors at either end of a 7 m tall electromagnetic spectrometer to measure the electron energy and the proton time of flight. Decay protons are guided to the upper detector by the magnetic field. The maximum kinetic energy that the protons can have from the decay is 751 eV, which is too low for them to bypass the dead layer of the detector. In order to detect them, they are boosted by a ~ -30 kV potential just before they reach the upper detector. Even with the boost, noise due to thermally excited electron-hole pairs in room-temperature silicon detectors would be too high to detect the protons and would decrease the energy resolution (important for both electrons and protons), so the detectors must be actively cooled. This work presents

the closed-loop helium gas recirculating cooling system for the Nab detectors. Design for the cooling system was finalized, updates to the design were implemented, and the system was successfully commissioned. The detector cooling system performance has been demonstrated to exceed the design goals. It is able to cool the upper detector to ~ 100 K and the lower detector to ~ 115 K with sub ± 0.5 K stability. It is capable of independently stabilizing each detector at a full range of temperatures from the minima up to 300 K. This dynamic temperature stabilization enables precise temperature-dependent studies.

In order to reach the precision goal for Nab, the systematic effects present in the measurement must be minimized, they must be well-characterized, and their impacts on $\Delta a/a$ must be well-understood. Pursuant of this, analysis for the Nab experiment is largely comprised of systematic studies and interpretation of their results.

One of the systematic effects for the Nab detectors is temperature-dependent gain shifts. The energy band gap in silicon increases as temperature decreases. This directly impacts the number of electron-hole pairs which an incoming charged particle will liberate when it interacts with the detector. As temperatures decrease, the detected energy will decrease. A conservative estimate for the allowable gain shift from this effect was set to 1×10^{-4} . This work reviewed literature values for the temperature-dependent electron-hole pair creation energy and synthesized results from the two most precise measurements (49; 53) to set a worst-case limit on the allowable temperature variation. The 1×10^{-4} gain shift was found to correspond to ~ 0.588 K, so the required temperature stability was set to 0.5 K. The literature review also revealed that there is a dissimilarity in observed behavior from one detector to another. In response to this, a critical part of this work was to measure the observed gain shift with temperature. This measurement utilized 207-Bi sources to characterize this effect for three Nab detectors (“Manitoba”; “Goop!”; and “VALENTINE”) in situ. For all three detectors, it was shown that a temperature variation of 0.5 K resulted in a gain shift of $< 1 \times 10^{-4}$. The results from this study

are being used to inform detector cooling system operation and to make temperature-dependent corrections to calibrations between data sets that were taken at different temperatures.

An important extension of the work to set the temperature variation limit on the Nab detectors was to investigate the thermal profile of the detectors. If the temperature range on the face of a detector exceeded the 0.5 K limit then pixel-by-pixel corrections would be necessary. This work consulted the detector surface heat map modeled in Ansys to strategically place calibrated temperature sensors on the face of the “Dummy” detector for the measurement. The thermal profile of the “Dummy” detector was investigated over a wide set of detector cooling system settings within a test vacuum vessel (the “Mini-Chamber”) that was outfitted with a radiation shield. The maximum observed temperature variation on the face of the detector was 0.17 K. This measurement showed that no pixel-by-pixel temperature-dependent gain corrections are necessary.

Each of the past Nab data-taking campaigns (2023, 2024, and spring 2025) has resulted in a different observed average proton peak energy. The average proton energy expected from early simulations is 20 keV. The 2023 proton energy peak was observed just below 10 keV. In response, a new detector was installed (“Manitoba” $\rightarrow$ “Goop!”). The highest proton energy peak was observed around 18 keV with “Goop!” during the 2024 campaign. The spring 2025 campaign saw protons at roughly 14 keV. The shift in proton energy is attributed to contamination on the upper detector creating an unexpected dead layer on the surface. While Nab does not use the detected proton energies directly in the calculation of a , variations in the proton energy impact the uncertainty on a . Specifically, the proton detection efficiency is energy dependent. Thus, a change in the proton energy distribution will impact how well the contribution of the proton detection efficiency to the relative uncertainty on a is understood.

In 2025, new simulations were conducted to model the energy dependence of the proton detection efficiency for a 150 nm silicon dead layer on the detector and a

1.09 keV gaussian noise peak. The relative uncertainty on a for various detector thresholds was calculated from the values obtained from the simulation. This work used results from these simulations and the technique laid out by the calculations to develop a method to determine the same values from 2025 proton data. The proposed method was demonstrated for pixel 51, the results were compared to results from simulation, and recommendations for future work were made. Given the high threshold set during this analysis, the $(\Delta a/a)_{\text{meas}} \approx 0.10 \pm 0.08$ result for pixel 51 is not an unreasonable estimate.

The Nab experiment is proceeding with production data-taking, now (fall 2025 campaign) with “VALENTINE” as the upper detector (lower detector for 2024 and spring 2025 campaigns) and “Goop!” as the lower detector (upper detector for 2024 and spring 2025 campaigns). With this swapped configuration, it may be possible to isolate whether effects are detector dependent or electronics dependent. The outlook for improved proton energies is also positive (early measurements indicate a proton peak near 18 keV). Going forward the work that was presented here will continue informing handling of the detector cooling system operation. The temperature dependent gain variations will be used as an estimate for comparing data taken at different temperatures. The method for determining the proton detection efficiency’s contribution to $\Delta a/a$ will also be useful to future Nab data analysis.

Bibliography

- [1] (2014). Physical constants. <https://pdg.lbl.gov/2014/reviews/rpp2014-rev-phys-constants.pdf>. Accessed: 2025-05-12. 12
- [2] (2020 (accessed Mar 27, 2020)). *CH-110 Specifications*. 42, 56
- [3] (2024). n mean life. <https://pdglive.lbl.gov//DataBlock.action?node=S017T>. Accessed: 2025-05-12. 12
- [4] (2024 (accessed May 6, 2024)). *CFHT Product Specs*. 54
- [5] (2025). Pdg live. <https://pdglive.lbl.gov//DataBlock.action?node=S017AV>. Accessed: 2025-05-19. 15
- [6] Anonymous (1948). Minutes of the meeting at washington, april 29 to may 1, 1948. *Phys. Rev.*, 74:1201–1253. 3, 5
- [7] Baessler, S. (2025a). Conversation about the gain limitations for the detector system. Private communications. 59, 99, 103
- [8] Baessler, S. (2025b). The neutrino electron correlation coefficient in neutron beta decay. Presented at the 31st International Seminar on Interaction of Neutrons with Nuclei: Fundamental Interactions & Neutrons, Nuclear Structure, Ultracold Neutrons, Related Topics (ISINN-31), Dongguan, China. [Invited Talk]. 17
- [9] Baeßler, S. et al. (2024). Study of neutron beta decay with the Nab experiment. *EPJ Web Conf.*, 303:05001. 51

- [10] Beck, M., Heil, W., Schmidt, C., Baeßler, S., Glück, F., Konrad, G., and Schmidt, U. (2024). Reanalysis of the $\beta-\bar{\nu}_e$ angular correlation measurement from the aspect experiment with new constraints on fierz interference. *Phys. Rev. Lett.*, 132:102501. [18](#), [19](#)
- [11] Birge, N. W. (2019). *Measurement of the Fierz Interference Term for Calcium-45*. PhD dissertation, The University of Tennessee, Knoxville. [40](#)
- [12] Blackett, P. M. S. (1925). The ejection of protons from nitrogen nuclei, photographed by the wilson method. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, 107(742):349–360. [2](#)
- [13] Burgess, C. and Moore, G. (2006). *The Standard Model: A Primer*. Cambridge University Press. [6](#), [8](#), [9](#)
- [14] Bussolati, C., Fiorentini, A., and Fabri, G. (1964). Energy for electron-hole pair generation in silicon by electrons and α particles. *Physical review*, 136(6A):A1756–A1758. [60](#)
- [15] Canali, C., Martini, M., Ottaviani, G., and Quaranta, A. A. (1972). Measurements of the average energy per electron-hole pair generation in silicon between 5-320°k. *IEEE Transactions on Nuclear Science*, 19(4):9–19. [60](#)
- [16] Canali, C., Ottaviani, G., and Alberigi Quaranta, A. (1971). Drift velocity of electrons and holes and associated anisotropic effects in silicon. *The Journal of physics and chemistry of solids*, 32(8):1707–1720. [60](#)
- [17] Chadwick, J. (1932a). The existence of a neutron. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, 136(830):692–708. [2](#), [3](#)
- [18] Chadwick, J. (1932b). Possible existence of a neutron. *Nature (London)*, 129(3252):312–312. [2](#)

- [19] Chadwick, J. and Goldhaber, M. (1935). The nuclear photoelectric effect. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 151(873):479–493. [3](#)
- [20] Choi, J. H. (2025). Physics overview of the nab experiment. Presented at the 2024 Fall Meeting of the APS Division of Nuclear Physics, Hilton Boston Park Plaza, [Boston, MA] [8/8/2024]. [95](#), [96](#)
- [Commons] Commons, W. Standard model of elementary particles. https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg; <https://creativecommons.org/licenses/by/3.0/legalcode>. [7](#)
- [22] Dubbers, D. and Schmidt, M. G. (2011). The neutron and its role in cosmology and particle physics. *Reviews of Modern Physics*, 83(4):1111–1171. [10](#), [14](#), [16](#), [18](#), [21](#)
- [23] et al, L. B. (2017). Neutron decay correlations in the nab experiment. *J.Phys.*, Conf. Ser. 876(012005). [27](#)
- [24] Fomin, N. et al. (2015). Fundamental neutron physics beamline at the spallation neutron source at ornl. *Nuclear Instruments and Methods in Physics Research A*, 773:45–51. [24](#), [25](#), [26](#)
- [25] Fomin, N., Fry, J., Pattie, R. W., and Greene, G. L. (2022). Fundamental neutron physics at spallation sources. *Annual Review of Nuclear and Particle Science*, 72(1):151–176. [12](#), [13](#)
- [26] Fry, J. et al. (2019a). The nab experiment: A precision measurement of unpolarized neutron beta decay. *EPJ Web of Conferences*, 219(04002). [xiv](#), [23](#), [28](#), [30](#)
- [27] Fry, J. et al. (2019b). The nab experiment: A precision measurement of unpolarized neutron beta decay. *EPJ Web of Conferences*, 219(04002). [18](#)

- [28] Gibson, W. M. (1966). The role of particle channelling in detector systems. *IEEE Transactions on Nuclear Science*, 13(3):162–175. [97](#)
- [29] Godri, R., Alarcon, R., Baeßler, S., Broussard, L. J., Clymer, S., Crawford, C. B., Dodson, G. W., Fry, J., Fomin, N., Gonzalez, F. M., Hamblen, J., Hendrus, C., Jiang, C. P., Landgraf, C., Nelsen, A., Macsai, N., Mammei, R., Mueller, P. E., Pate, J. H., Penttilä, S., Pierce, J., Počanić, D., Rahangdale, H., Ramsey, J. C., Richburg, L., Saunders, A., and Wallace, I. (2025). Characterizing the afp spin flipper for the nab experiment. *PoS - Proceedings of Science*, 472. [26](#)
- [30] Gonzalez, F. M., Choi, J. H., Acharya, H., Clymer, S., Hagemeyer, A., Mathews, D. G., Mendelsohn, A., Nelsen, A., Rahangdale, H., Richburg, L., Alarcon, R., Atencio, A., Baeßler, S., Bailey, T., Birge, N., Borissenko, D., Bowler, M., Broussard, L. J., Bryant, A. T., Caylor, J., Chupp, T., Crawford, C., Croley, R. A., Cruz, M., Dodson, G., Fan, W., Fellers, D., Fomin, N., Frlež, E., Frost, M., Fry, J., Fuehne, D., Gericke, M. T., Gervais, M., Gilbert, C., Glück, F., Godri, R., Greene, G. L., Greene, W., Hamblen, J., Harmston, P., Hayen, L., Hedinger, C., Hendrus, C., Hollander, S., Imam, K., Iverson, E. B., Jezghani, A., Jiang, C., Li, H., Macsai, N., Makela, M., Mammei, R., Marshall, R., Martinez, M., McCrea, M., McGaughey, P., McGovern, S., McLaughlin, D., Mirabal-Martinez, J., Mueller, P., Mullins, A., Musk, W., O’Kronley, J., Penttilä, S. I., Perryman, D. E., Pierce, J., Pioquinto, J. A., Počanić, D., Presley, H., Ramsey, J., Randall, G., Raney, Z., Ricketts, J., Riley, G., Salas-Bacci, A., Samiei, S., Saunders, A., Schreyer, W., Scott, E. M., Shelton, T., Singh, A., Smith, A., Smith, E., Stevens, E., Taylor, R. J., Tinius, L., Wallace, I., Wexler, J., Wilburn, W. S., Young, A. R., and Zeck, B. (2025). First full dalitz plot measurement in neutron β -decay using the nab spectrometer and implications for new physics. [20](#), [27](#), [93](#), [94](#)
- [31] Gonzalez, F. M. et al. (2021). Improved neutron lifetime measurement with UCN τ . *Phys. Rev. Lett.*, 127(16):162501. [15](#)

- [32] Hamblen, J. (2025). Conversation about the proton trigger efficiency. Private communications. Accessed: 10-01-2025. [97](#), [101](#), [102](#), [103](#), [104](#)
- [33] Hardy, J. C. and Towner, I. S. (2015). Superaligned 0^+ to 0^+ nuclear beta decays: 2014 critical survey, with precise results for ν ud and ckm unitarity. *Physical Review C*, 91(2). [12](#)
- [34] Hayen, L., Choi, J. H., Combs, D., Taylor, R. J., Baeßler, S., Birge, N., Broussard, L. J., Crawford, C. B., Fomin, N., Gericke, M., Gonzalez, F., Jezghani, A., Macsai, N., Makela, M., Mathews, D. G., Mammei, R., McCrea, M., Mendelsohn, A., Nelsen, A., Riley, G., Shelton, T., Sjue, S., Smith, E., Young, A. R., and Zeck, B. (2023a). Precision pulse shape simulation for proton detection at the nab experiment. *Physical review. C*, 107(6). [30](#), [33](#)
- [35] Hayen, L. et al. (2023b). Precision pulse shape simulation for proton detection at the Nab experiment. *Physical Review C*, 107, 065503. [18](#), [39](#), [59](#), [60](#)
- [36] Jackson, J. D., Treiman, S. B., and Wyld, H. W. (1957). Possible tests of time reversal invariance in beta decay. *Phys. Rev.*, 106:517–521. [13](#)
- [37] Jean-Louis Basdevant, J. R. and Spiro, M. (2005). *Fundamentals in Nuclear Physics: From Nuclear Structure to Cosmology*. Springer Science + Business Media, Inc., New York, NY. [2](#)
- [38] Key, J. R. and Rabson, T. A. (1971). Average energy expended per ionized electron-hole pair for particles in si(li). *IEEE transactions on nuclear science*, 18(1):184–186. [60](#)
- [39] Knoll, G. F. (2000). *Radiation Detection and Measurement*. John Wiley Sons, Inc., New York. [30](#), [31](#), [39](#)
- [40] L. J. Broussard *et al.* (2017). Neutron decay correlations in the Nab experiment. *Journal of Physics: Conference Series*, 876:012005. [18](#)

- [41] Laemmerzahl, A. F. (2018). Normal distribution table. <https://mason.gmu.edu/~alaemmer/bio214/normal-table.pdf>. Accessed: 10-10-2025. 98, 108
- [42] Lehmann, J. (2019). Z-score Basics. <https://ubalt.pressbooks.pub/mathstatguides/chapter/z-score-basics/>. Accessed: 10-12-2025. 98
- [43] Ltd, C. (2025). Actively shielded nab spectrometer: Target cryogen-free system in the world successfully installed! Accessed: 09-24-2025. 27
- [44] Macsai, N. (2023). *Silicon Detector Testing for Neutron Beta Decay Experiment Nab*. Doctoral dissertation, University of Manitoba. 93
- [45] Mathews, D. (2020). nabPy. <https://gitlab.com/NabExperiment/pyNab>. Accessed: 06-10-2025. 64
- [46] Mathews, D. G., Acharya, H., Crawford, C. B., Gervais, M. H., Jezghani, A. P., McCrea, M., Nelsen, A., Atencio, A., Birge, N., Broussard, L. J., Choi, J. H., Gonzalez, F. M., Li, H., Macsai, N., Mendelsohn, A., Mammei, R. R., Riley, G. V., and Whitehead, R. A. (2024). A flexible data acquisition system architecture for the nab experiment. 33
- [47] Navas, S. et al. (2024). Review of particle physics. *Phys. Rev. D*, 110(3):030001. 16
- [48] NIST (2025). Estar : Stopping power and range tables for electrons. <https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html>. Accessed: 09-25-2025. 32
- [49] Pehl, R., Goulding, F., Landis, D., and Lenzlinger, M. (1968). Accurate determination of the ionization energy in semiconductor detectors. *Nuclear instruments methods*, 59(1):45–55. 60, 61, 111
- [50] Ramsey, J. (2025). Conversation about the thermal profile. Private communications. Accessed: 10-01-2025. 80

- [51] Robson, J. M. (1950). Radioactive decay of the neutron. *Phys. Rev.*, 78:311–312. [3](#)
- [52] Rutherford, E. (1920). Bakerian lecture: Nuclear constitution of atoms. *Proc. R. Soc. Lond. A*, 97:374–400. [2](#)
- [53] Ryan, R. D. (1973). Precision measurements of the ionization energy and its temperature variation in high purity silicon radiation detectors. *IEEE transactions on nuclear science*, 20(1):473–480. [59](#), [60](#), [61](#), [111](#)
- [54] Sakharov, A. D. (1991). Violation of cp invariance, c asymmetry, and baryon asymmetry of the universe. *Soviet Physics Uspekhi*, 34(5):392. [10](#)
- [55] Snell, A. H., Pleasonton, F., and McCord, R. V. (1950). Radioactive decay of the neutron. *Phys. Rev.*, 78:310–311. [3](#), [4](#)
- [56] Wietfeldt, F. E. et al. (2024). Recoil-order and radiative corrections to the aCORN experiment. *Phys. Rev. C*, 110(1):015502. [18](#), [19](#)
- [57] Wietfeldt, F. E. and Greene, G. L. (2011). Colloquium: The neutron lifetime. *Rev. Mod. Phys.*, 83:1173–1192. [3](#), [4](#), [15](#)
- [58] Wietfeldt, F. E., Snow, W. M., Liu, C.-Y., Crawford, C. B., and Kurahashi Neilson, N. (2022). BL3 Neutron Lifetime Apparatus. NSF Award Number 2131864. Directorate for Mathematical and Physical Sciences, Division Of Physics. 2022. [17](#)
- [59] Workman, R. L. and Others (2022). Review of Particle Physics. *PTEP*, 2022:083C01. [13](#), [18](#)

Appendix A

The detector cooling system piping and instrumentation diagram (P&ID) is on the next page. This is the P&ID for the lower loop, but the upper loop is nearly identical.

Vita

Love Richburg was born in Austin, Texas in 1997. She graduated in the top 1% of her class in 2015 from Madison Central High School in Richmond, Kentucky. For her undergraduate studies, she attended Eastern Kentucky University. During her time there, she co-founded the Swing Dance Club at ECU, served on the Honors Student Advisory Council for two years, and helped revitalize the Society of Physics Students by serving as the treasurer. She graduated with honors and a dual degree in Physics and Mathematics in 2019. Soon after this she started her graduate studies in the Physics department at the University of Tennessee. She has studied in Professor Nadia Fomin's Fundamental Neutron Symmetries Group. During this time she earned an Office of Science Graduate Student Research Award, and she currently serves on the Nab Executive Board.