Radon Measurement for Neutrinoless Double Beta Decay

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RADON MEASUREMENT FOR
NEUTRINOLESS DOUBLE BETA DECAY

by

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B.S., PHYSICS, NEW MEXICO INSTITUTE OF MINING
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THESIS

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Dedication

In dedication to my beloved grandmothers, Evangeline G. Quintana and Rebecca M. Lucero. I am eternally grateful for the many memories and lessons you have given me over our time shared together. May this document serve as statement of your legacy.
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I wish to thank the UNM Earth Science Department for lending a rock sample. I also wish to thank Granite Passion for donating granite samples for testing and measurement.
ABSTRACT

This thesis details the design and operation of a high-sensitivity radon detector for use in background radiation characterization and mitigation for the MAJORANA DEMONSTRATOR Neutrinoless Double Beta Decay Experiment and Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND) Collaboration. Understanding and mitigating background radiation is especially important in searches for very rare nuclear processes, which utilize sensitive detectors. One such rare process is the yet-to-be-observed neutrinoless double beta decay. Observation of this process would imply that the neutrino is its own antiparticle, called a Majorana particle, violate lepton number, and provide experimental constraints on the masses and mixing angles between neutrino mass and flavor eigenstates.
While most sensitive rare search experiments are placed deep underground to shield from cosmic radiation, radon provides a significant and pervasive source of background radiation. This background radiation could potentially make an experiment futile as any small signal of interest could be hidden in a large amount of background events. Radon is a decay product of both uranium and thorium, which are found in rock, soil, and many common materials. Radon is the only daughter in the uranium and thorium decay chains that is gaseous, so it is able to escape materials either through pores and fissures or diffusion through the material.

Our radon detector utilizes a large electropolished stainless steel vessel to collect gas and a high electric field to collect charged radon daughters on a silicon PIN photodiode. Alpha particles from radon daughter decays, primarily that of $^{214}$Po, are measured with the photodiode and a radon concentration in the gas is determined from the measured activity. The collection efficiency, and thus calibration factor from photodiode activity to radon activity, is determined by using air and an ore-like mineral as sources and a Durridge RAD7 radon detector as a calibration standard. The detector also includes an in-line emanation chamber to test the radon emanation from materials of interest. Utilization of this detector in the construction and operation of any ultra-low background search provides valuable quantization of ambient radon backgrounds to a sensitivity of the order mBq/m$^2$. 
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1 Theoretical Background

Observation of the theoretical nuclear rare decay process neutrinoless double beta decay (0νββ) would provide us with a few important pieces of information on the nature and interaction of the weak nuclear force, the properties and nature of neutrinos, and physics beyond the standard model. Observation of 0νββ would provide compelling evidence that the neutrino is its own anti-particle, called a Majorana particle [1]. Proof of the Majorana nature of the neutrino could influence theories of the early universe by testing theories of baryogenesis [2], the origin of matter-antimatter asymmetry in the observed universe. Further, Majorana particles open new possibilities for theories of dark matter candidates [3], as well as provide information on the properties of the neutrino, including the masses and oscillation dynamics of the mass eigenstates [1]. Further, this process would show that lepton number is not always conserved, which may also shed new light on theories of baryogenesis [2].

1.1 Dirac and Majorana Fermions

The notion of a particle which is its own antiparticle is related to the very discovery of antiparticles themselves. In 1928, while extending the Schrodinger and Klein-Gordon equations to the electron, Paul Dirac developed a relativistic wave equation that is applicable to all spin-1/2, massive particles [4]:

\[ (i\hbar \gamma^k \partial_k - m) \psi = 0 \quad k = 1, 2, 3, 4 \]  

(1)

where \( m \) and \( \psi \) are the mass and wavefunction of the particle, respectively, \( \partial_k \) is the derivative with respect to the kth component, and \( \gamma^k \) are matrices given by the following:
\[ \gamma^0 = \begin{pmatrix} I_2 & 0 \\ 0 & -I_2 \end{pmatrix}; \quad \gamma^k = \begin{pmatrix} 0 & \sigma_k \\ -\sigma_k & 0 \end{pmatrix} \]

\[ I_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}; \quad \sigma_i = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}; \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}; \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \]

This formulation is a remarkable feat of unifying both quantum mechanics and special relativity into a single theory that fully describes massive fermions, including electrons, neutrinos, and quarks. One problem with the Dirac Equation is that it is equally valid for electrons of positive and negative energies. Classically, and intuitively, these negative energy solutions do not make physical sense. Dirac’s initial resolution of this problem was to interpret the negative energy solutions as positive energy solutions of a particle with opposite charge. This brought additional difficulties that Dirac explored in a later paper [5], specifically that the negative energy solutions should be available to all electrons and thus a transition from positive energy to negative energy of a particular electron would lead to a violation of the conservation of charge, and conservation of momentum if that electron were in an electric field.

Dirac further resolved the negative energy solutions by supposing that a nearly infinite number of electrons exist and fill nearly all the negative energy states available in the universe. All of these negative energy electrons would have an almost uniform distribution and thus contribute no net electric field to the universe. The only departure from this even distribution of negative energy electrons would be when there is a vacancy in a negative energy state, i.e. a hole. Dirac theorized that these holes were in fact occupied by protons. Cosmic ray experiments performed by Carl Anderson later discovered a particle with positive charge yet mass much less than the proton, on the
order of the electron mass [6]. Anderson identified this particle to be the positron, or positive electron. Dirac incidentally predicted antimatter through his “hole” theory, and Anderson observed that antimatter.

In response to Dirac’s hole theory, and the discovery of the positron, Ettore Majorana proposed a new representation which would change the Dirac equation. Majorana suggested that we can consider a case where the Dirac Equation is purely real by considering the electron wavefunction to have a real part and an imaginary part and taking only the real part [7]. This is functionally done by redefining the gamma matrices to be purely imaginary [8]. The consequence of this is a modified Dirac equation called the Majorana Equation [9]:

$$i\hbar \gamma^k_M \partial_k \psi - m_M \psi^C = 0 \quad k = 0, 1, 2, 3$$

$$\psi^C = \begin{pmatrix} 0 & i\sigma_2 \\ -i\sigma_2 & 0 \end{pmatrix}, \quad \gamma^k_M = R \gamma^k R^+$$

$$R = R^+ = \frac{1}{\sqrt{2}} \begin{pmatrix} I_2 & \sigma_2 \\ \sigma_2 & -I_2 \end{pmatrix}$$

$\psi^C$ is the particle wavefunction upon charge conjugation, $m_M$ is the effective particle mass in the Majorana representation, and $\gamma^k_M$ are the gamma matrices in Majorana’s representation. One interesting outcome of this is that the equation is not valid for charged particles since the effect of the charge conjugation operator would lead to predictions of violation of charge in Majorana’s representation. Therefore, the Majorana Equation is only valid for massive fermions which are also electrically neutral. Further, Majorana’s form does not predict antiparticles as Dirac did, and actually implies that a particle which satisfies this equation may be its own antiparticle since particle and antiparticle are identical under complex conjugation. Majorana suggested that the recently theorized neutrino could satisfy his equation. Initially, Majorana’s theory was
not seriously considered since it was, at the time, widely believed that neutrinos were massless. After it was proven that all flavors of neutrinos must have mass, the notion of a Majorana neutrino was re-introduced [10]. One prospective test for the possible Majorana nature of the neutrino is $0\nu\beta\beta$.

1.2 Single Beta Decay

Before exploring the theory and implications of $0\nu\beta\beta$, we first briefly discuss two similar processes that have indeed been observed: beta decay and ordinary, or two neutrino double beta decay ($2\nu\beta\beta$). Beta decay involves the nuclear transmutation of a nucleus that results in the emission of a beta particle, which is an electron or positron depending on the details of the transmutation, and an electron-type antineutrino (or neutrino) [10]. Beta decay has a special role in nuclear physics as it was the first decay process to be observed, via the work of Becquerel and Rutherford [11]. Inconsistencies in its experimentally observed energy spectra were the basis for the theoretical prediction of the neutrino [12]. Its relatively simple transition made it among the first decay processes to have an energy spectrum derived from theory [13], and today we search for a special kind of beta decay.

Specifically, beta decay is a flavor-changing charged-current weak interaction that involves the transition of a down quark into an up quark (or vice versa) via a virtual charged W boson, which decays into an electron and an antineutrino (or positron and neutrino) [10]. This quark flavor change transforms a neutron into a proton (or vice versa), which in turn results in the transmutation. The process where a neutron becomes a proton is called $\beta^-$-decay due to the charge of the virtual W boson ($W^-$). Similarly, the
process where a proton transforms into a neutron is called $\beta^-$-decay. The following reactions summarize these two processes:

\[
\begin{align*}
\beta^-: & \\
d \rightarrow u + e^- + \bar{\nu}_e \\
n \rightarrow p + e^- + \bar{\nu}_e \\
(A, Z) \rightarrow (A, Z + 1) + e^- + \bar{\nu}_e
\end{align*}
\]

\[
\begin{align*}
\beta^+: & \\
u \rightarrow d + e^+ + \nu_e \\
p \rightarrow n + e^+ + \nu_e \\
(A, Z) \rightarrow (A, Z - 1) + e^+ + \nu_e
\end{align*}
\]

It is useful to note that experimental inconsistencies of beta decay measurement led to the proposal of the neutrino. Upon careful measurement of the energy of the emitted electron, there seemed to be missing kinetic energy. According to the proposed two-body kinematics of beta decay, with $(A, Z) \rightarrow (A, Z - 1) + e^-$ and assuming that the
recoil kinetic energy of the daughter nucleus is negligible, the total energy of the emitted electron would be equal to the difference in rest mass energy between the parent and the daughter nuclei, known as the Q-value:

\[
m_p c^2 = \sqrt{(m_p c^2)^2 + (p_p c)^2} + E_e \approx m_p c^2 + E_e \quad (m_D \gg m_e)
\]

\[
E_e \approx (m_p - m_D) c^2 = Q_\beta = E_e = \sqrt{(m_e c^2)^2 + (p_e c)^2}
\]

\[
\therefore \quad p_e c \approx \sqrt{Q_\beta^2 - (m_e c^2)^2} = \text{const.}
\]

where \(m_i c^2\) are the rest mass energies, \(p_i c\) are the kinetic energies, \(E_e\) is the total energy of the emitted electron, \(Q_\beta\) is the Q-value of the reaction. The assumption that recoil energy of the daughter nucleus is negligible is valid due to conservation of momentum. The mass of the daughter nucleus is much larger than the mass of the electron, so the nucleus would have very little velocity compared to the electron. Since the rest mass energies are fixed values, the kinetic energy of the emitted electron would be a singular value. Rather, the kinetic energy of the electron was observed to be a continuous spectrum, with an endpoint at \(Q_\beta\), but a peak at approximately 1/3 of the \(Q_\beta\).

In 1930, Wolfgang Pauli surmised that the missing energy may be attributed to a yet-to-be-detected particle which he called the neutron (slightly before James Chadwick first detected the nucleonic neutron), which he predicted to be a neutral, massive, spin-1/2 fermion that interacts with matter about as often as, or less often than, a gamma ray [12]. By predicting another particle to be part of the beta decay reaction, the kinematics then involves 3 bodies, rather than two. Instead of the total energy of the electron being equal to the Q-value, the combined energies of the electron and Pauli’s “neutron” would sum to \(Q_\beta\). This theory was refined, and the decay kinematics and lifetimes were developed in detail, in 1934 by Enrico Fermi [13]. In this paper, Fermi also used the term “neutrino”
for the third particle in the reaction, which clearly stuck. It is remarkable that Fermi
developed a theory that so closely matches observation, and that beta decay continues to
be among the most useful tools for probing nuclear and particle physics.

In order to understand the conditions that allow double beta decay (and in which
isotopes it might occur), it is useful to briefly discuss the conditions under which regular
beta decay occurs. Radioactive decay, in general, occurs when a nucleus is not in the
lowest possible energy configuration. The nucleus could be energetically excited, or the
arrangement of protons and neutrons in the nucleus not most favorable. The former case
usually leads to the emission of a gamma ray with energy equal to the difference between
the excited state and the final state (which may or may not be the ground state), and
otherwise leaves the nuclei intact. The latter case typically leads to one of three decay
processes, the first being the emission of an alpha particle, which is a \( ^4 \)He nucleus, the
second being fission of a very heavy nuclei, and the third being beta decay. Alpha decay
and fission mostly occur in heavier nuclei, where losing an entire helium nucleus or
splitting into two separate nuclei is still energetically favorable to remaining intact. Beta
decay, on the other hand, causes no change in mass number and could occur at atomic
mass.

1.2.1 Nuclear Stability and Decay Conditions

Multiple factors affect the stability of a nucleus to radioactive decay. The strong
nuclear force provides strong attraction between nucleons to bind the nucleus, but it only
acts on very small length scales. At larger distances within the nucleus, the strong nuclear
force is overcome by other forces, particularly the electromagnetic force between
protons. These opposing forces result in a tug-of-war between nucleons, with some forces
holding the nucleus together and others conspiring to break it apart. The net effect of these forces can be summarized by the binding energy of the nucleus, the net energy that holds the nucleus together. The effective rest mass energy of a nucleus is the mass of all the constituent nucleons minus the binding energy. Thus, for nuclear isobars, the most stable isobar will have the lowest rest mass energy (and be the most energetically favorable configuration). An effective characterization of the binding energy is given by the Weizsacker Equation [14]:

$$E_B = a_1 A - a_2 A^{2/3} - a_3 \frac{Z(Z-1)}{A^{1/3}} - a_4 \frac{(A-2Z)^2}{A} \pm \Delta$$

(7)

$$\Delta = \begin{cases} -a_5 A^{-m_6} & N, Z \text{ odd} \\ 0 & A \text{ odd} \\ +a_5 A^{-m_6} & N, Z \text{ even} \end{cases}$$

where $a_i$ are empirically derived values, A is the atomic mass number, Z is the atomic number, and N=A-Z is the neutron number. This formula is also called the semi-empirical mass formula because it is partially based on theoretical predictions of how the strong and electromagnetic forces act on nucleons, but the relative strengths of each term, the coefficients, are determined by fitting to a curve of measured nuclear masses. Figure 2 shows a plot of the binding energy per nucleon predicted by the Weizsacker Equation for all nuclei with $0 \leq Z \leq 120$, $0 \leq N \leq 150$ ($0 \leq A \leq 270$). It is evident from this plot that the most stable nuclei (those with highest binding energy) occur near a line N=Z at low A but N>Z at higher A (Figure 3). The cause of this is that as Z increases, the electrostatic repulsion between protons increases and more neutrons are required to provide additional strong force. Since the electrostatic force acts at a greater range than
Figure 2: Binding Energy per Nucleon predicted by the Weizsacker Equation
the strong force and the nuclear radius $R \propto A^{1/3}$, more neutrons than protons are necessary to provide stability for heavier, larger nuclei.

This so-called “valley” of stability serves as a guidepost for what type of beta decay a nucleus will undergo. Nuclei with proton number greater than the valley of stability will likely undergo $\beta^+$ decay, while nuclei that are proton-deficient compared to the valley of stability will be $\beta^-$-unstable. Nuclei with high $A$ or high $N$ or $Z$ number may more likely decay via emission of one or more nucleons, or via spontaneous fission.

### 1.3 Two-Neutrino Double Beta Decay

A special case of beta decay occurs due to the $\Delta$ term in the Weizsacker Equation, which is called the pairing term. This term comes from the fact that nucleons prefer to occupy the lowest energy level possible. The Pauli Exclusion Principle, in this context, forbids two identical nucleons from occupying the same energy state, represented by

![Figure 3: Line that traces the Valley of Stability](image_url)
nuclear orbitals, within the nucleus. Thus, each energy level will consist of two paired nucleons with opposing spins. The spin-pairing effect results in an increase in binding energy. Nuclei with even numbers of both neutrons and protons will have all nucleons paired, while nuclei with odd numbers of both neutrons and protons will have 2 unpaired nucleons. In the latter case, it may be energetically advantageous for one of the unpaired nucleons to beta decay to pair with the other unpaired nucleon, despite a possible increase in the fourth term $\propto(A-2Z)^2/A$. This also means that if a nucleus is even-even in $N$ and $Z$, but not in the lowest energy state (in the valley of stability), any beta decay would transmute the nucleus into one that is odd-odd and potentially lower the binding energy due to spin-pairing. In this situation, the only decay that may be energetically favorable would be two simultaneous beta decays, i.e. double beta decay. For example, the nucleus $^{76}\text{Ge}$ has $Z=32$ and $N=44$ and thus will have a positive contribution to binding energy due

Figure 4: $A=76$ masses with the spin pairing term exaggerated slightly to show likely $\beta\beta$ decay from $^{76}\text{Ge}$ to $^{76}\text{Se}$
to spin pairing. A single $\beta^-$ decay will transmute the nucleus to $^{76}\text{As}$, with a negative contribution to binding energy due to no spin pairing and an overall lower binding energy. This means that it would take some external input of energy to convert $^{76}\text{Ge}$ to $^{76}\text{As}$. However, double beta decay to $^{76}\text{Se}$, also even-even, would be energetically favorable and seemingly the only energetically favorable beta decay of $^{76}\text{Ge}$.

Double beta decay requires two simultaneous nuclear processes, and thus is much rarer compared to ordinary beta decay. There are two types of double beta decay, ordinary (or 2-neutrino) double beta decay ($2\nu\beta\beta$) and neutrinoless double beta decay ($0\nu\beta\beta$). First, we will discuss $2\nu\beta\beta$ since it is much closer to a simple extension of classical beta decay theory. $2\nu\beta\beta$ can be represented by the following:

$$2d \rightarrow 2u + 2e^- + 2\bar{\nu}_e$$
$$2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$$
$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e$$  \hspace{1cm} (8)

![Feynman Diagram depicting $2\nu\beta\beta$][10]

Figure 5: Feynman Diagram depicting $2\nu\beta\beta$ [10]
In fact, $2\nu\beta\beta$ is observationally identical to two $\beta$ decays which had occurred simultaneously. Since detecting the electron antineutrinos from $2\nu\beta\beta$ is very difficult, detection of the two electrons created simultaneously is evidence of $2\nu\beta\beta$. Similarly to single $\beta$ decay, the antineutrinos take some momentum and energy with them and thus the summed energy of both electrons is observed to be a continuous spectrum with an endpoint at $Q_{\beta\beta}$.

1.3.1 Decay Rates and Nuclear Matrix Elements

The likelihood and lifetime of $2\nu\beta\beta$, or any decay, can be determined by Fermi’s Golden Rule. For $2\nu\beta\beta$ specifically, Fermi’s Golden Rule can be written in the form [15]:

$$\Gamma^{2\nu} = \ln 2 \cdot \left( T_{1/2}^{2\nu} \right)^{1/2} = G_{2\nu} \left| \mathcal{M}_{2\nu} \right|^2$$ (9)

where $\Gamma^{2\nu}$ is the predicted decay rate for $2\nu\beta\beta$, $T_{1/2}^{2\nu}$ is the predicted half-life, $G_{2\nu}$ is a phase space factor, and $\mathcal{M}_{2\nu}$ is defined as the nuclear matrix element (NME). The NME is a representation of the underlying physics of the interaction. Factors that affect the NME are the initial and final states and the physical interaction that takes one state to the other, represented by the Hamiltonian. Generally, it is less likely to transition between states that are very different and easier to transition between similar states.

The Hamiltonian of the interaction could be very complex, however accurately predicting its effect and comparing to experimental results could help to refine our understanding of the underlying physics. As mentioned above, $2\nu\beta\beta$ is very rare compared to single $\beta$ decay, even when single $\beta$ decay is suppressed via nuclear matrix elements. This is due to the fact that $2\nu\beta\beta$ is a second-order weak process, and thus the interaction will be more complex. The comparison between theory and experiment is
especially useful for rare processes such as $2\nu\beta\beta$ and $0\nu\beta\beta$. Additionally, as we will discuss later, understanding the NME for $0\nu\beta\beta$ can potentially help us to understand physics beyond the standard model. Determining the NMEs for $2\nu\beta\beta$ can help us understand the physics of $\beta\beta$ decay in general, the conditions under which we might observe $0\nu\beta\beta$, and the implications of the observation of $0\nu\beta\beta$.

1.4 Neutrinoless Double Beta Decay

While rare, $2\nu\beta\beta$ is entirely consistent with the Standard Model and has indeed been observed. $0\nu\beta\beta$ has not been conclusively observed, and its potential detection would change our understanding of the Standard Model and would inform physics beyond the Standard Model. To see why, we must discuss how $0\nu\beta\beta$ might occur. Unlike $2\nu\beta\beta$, $0\nu\beta\beta$ is not identical to two simultaneous $\beta^{-}$ decays. The most popular model of the reaction proceeds via the exchange of a massive virtual Majorana neutrino (meaning a neutrino which is its own antineutrino) [16]. In this model, observation of $0\nu\beta\beta$ implies that the neutrino is Majorana in nature. This exchange results in no neutrinos emitted from the reaction, only the two electrons. An implication of this lack of emitted neutrinos is that lepton number, the total number of leptons, is not conserved since zero leptons existed before yet two leptons came out. $\beta$ decay and $2\nu\beta\beta$ do not violate lepton number since each electron ($L=+1$) is accompanied by an electron antineutrino ($L=-1$), and each positron by an electron neutrino, conserving both lepton number and leptonic flavor number. Specifically, $0\nu\beta\beta$ consists of the following reaction:

$$
\begin{align*}
2d & \rightarrow 2u + 2e^{-} \\
2n & \rightarrow 2p + 2e^{-} \\
(A, Z) & \rightarrow (A, Z + 2) + 2e^{-}
\end{align*}
$$

(10)
Thus far, there has been no observed evidence of a nuclear interaction that violates either lepton number or baryon number. However, there is no fundamental reason why these quantities should always be conserved, particularly at energy scales that we have not yet observed [16]. Along those lines, we have already observed and developed a robust theory for a lepton-flavor violating process, neutrino oscillation. Neutrinos exist in 3 flavor eigenstates, electron, muon, and tau, and each flavor is a linear superposition of 3 mass eigenstates. By changing the ratio of each mass eigenstate, the neutrino can change its flavor, which is called neutrino oscillation. The specific ratios of each mass eigenstate in each flavor are not known exactly, and are called the mixing matrix elements, expressed in terms of mixing angles in analogy to oscillation being a rotation transformation. In the same way that neutrino oscillations triggered a fundamental change in our understanding of the neutrino, the observation of lepton number violation (either through $0\nu\beta\beta$ or some other interaction) would provide

Figure 6: Feynman Diagram depicting $0\nu\beta\beta$ mediated by a Majorana neutrino [10]
additional information about physics beyond the Standard Model. Specifically, details of lepton number violation could provide information on baryogenesis and details on the physical origin of neutrino mass, perhaps through the seesaw mechanism \[^2\].

Baryogenesis is the process which explains why there is more matter than antimatter in the observable universe. The seesaw mechanism theorizes that there are yet-unobserved heavy neutrinos that correspond to each flavor of observed light neutrinos.

One experimental advantage of the lack of emitted neutrinos in $0\nu\beta\beta$ is that the total energy of the two emitted electrons should be exactly equal to $Q_{\beta\beta}$. For example, the $\beta\beta$ decay of $^{76}$Ge to $^{76}$Se would have a $Q_{\beta\beta}$ of \[^{17}\]:

$$Q_{\beta\beta}(^{76}\text{Ge} \rightarrow ^{76}\text{Se}) = (m_{^76\text{Ge}} - m_{^76\text{Se}})c^2 = 2039.061 \pm 0.024 \text{ keV}$$ \[^{11}\]

Thus, we would expect the total energy from the two electrons to be monoenergetic and approximately 2.039 MeV. This feature makes the potential detection of $0\nu\beta\beta$ easier, though the rarity of the process brings extra challenges. $0\nu\beta\beta$ is predicted to be even rarer than $2\nu\beta\beta$ because, in addition to the same second-order weak interaction that causes $2\nu\beta\beta$, the neutrinoless variant also must involve the exchange of some virtual particle, whether that be the Majorana neutrino as is most commonly theorized or some other virtual particle. In a manner similar to $2\nu\beta\beta$, we can define the decay rate of $0\nu\beta\beta$ to be of the form \[^{15}\]:

$$\Gamma^{0\nu} = G_{0\nu} |M_{0\nu}|^2 |f(m_i, U_{ei})|^2$$ \[^{12}\]

where $G_{0\nu}$ and $M_{0\nu}$ are the phase space factor and NME, respectively, for $0\nu\beta\beta$, and $f(m_i, U_{ei})$ is a function that contains the effects of physics beyond the Standard Model due to neutrinos with masses $m_i$ and neutrino mass mixing matrix elements $U_{ei}$. The NME for $0\nu\beta\beta$ and $2\nu\beta\beta$ differ due to the fact that $0\nu\beta\beta$ cannot have an angular
momentum state greater than 1, due to only two spin-1/2 electrons in the final state, as well as a difference in the neutrino potential in the two processes [15, 16]. While both the NME and the \( f \) factor are generally quite complex, there has been substantial work to predict these values [15]. Understanding these values can help us understand the likelihood and consequences of 0νββ. The function \( f \left( m_i, U_{ei} \right) \) is intricately tied to the properties of the neutrino, with a light neutrino exchange form proportional to [16]:

\[
 f \left( m_i, U_{ei} \right) \equiv \frac{m_{\beta\beta}}{m_e} = \frac{1}{m_e} \left| \sum_{k=1,2,3} U_{ek}^2 m_k \right|
\]  

(13)

where \( m_{\beta\beta} \) is the effective mass of the exchanged neutrino and \( m_e \) is the mass of the electron. The effective mass \( m_{\beta\beta} \) is also called the effective Majorana mass. Previous experiments give us estimates of the mixing angles, and thus mixing matrix elements, and the differences in masses between the mass eigenstates, but we have only upper limits for the absolute masses. Using calculations of the NME and phase space factor, an experimental measurement of the lifetime of 0νββ would provide a direct measurement of the effective Majorana mass [16]:

\[
 m_{\beta\beta} \leq \frac{m_e}{\mathcal{M}_{0e} \sqrt{C_{0e} \Gamma_{1/2}^{0e}}} \]  

(14)

A direct measurement of this in the lab would serve to set better limits on the absolute mass values of the neutrino, as well as potentially determine the hierarchy, or order, of mass eigenstates. Using neutrino oscillation data, we have values of the differences in squared masses between the mass eigenstates, but we do not necessarily know the ordering of mass eigenstates 2 and 3. Solving the mass hierarchy problem has implications for particle physics and cosmology, including understanding the source of baryogenesis [18].
Figure 7: Modeled activity vs energy (scaled to units of $Q_{\beta\beta}$) for $2\nu\beta\beta$ (blue dotted line) and $0\nu\beta\beta$ (red solid line) with an energy resolution of 2%. $2\nu\beta\beta$ is normalized to 1, $0\nu\beta\beta$ is normalized to $10^{-2}$ in the primary plot and $10^{-7}$ in the inset. [1]
Most significantly, observation of $0\nu\beta\beta$ would imply that the neutrino is its own antiparticle [1]. Thus far, all observed fermions have distinct antiparticles, i.e. same mass but opposite charge, lepton number, baryon number, and all other quantum numbers. However, since neutrinos have no charge, the key difference between a neutrino and an antineutrino is that the latter will have opposite lepton number and handedness. Since lepton number may not be conserved, it is possible that a Majorana neutrino may not conserve that quantity. Handedness is a description of the spin of a particle in relation to its momentum. Right-handed particles have a spin vector that is in the same direction as the momentum vector, while left-handed particles have a spin vector antiparallel to the momentum. Further, handedness is frame-dependent for particles which have mass, and therefore travel slower than the speed of light. Changing reference frames could result in an opposite sign of the momentum vector in the new frame. Further, an interesting property of neutrinos is that in all observations thus far, all neutrinos are left-handed and all antineutrinos are right-handed [19]. One possibility is that the weak interaction only couples to left-handed neutrinos while the right-handed variant has no interaction, or the right-handed neutrino simply does not exist. A massive neutrino that is left-handed in one reference frame would be right-handed in a different frame, and thus could be observed as an antineutrino. Evidence of the Majorana nature of the neutrino, or conversely evidence that the neutrino is purely a Dirac particle, would shed light on why the weak interaction only couples to left-handed particles.
2 Experimental Efforts for $0\nu\beta\beta$

Several experiments, spread globally, are designed to search for $0\nu\beta\beta$. Each use varying candidate nuclides and detection techniques. There are a few factors that determine the feasibility and potential efficiency of a very rare event search in general, and a $0\nu\beta\beta$ search in particular. These factors include a large mass of the isotope of interest per unit mass of total detector material, detector technology with good energy resolution in the expected energy range of the signal, and very low background activity from natural and anthropogenic radiation [16]. All of these factors are intended to increase the likelihood of detecting events, while reducing the background noise.

Some rare events, such as $2\nu\beta\beta$, $0\nu\beta\beta$, and even the ordinary $\alpha$ or $\beta$ decay of some nearly stable nuclides, occur with lifetimes on the order of the age of the universe ($\sim 10^{10}$ years), or orders of magnitude higher. An experiment that must run for anything more than several years is not feasible. To get around the very long decay lifetimes of each individual nuclide, a large number of nuclides is required. This need for a large mass often conflicts with other operating parameters. Chiefly, larger mass typically translates to larger volume. As the detector volume increases, so does the amount of support material that could possibly introduce background, as well as the logistical difficulty of building such a large detector and associated electronics. Additionally, despite being extraordinarily long-living, many candidate isotopes are not as abundant as other isotopes of that element. This means that naturally-occurring material must be enriched in the isotope of interest in order to avoid a large mass of detector material that is mostly inert to the signal of interest. The most notable example of this process is the enrichment of
uranium in $^{235}\text{U}$ for use in nuclear weapons, where the most abundant isotope, $^{238}\text{U}$, is not suitable for weaponization. While the need for enrichment for $0\nu\beta\beta$ experiments may not be as intensive as enriching 0.72% $^{235}\text{U}$ to close to 90%, the need is just as critical to operation. Thus, the natural abundance and feasibility of enrichment (including chemical properties), is as important to the choice of an ideal $\beta\beta$ radioisotope as other parameters such as $Q_{\beta\beta}$ and expected lifetime.

For $0\nu\beta\beta$ specifically, favorable energy resolution is particularly important. The energy signature of $0\nu\beta\beta$, with the total energy of the two electrons precisely at $Q_{\beta\beta}$, is very important in identification of events of interest. However, this is only true as long as the detector has sufficient energy resolution. As the resolution decreases, the energies of observed events are distributed normally with increasing width and decreasing peak height. This diffuse peak could then be obscured by noise from both background radiation, and from $2\nu\beta\beta$ events. The requirement for good energy resolution could be mitigated by choice of a candidate nuclide with high $Q_{\beta\beta}$, above many background radiation $\beta$ events, though a background would still persist from $2\nu\beta\beta$ events (as seen in Figure 7). 

Currently, the detector technology with the highest energy resolution, as well as efficiency of detection, are calorimetric detectors where the source material is collocated with detector material [16]. This technique can be accomplished via either embedding the source material within the detector material, or by using a source that also behaves as a detector (such as one that scintillates). One attractive option is using high-purity germanium (HPGe) semiconductor detectors enriched in $^{76}\text{Ge}$ since HPGe detector technology is well developed and has a good energy resolution and $^{76}\text{Ge}$ undergoes $\beta\beta$. 
Perhaps most importantly, however, is the requirement for very low backgrounds. An excess of background events easily leads to a case where any signal from an event of interest is completely buried within noise. While it is possible to do some background subtraction from the data, a background level that is very large compared to the expected signal will make effective background subtraction difficult. Based on theoretical and past experimental limits on the lifetime of 0νββ, as well as a few detector parameters, the expected count rate due to 0νββ is of order (adapted from [2]):

\[
A_{0
\nu} = \ln 2 \frac{N\alpha M}{T_{1/2}} f \epsilon \\
\]

where M represents the total mass of the source material, f represents enrichment fraction in the ββ isotope, and ε is the detection efficiency of the detector. Assuming a combined \( f \epsilon \) factor of 0.7, and a \( t_{1/2} \) of \( 2 \cdot 10^{25} \) years [19], this rate corresponds to approximately 0.2 events per kilogram·year for the 0νββ decay of \(^{76}\)Ge. For comparison, contamination in the detector of 1 pCi per kg, equivalent to approximately 3 parts per billion of uranium, would correspond to approximately \( 10^6 \) counts/kg·yr. While not all of the background radiation has an energy that is in the region of interest, a few keV around \( Q_{\beta\beta} \), it is clear that the need for extraordinarily low background is necessary.

Using Equation 15, and assuming a flat background in the region of interest, we can also place an upper limit on the detectable 0νββ lifetime. The detector will only be sensitive to 0νββ lifetimes that correspond to nearly equal numbers of background events to source events. Expressed alternatively, the lowest activity a detector can observe within a given confidence level correspond to a signal to noise ratio of 1 in that region. From Equation 15 we find the number of 0νββ events in a given time, t, to be:
$$N_{0\nu} = A_{0\nu} t = \frac{\ln 2 N_A f \varepsilon}{T_{1/2}^{0\nu}} M_t$$

(16)

where the quantity $M_t$ is also called the exposure, usually expressed in units of kg\cdot year or ton\cdot year. By assuming a background that has a constant activity, $A_B$, in an energy range of $\delta E$ around $Q_{\beta\beta}$, we can also find the number of background events in a time $t$ [2]:

$$N_B = A_B M_t \delta E$$

(17)

where $A_B$ is in units of activity per unit mass per unit energy, e.g. cts/(yr\cdot kg\cdot keV). Our choice of $\delta E$ should not be arbitrary, but rather will depend on our energy resolution. Since real detectors are not perfectly efficient nor have perfect resolution, even a monoenergetic source will be detected with a broader range of energies. The spectral response of a monoenergetic peak due to energy resolution is approximately Gaussian with mean energy equal to the energy of the source and variance, $\sigma^2$, related to a quantity called full-width at half-maximum (FWHM). As the name suggests, FWHM is the width of a function between two points at half of its maximum amplitude and is a measured characteristic of the specific detector system. For a Gaussian, we can relate FWHM to $\sigma$ via:

$$\exp\left(-\left(\frac{FWHM}{2\sigma}\right)^2\right) = \frac{1}{2} \therefore FWHM = 2\sqrt{2\ln 2\sigma}$$

(18)

Thus, we can estimate the maximum detectable half-life to be where $N_B$ and $N_{0\nu}$ are approximately equal:

$$T_{1/2}^{0\nu} \leq \ln 2 \frac{N_A f \varepsilon}{m A_B \delta E}$$

(19)

Therefore, we can clearly see from this one equation that a sensitive measurement of the $0\nu\beta\beta$ lifetime depends on having a large amount of our desired isotope, both in
total number and relative fraction, a detector with excellent efficiency and resolution, and very low background.

There have been numerous experiments to date that have detected $2\nu\beta\beta$ and placed limits on the half-life of $0\nu\beta\beta$ in various isotopes. These experiments have used $^{130}$Te, $^{76}$Ge, $^{100}$Mo, and $^{136}$Xe as the $\beta\beta$ isotope. Three experiments of interest to the Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay Collaboration (LEGEND) are the Heidelberg-Moscow Experiment, the Germanium Detector Array (GERDA), and the MAJORANA DEMONSTRATOR. All three of these experiments use HPGe detectors enriched in $^{76}$Ge. The Heidelberg-Moscow Experiment was a collaboration between the Max-Planck Institute for Nuclear Physics (MPI Kernphysik) and the Radiophysical Research Institute (НИРФИ) that used 5 Ge detectors located in the Gran Sasso underground laboratory in Italy. In 2001, some members of this collaboration (referred to as Klapdor-Kleingrothaus) announced a detection of $0\nu\beta\beta$ with $t_{1/2}^{0\nu} = (0.8-18.3) \cdot 10^{25}$ y (1.96σ) from a 54.98 kg⋅yr exposure [20]. This result was later refined to $t_{1/2}^{0\nu} = (2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ y from analysis of a 71.7 kg⋅yr exposure, which the authors claimed to be a signal of $0\nu\beta\beta$ with a confidence level of over 6σ [21].

However, subsequent peer review found inconsistencies in the analysis that the claim used as evidence, including the lack of a null hypothesis analysis, failure to explain other apparent peaks in the data, and a $t_{1/2}^{0\nu}$ that conflicted with earlier published results of Heidelberg-Moscow [22].

GERDA also operates at Gran Sasso with HPGe detectors, some of which came from Heidelberg-Moscow. A unique trait of GERDA is that it uses liquid argon (LAr) to cool the detectors, which must be operated in cryogenic conditions. Background
radiation, particularly gamma rays, coming into the detector volume may interact with both the detectors and the LAr. This background causes the Ar to scintillate, and that scintillation light can be detected separately and used to veto an event as background. Utilization of LAr provides another tool to reduce the impact of background events. Using a 34.4 kg·y exposure of $^{76}$Ge in two phases, GERDA announced a limit $\tau_{1/2}^{0\nu} > 5.3 \cdot 10^{25}$ y. This result further reduces the validity of the Heidelberg-Moscow 0νββ detection claim. [23]

MAJORANNA DEMONSTRATOR (MJD) has a primary goal of discovering what technology and experimental techniques are required to operate a large-scale enriched Ge experiment. This goal involves proving the scalability of the experiment from the tens of kg scale to the ton or greater scale, as well as demonstrating background mitigation to a level of 1 background event per ton·year in the 4 keV FWHM region around $Q_{\beta\beta}$ [24]. Further, MJD seeks to search for 0νββ, test the claim from KK, and search for additional physics beyond the standard model such as dark matter. The experiment operates via vertical arrays of HPGe detectors, called strings, within liquid nitrogen-cooled cryostats, and is located in the Sanford Underground Research Facility (SURF). MJD mitigates background by using a layered shielding scheme consisting of an ultra-clean electroformed copper cryostat and inner layer, a layer of oxygen-free high thermal conductivity copper, a layer of high-purity lead, a radon-exclusion box which encloses the lead, an active muon veto system consisting of scintillating plastic, and two layers of high-density polyethylene, one of which is borated [24]. Figure 8 depicts the schematic layout of these layers with respect to the overall design of MJD. Additionally, MJD uses
p-type point contact HPGe detectors, which have very good energy resolution with a FWHM of 2.4 keV. [24]

The Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND) is a collaboration between GERDA and MJD intended to use the experimental and engineering experience of both experiments to build a ton-scale detector experiment. The purpose of building such a large detector is to increase the total exposure, and thus increase the likelihood of observing a $0\nu\beta\beta$ event or at least set a better limit on the lifetime of this process. In addition to a larger exposure, work must be done in improving the data analysis, improving the veto system, and maximizing the radiopurity of the system in order to reduce the amount of background events and discriminate against non-$\beta\beta$ events. [25]


2.1 Background Sources

Background radiation, in general, comes from various natural and man-made sources. Natural sources include primordial radionuclides, cosmogenic radionuclides, and cosmic rays \[1\]. Anthropogenic radionuclides include those which have been produced as a part of human activity, chiefly through nuclear energy production and nuclear weapons programs. Natural and anthropogenic sources of background radiation are pervasive throughout Earth. In fact, due to primordial and cosmogenic radionuclides alone, most objects on the surface of the earth are radioactive to some degree. Underground there are much fewer anthropogenic radionuclides and cosmic rays are attenuated, however, primordial nuclides and cosmic ray-produced muons present a strong source of background.

Primordial radionuclides are those which were created long ago by nucleosynthesis during the Big Bang, supernovae, fusion within stars, and other high energy nuclear processes in space \[26\]. These nuclides were present during the formation of Earth, and thus are very long-lived. Accordingly, these nuclides have half-lives on the order of the age of the Earth. Such long half-lives mean that on the time scales we consider, even decades, the number and decay rate of primordial radionuclides in the world is approximately constant. This makes primordial nuclides particularly pervasive, but also makes it such that their decay can be very well characterized. Primordial radionuclides of interest to this work are $^{238}\text{U}$, $^{235}\text{U}$, $^{232}\text{Th}$, and $^{76}\text{Ge}$ \[27\]. The first three are parents of radon and decay via alpha particles which can cause a background themselves, and the last is a strong candidate isotope for $0\nu\beta\beta$. 


Cosmic rays are high energy nuclei which originate from space. When these high
energy nuclei enter the atmosphere, they collide with nuclei in the atmosphere (likely
oxxygen or nitrogen in air). These collisions are very energetic and produce secondary
energetic particles such as pions and baryons. The secondary particles could decay or
could collide with other nuclei to form additional secondary particles. The result is a
shower or cascade of fairly high-energy particles that are incident upon the surface of the
Earth, primarily leptons and gamma rays from pion decays. Since most of these cosmic
ray shower particles are strongly absorbed by matter on the surface, the best way to shield
from cosmic rays is to place an experiment underground. However, even underground
there is a background from cosmic rays in the form of muons formed from charged pion
decays [28]. Since muons have approximately 200 times the mass of the electron, muons
will experience less deflection while passing through matter and will have less energy
loss due to bremsstrahlung. Thus, at intermediate energies, GeV to TeV, muons will
generally have a low weak interaction cross section and low radiative energy loss [29].
The result is that cosmic ray secondary muons are able to penetrate deep into the earth,
and into deeply buried experiments.

Cosmogenic nuclides are those which were created via spallation or activation
during collisions between nuclei on Earth and cosmic rays. Nuclear spallation is the
process where nucleons are ejected from the target nuclei due to the energy of the
incoming particle. One analogy is a billiard cue ball striking a larger group of balls,
knocking one or more out of the group. Activation is the process where a nucleus absorbs
a nucleon to transmute into another, usually unstable isotope. Cosmogenics can be
created by incident cosmic rays, as well as by secondary particles in the cosmic ray
shower. Deep underground, the production rate of cosmogenics is nearly zero, however there is still a chance for activation from delayed neutrons. The main source of cosmogenic background in an underground experiment is via materials that were activated on the surface and then later decay in-situ in the experiment. For a Ge experiment, two significant cosmogenics are $^{68}$Ge and $^{60}$Co [27], both of which are produced by activation of detector material while on the surface of the Earth.

Anthropogenic nuclei are those that are created via human interaction, predominately through activities that use nuclear fission. Two types of anthropogenic nuclei are fission products and activation products. Fission products are isotopes that are formed when heavy nuclei fission. Since spontaneous fission is relatively rare, most of the fission products in the world are human-induced as a result of nuclear weapons and reactors. The number and species of fission products produced depends on the nucleus that fissions and the energy of the neutron that induces that fission. Anthropogenic activation products are produced in an identical fashion to those that are cosmogenically activated, except that the source of activation nucleons is instead some man-made reaction such as thermal neutrons from fission. In an underground experiment, contamination from fission and activation products will decay and present a background. Efforts to mitigate the effects of anthropogenic background include obtaining materials that have had as little exposure to activation as possible. For some experiments, that has historically included salvaging iron and lead from sunken ancient ships, that were constructed (and sunk) before the first nuclear weapons test [30, 31].
3 Natural Production of Radon

Backgrounds from primordial isotopes are especially pervasive in an underground environment. The soil and rock surrounding a tunnel passage contain varying levels of naturally-occurring elements, some of which are primordial radionuclides. Uranium, thorium, and potassium content present the largest contributions to underground natural radioactivity due to a combination of high relative abundance and relatively short lifetime compared to other primordial nuclides. The contribution from $^{40}$K is not significant for $0\nu\beta\beta$ since it decays via beta decay with energy less than $Q_{\beta\beta}$ so that it will not have a background in the region of interest [32]. However, the major constituent isotopes of uranium, $^{235}$U and $^{238}$U, and thorium, $^{232}$Th, all alpha decay with energy greater than $Q_{\beta\beta}$. It may seem that these alpha decays would be of too great energy to contribute to a background in the region of interest, but the alphas could be detected in the region of interest if they are incident at a large angle or if they lose sufficient energy while passing through some dead layer on the detector surface. Contamination of U and Th on the detector surface, or perhaps very close on the detector mounting hardware, could produce signals from degraded alpha particles. Otherwise, these decays will have short range and are easily shielded from the detectors.

The decay products of U and Th decays are certainly harder to shield, particularly radon. As the first gaseous product in the U and Th decay chains, radon will be the first daughter to escape any materials containing U or Th contamination. Further, radon’s chemical properties, as a noble gas, mean that any radon that is released is generally free to transport without being chemically captured or adsorbed. Even radon that originates
relatively far from the detector could diffuse into the detector enclosure and present a background. This is particularly true for $^{222}$Rn, a daughter of $^{238}$U decay, which is fairly long-lived with a 3.82-day half-life, though less true for other Rn isotopes which have half-lives closer to seconds or minutes. Radon presents such a significant background because, in addition to the direct effect of its alpha decay, many of the subsequent daughter decays could have an energy in the region of interest. Figures 9 and 10 depict a portion of the decay chains of the most significant primordial radionuclides in an underground environment, $^{238}$U and $^{232}$Th, both starting at the first Rn daughter in the chain. Some of the isotopes have branching ratios towards other decays or may have a different decay in excited states, however most of these branching ratios are typically less than one percent. One notable exception is $^{212}$Bi in the $^{232}$Th chain, which beta decays about 64% of the time but may also alpha decay about 36% of the time [32].

Other isotopes of uranium and thorium likewise have decay chains that include radon, but these other isotopes collectively constitute less than one percent of all U and less than one tenth of one percent of all Th, respectively. Further, all material underground has the same relative isotopic composition of U and Th, i.e. there is no significant mechanism for enrichment underground beyond the differences in decay rates between isotopes (which occurs over long time scales).
Figure 9: $^{238}$U decay chain, beginning at $^{222}$Rn, energies are Q values [32]

Figure 10: $^{232}$Th decay chain, beginning at $^{220}$Rn, energies are Q values [32]
It is useful to note that the half-lives on Figures 9 and 10 are for the ground state and the energies listed are Q-values. As noted in section 2.2, some of the energy of the decay goes into the emitted particle(s), and some goes into recoil energy of the daughter nucleus. Since the momentum of the parent nucleus must be conserved between the daughters, the recoil energy is not arbitrary. The emitted particles are very light compared to a nucleus for beta decay, so the recoil energy is small. However, an α particle is not negligible in mass compared to even transuranic nuclei so that a nucleus which alpha decays will have appreciable recoil energy and the kinetic energy of the outgoing α will be somewhat diminished. The recoil and decay particle energies may be calculated by conservation of energy and momentum, however precise measured values are available via the Evaluated Nuclear Structure Date File (ENSDF) [32].

Accordingly, by measuring the levels of $^{232}$Th and $^{238}$U alone in a material, we can determine the total amount of U and Th contamination in that material. An effective and nondestructive method of measuring the amounts of these radioisotopes is to directly measure the activity levels of their daughter decay products. Because the lifetime of $^{232}$Th and $^{238}$U are so long compared to their daughters, and the amount of $^{238}$U and $^{232}$Th in the environment is constant over very long timescales, the level of both parents and daughters will maintain an equilibrium. If all daughters in a decay chain of a very long-lived nuclide have lifetimes much shorter (orders of magnitude) than the parent, all decay products in the chain will reach an approximately steady state. This steady state, called secular equilibrium, is represented by a constant ratio of the number of parent nuclides to the population of the decay product, or daughter population, where A is activity:

$$N_D = \frac{t_{1/2}^D}{t_{1/2}^P} N_P \Rightarrow A_p = A_D$$  \hspace{1cm} (20)
Of course, this equilibrium is broken if any of the daughters are removed via some other process (such as flushing out the radon gas). It would take only a few half-lives of the daughter to return to equilibrium.

The primary concern of radon to most people is that of human health due to radon in basements and homes. Radon and its decay products are inhaled and ingested and pose an internal health risk. If radon decays within the body, in the lungs or elsewhere, much of the energy will be absorbed by internal organs, damaging cells which could then form cancers. As a gas, the major concern of radon is an elevated risk of lung cancer [33]. Buildings that have a high natural concentration of radon, usually from surrounding rock and soil, must install systems that filter radon out of the building air in order to mitigate this health risk.

Radon levels can be very high in an underground or mine environment, with much more exposure to uranium-bearing rock and confined spaces for radon to collect. Air filtering and other mitigation systems exist for the health of mine personnel; however, these mitigation systems do not remove all radon. The exposure to radon in an underground environment persists as a large source of background for sensitive experiments. A successful experiment must integrate a system to either remove or exclude radon from the detector volume. MAJORANA accomplishes most radon mitigation via aluminum panels enclosing additional shields [24, 34], while GERDA does so through a combination of using water as a passive shield and the liquid argon active veto system [23].
However, even if all efforts to mitigate radon that originates external to the detector volume are successful, there will still be a background due to radon originating from the detector components themselves. Radon can emanate not only from rock and soil, but also from other materials. In fact, many materials contain uranium and thorium in some minute quantity. On average, the crust of the earth contains 2.5 parts per million (ppm) by mass of uranium and 13 ppm of thorium [35], although some minerals such as ores may have much more, and some may have less. Ordinarily, the amount of uranium and thorium present in most materials is far below a level of concern for health risk, or even for background radiation in experiments that do not require ultra-low background.

In an application where there is a requirement for close to zero background radiation, even tiny amounts of uranium, thorium, or any of the radioactive decay products of the two, are significant. Assuming U and Th concentrations equal to the average of the Earth’s crust and using the ratio $t_{U/2}^\nu / t_{U/2}^\beta$ in Equation 20, we can see that, in equilibrium, the amount of $^{222}$Rn coming from the $^{238}$U decay chain is about 3 orders of magnitude greater than the amount of $^{220}$Rn coming from the $^{232}$Th decay chain. This means that most radon that contributes to the background will come from $^{238}$U, unless there is an unusually high thorium content.

A successful experiment must make every effort to reduce and characterize the radon background. In order to do so, radon assay is required. The concentration of radon in an experiment depends heavily on the levels of U and Th. However, other factors affect Rn emanation and the U and Th content of materials are often not precisely known. Therefore, it is not easy to determine the Rn activity in an experiment without direct measurement.
3.1 Radon Mitigation through Material Assay

The ideal goal of radon mitigation is to have zero radon in the detector volume. While this is not practically feasible, it is certainly possible to use materials that would reduce the amount of radon as much as possible. The amount of radon coming from a sample is based on the amount of uranium and thorium in the material and the material properties that allow radon to escape, such as thermal and chemical stability, density, and surface properties of the material. [36] Radon can also escape a material via diffusion or nuclear recoil of radium α decay. Radon has a fairly small diffusion coefficient [37], so that the contribution from nuclear recoil will usually be dominant. The alpha decay results in a nuclear recoil. If this α decay of radium occurs on or near the surface of the material, or on or near an internal cavity of the material, the radon can escape [36]. Once the radon has escaped the material, it can flow out through pores and fissures of the material or diffuse out.

As mentioned earlier, the level of uranium or thorium alone does not determine the amount of radon that will emanate from the material. The intrinsic physical and chemical properties of the material are one important factor [37]. For example, material with high porosity will allow radon to diffuse much easier. Also, materials that have poor stability to changes in temperature or humidity are not ideal since they may have an inconsistent radon emanation rate. It is certainly beneficial to choose a material that has both low U and Th content, as well as excellent thermal and chemical properties.

Besides the inherent properties of the material, the sourcing, construction, and finish of the material are also important. Radon emanation of a particular material could
vary with manufacture location due to variations in manufacturing procedures and variations in environmental conditions. Material with a coarse, uneven surface profile could allow more radon to escape compared to a polished surface due to a much higher exposed surface area. Small imperfections such as pits or bumps in the surface finish will result in an exposed effective surface area which is greater than its macroscopic surface area. The degree of this difference from the macroscopic surface area is proportional to the surface roughness. For this reason, surface finishing procedures such as electropolishing, electroplating, or coating could result in a lower radon emanation rate.

Determining the radon emanation rate from a specific material or object is important in selecting materials that will most effectively mitigate the overall radon level of an experiment. To do so requires a sensitive material assay capability. With a sensitive radon detector, it is possible to determine what materials, surface finishes, and construction techniques have the lowest radon emanation rate. Ideally, the detector should have zero background contribution from radon, and material selection through radon assay is an important factor in pursuing that goal.

### 3.2 Radon Background Characterization through Material Assay

Total uranium and thorium content is proportional to the mass of detector and construction materials, and radon emanation is proportional to the exposed surface area. Increasing the mass of detector material will increase the sensitivity to rare events such as $0\nu\beta\beta$ since the likelihood of observing an event is proportional to the number of candidate nuclei. However, increasing the detector mass will also require additional inert construction material which does not increase the sensitivity to $\beta\beta$ events but does increase the radon background.
The goal of material assay for radon mitigation is to compare various materials and parts to determine which have the lowest radon emanation. All that is needed to achieve this is to compare the relative radon rates in each material, but not necessarily the absolute rates of each. However, an accurate characterization of the radon background is crucial to understanding the overall sensitivity of the experiment. The sensitivity of the experiment is proportional to its net background activity, as is evident in Equation 19 via a longer maximum detectable $\beta\beta$ half-life. A precise measurement of $A_B$ requires a precise measurement of the total radon emanation rate of all material exposed to the detector volume, either emanated directly or diffused. In fact, successful radon mitigation drives a need for even more precise characterization of the radon background since lower backgrounds require increasingly more sensitive radioassay techniques.
### 4 MAJORANA Demonstrator Radon Detection Chamber

#### 4.1 Motivation

This project entails building a radon detection chamber for use in characterization and mitigation of radon background for the MAJORANA Demonstrator (MJD) experiment. The goal of this detector is to develop a Rn monitoring capability for both real-time monitoring and very sensitive emanation measurements. To date, radioassay efforts for MJD have focused on γ-ray counting, mass spectroscopy, and neutron activation analysis. A radon assay capability, sensitive to α backgrounds, will certainly be beneficial to the MJD assay program. A radon detection chamber could primarily be utilized to assess radon levels of MJD components, including both construction materials and support materials such as tools. While MJD uses a series of shielding material, including a radon exclusion layer, it is important to know the effectiveness of this shielding. The MJD radon detection chamber may also be used to monitor the radon activity of the gas within the HPGe detector volume.

#### 4.2 Detector System Design

The MJD radon detector consists of a large, upright cylindrical stainless-steel vessel, similar to a bell jar, with a silicon PIN-type semiconductor photodiode mounted on the lid. A large positive voltage is applied to the vessel via a high-voltage power supply connected to the lid. The photodiode, electrically insulated from the vessel, is given a negative operating bias voltage. The large potential difference
Figure 11: MAJORANA Radon Detector Vessel
**Figure 12:** Inlet pipe, the shape is designed to minimize disruption of the electrostatic field

**Figure 13:** Vessel with vacuum valve and inlet pipe installed; C-clamps provide additional sealing between the lid and the vessel
between the walls and the photodiode result in a large electric field pointing from the walls to the small photodiode, resembling a nearly point charge-like field distribution near the photodiode.

Choice of a Si PIN photodiode is advantageous since they typically have low dark current, which is partially due to relatively low operating bias voltage, and relatively high photosensitive area. The photodiode used was initially a Hamamatsu S3204-09, and later changed to a Hamamatsu S3584-09, Si PIN photodiode. Functionally, the two differ only in size, with small differences in dark current, cutoff frequency, and capacitance. The former has a photosensitive area of 18mm x 18mm, while the latter is 28mm x 28mm, a factor of 2.4 greater photosensitive area than the smaller version. Both have a maximum operating bias of 100V, and a maximum dark current of 30 nA (@25°C, 70 V) [38]. The photodiode is operated at a bias of 50V to avoid electrical noise. The signal is read out through an Ortec 142AH pre-amplifier and Ortec 672 spectroscopy amplifier to an Ortec 927 Multi-channel analyzer (MCA). The data from the MCA is collected by ORCA software [39] and analyzed via ROOT [40].

The vessel is made of electropolished stainless steel and is h=69.53 cm (27.325”) in height, with an inner diameter of D=60.96 cm (24”). The aluminum lid has a diameter of 71.12 cm (28”), with a 4” diameter hole bored through the center and two 1.5” holes bored 9” from the center along a diameter. The central hole is used to mount the photodiode via an acrylic mounting plate (tophat) with a 15-pin D-SUB signal feedthrough, while the other two holes are used to provide an inlet and outlet for gas via KF-40 flange fittings. An electropolished stainless steel ¼” tube is placed at the inlet and extends to the bottom of the tank, bent in such a way that it runs along the wall of the
vessel to minimize any deviations from a uniform electric field inside the vessel. The bottom of the vessel is curved, with an approximate radius of curvature of R=59.40 cm. This results in a total vessel volume and surface area of:

\[
V = \pi \left( \frac{D}{2} \right)^2 (h - h') + \frac{\pi h'^2}{3} (3R - h')
\]

\[
S = \pi \left( \frac{D}{2} \right)^2 - \pi r_{100}^2 - 2\pi r_{40}^2 + \pi D(h - h') + 2\pi Rh'
\]

\[
r_{100} = 5.08 \text{ cm (2")}\]

\[
r_{40} = 1.91 \text{ cm (0.75")}
\]

The above measurements of the vessel give a total volume of 190.97L and a surface area, minus the surface area of the photodiode, tophat, and gas inlet, of 17660 cm². The entire vessel is placed in a cylindrical plastic tank as a safety measure to prevent exposure to high-voltage, and the tank is placed within a Faraday cage comprised of 6 aluminum sheets to shield the photodiode signal from RF interference.

A Durridge RAD7 commercial off-the-shelf (COTS) radon detector is used for calibration and efficiency measurements. The RAD7 is connected to the detector vessel via vinyl tubing, with two 0.45 μm inline air filters, an inline drying tube filled with Drierite desiccant. Additionally, a 31L liquid nitrogen dewar is connected to the vessel via perfluoroalkoxy (PFA) tubing to provide a supply of boil-off nitrogen gas in order to purge air from the vessel. A 2.95L sample/emanation chamber is also connected inline via PFA tubing, with 0.5μm air filters placed downline of the LN dewar and emanation chamber, when connected.

4.3 Principle of Operation

\(^{222}\text{Rn}\) nuclei within the vessel volume alpha decay to \(^{218}\text{Po}\) with a half-life of 3.8235 days. In some fraction of decays, approximately 65% [41], the \(^{218}\text{Po}\) nuclei will be emitted with a positive charge. The positive Po nuclei are then carried by the electric field
1. Rn gas flows into the vessel
2. Rn decays to Po, which has a + charge 65% of the time
3. Charged Po is attracted to the photodiode
   3a. Po decays in flight
   3b. Po is neutralized by collisions in the gas
4a. Po decays and the alpha is detected-50%
   4b. Po decays and the alpha is not detected- 50%
5. Po daughters from 2, 3ab, 4ab are collected on the photodiode and alpha decays are detected

Figure 14: Detection of Rn via electrostatic collection on the photodiode
to the surface of the photodiode, where they decay and can be detected. Additional daughters further down the \( ^{238}\text{U} \) chain that undergo alpha decay can also be detected in this manner. However, there is only a 50% chance of detecting an alpha decay on the surface of the photodiode since an additional 50% will have the alpha particle emitted away from the diode. Figure 14 is a chronological depiction of the detection of one radon atom.

While there are also beta decays in the decay chain of both \( ^{235}\text{U} \) and \( ^{232}\text{Th} \), these beta particles do not induce a significant signal in the silicon photodiode. At the energy ranges of the decay particles in these chains, approximately \( 10^{-1} \) to \( 10^{1} \) MeV, beta particles have a much lower energy loss from interactions with matter [42].

The rate of electronic, or ionizing, energy loss per unit distance, called stopping power, for alpha particles in a material \((A, Z)\) is given approximately by the formula [42]:

\[
\frac{dE_a}{dx}_{\alpha \rightarrow Z,A} = \frac{8\pi r_e^2 m_e c^2}{\beta_a^2} \frac{Z \rho}{uA} \ln \left( \frac{2m_e c^2 \beta_a^2}{I(1-\beta_a^2)} \right) - \beta_a^2
\]

(22)

where \( \beta_a \) is the velocity of the alpha particle in units of \( c \), \( r_e = \frac{1}{4\pi \varepsilon_0 m_e c^2} \) is the Compton radius of the electron, and \( \rho \) and \( I \) are the mass density and mean excitation energy of the material. This formula is a good approximation to the total attenuation of an alpha travelling at moderate energies of \( 10^0 \) to \( 10^3 \) MeV. At very high energies, there are additional contributions from radiative losses and polarization of the medium due to the electric field of the alpha. At energies below 10 keV, the cross section for nuclear interactions dominates. A similar equation giving the collisional energy loss for electrons is given by [42]:
\[-\left(\frac{dE_e}{dx}\right)_{\tau \rightarrow Z,A} = \frac{4\pi r_e^2 m_e c^2 Z \rho}{\beta_e^2 uA} \left[ \ln \left( \frac{m_e c^2 \tau \sqrt{\tau + 2}}{\sqrt{2I}} \right) + \frac{1}{2\gamma^2} \left( 1 + \frac{\tau^2}{8} - \frac{2\tau + 1}{2(2\tau + 1)^2} \right) \right] \quad (23)\]

where \(\tau = \gamma - 1\) is the ratio of kinetic energy to rest mass energy and \(\gamma\) is the Lorentz factor.

As with heavy charged particles such as \(\alpha\)'s, the attenuation of electrons at energies above 10MeV has a significant contribution from radiative losses.

Figures 15 and 16 depict the mass stopping powers, which is normalized for density, for electrons and alpha particles in Si [43]. In the energy range of the decay particles in the \(^{238}\)U and \(^{232}\)Th decay chains, \(\alpha\)'s have nearly 3 orders of magnitude lower range than electrons. Electrons will deposit a negligible amount of energy as they pass through a thin layer of Si, and thus will not create a significant signal in the PIN diode.

Measuring the activity of alpha particles coming from the decay chain of \(^{238}\)U and \(^{232}\)Th, and assuming approximate secular equilibrium, allows a measurement of the activity of \(^{222}\)Rn and \(^{220}\)Rn. As we will see in the next section, the best isotope to use for \(^{222}\)Rn measurement is \(^{214}\)Po while \(^{212}\)Po is most efficient for \(^{220}\)Rn measurement.
Figure 15: Total Mass Stopping Power for electrons in Si [44]

Figure 16: Total Mass Stopping Power for alphas in Si [45]
An example of a typical output of the MCA, as analyzed by ROOT is shown in Figures 17 and 18. Figure 17 is a plot of measured events in each of the MCA’s 16,383 channels, with the channel number scaled to be calibrated for energy. The calibration factor is photodiode-specific. It is determined by measuring the channel number corresponding to the maximum value of a polonium alpha peak and scaling that channel number by the expected energy of the specific alpha. For example, if the $^{214}$Po alpha energy spectrum had a peak on channel number 6095 on the MCA, the calibration factor would be the expected energy of the $^{214}$Po $\alpha$, 7.687 MeV [32], divided by the peak channel. The calibration factor would also correspond to the energy width of each channel detected by the MCA. For Figures 17 and 18 this calibration factor is approximately 1.3 keV/channel.

Semiconductor detectors operate by measuring electron-hole pairs induced by collisions with the incoming particle, with one pair produced every 3.62 eV of energy loss of the particle, on average [38]. Since 3.6 eV is much less than the typical $\alpha$ energy of a few MeV, the photodiode is able to observe nearly the entire energy loss of the particle, and the number of hole-electron pairs will scale linearly with the energy loss. For this reason, we should expect that the photodiode will have an output that is linearly proportional to the energy deposited in the photodiode by the penetrating particle. For alphas this should correspond to the total energy of the alpha, whereas for betas this will be a small fraction of the total energy due to their very low stopping power. Therefore, for the alpha decays of interest in this work, our scaling from MCA channel to energy would be close to constant across all channels.
Figure 17: Typical MCA Spectrum calibrated for energy, vertical lines represent decays products of $^{238}$U (solid red) and $^{232}$Th (dashed green)
Figure 17 demonstrates that the MJD Rn detector measurement and scaling from MCA channel number to energy are consistent with expectations of observing $^{222}\text{Rn}$ and $^{220}\text{Rn}$ decay chain $\alpha$’s.

Figure 18 is an MCA scatter plot of each measured event per time bin and per energy bin. This scatter plot is useful in determining the behavior of the Rn emanation as a function of time and energy, as well as to look for electronic noise or any other unexpected or undesired behavior in the system. Taking a projection along the y-axis, which is energy, over some portion of the x-axis, time, gives the net number of counts per energy bin in the chosen $\Delta t$. This would be identical to Figure 17 if $\Delta t$ was taken to be the entire run. Taking a projection along the time axis over some energy band gives the net number of counts per time bin in that energy band. This is especially useful in noting the time variance in activity of any isotope of interest. Figure 35 in Chapter 6.2 is an example of this time-series plot.
Figure 18: MCA measured events vs Time (x-axis) and Energy (y-axis); each mark indicates one count
4.4 Efficiency of ion collection

The drift range of heavy ions in air also affects the efficiency of the detector to measuring Rn. As Rn atoms in the vessel decay, and $^{218}$Po ions are swept to the detector, some $^{218}$Po ions decay in transit or collide with molecules in the vessel gas. The number of decays in transit is proportional to the drift time, $t_d$, of ions in the gas, and thus inversely proportional to the drift velocity [46]. We can approximate the mean drift velocity by:

$$v_d = \frac{l}{t_d} = KE; \quad 0 \leq l \leq l_{\text{max}}$$

(24)

where $l$ is the distance from an arbitrary point inside the vessel and the photodiode, $l_{\text{max}}$ is the largest possible value of $l$ allowed geometrically, $K$ is the ionic mobility of radon in air, and $E$ is the electric field strength. The drift velocity is determined by ionic mobility, the drift speed attained per unit electric field, $E$, in a given gas. For an ion of a certain mass and charge in a gas, the ionic mobility, $K$, is inversely proportional to the mass and density of the gas as well as the interaction cross section between the ion and the gas [46]. The likelihood of a Po$^{2+}$ ion reaching the detector are thus increased for a higher electric field and a vessel gas which is free of contaminants, such as water or trace heavy compounds, which could neutralize the drifting ion due to collisions.

The reduction in efficiency due to neutralization of ions in the gas depends primarily on the density and composition of the gas, and to a lesser extent on the drift velocity of the ion. However, the effect of decay prior to deposition on the photodiode surface is greater for lower drift velocities, and lower electric fields. Since the half-life of $^{218}$Po is 3.1 minutes, the effect due to decay in transit will be small. However, $^{216}$Po in the
\( ^{232} \text{Th} \) decay chain decays with a half-life of 145 ms, and it is certainly possible that a significant fraction of this ion will decay before reaching the photodiode. Assuming negligible loss due to collisions, the average fraction of ions deposited on the photodiode will be given by:

\[
f_{\text{Po}} = e^{-\langle t_d \rangle} \approx \exp \left( -\frac{l_{\text{max}}}{2 \cdot v \cdot t_{1/2}} \right) = \exp \left( -\frac{l_{\text{max}}}{2K \cdot E \cdot t_{1/2}} \right)
\]

(25)

where \( \langle t_d \rangle \) is the mean drift time, approximated as half of \( t_d \) at \( l_{\text{max}} \). Figure 19 shows the results of this equation as a function of voltage, with voltage normalized by a factor

\[
V_0 = \frac{l_{\text{max}}^2 \ln 2}{2Kl_{1/2}}.
\]

This suggests that, all else being equal, the collection efficiency will be small for small vessel potentials but will plateau to a constant value for large voltages.

For drift times of about 1 second, less than 0.5\% of \( ^{218}\text{Po} \) atoms will decay compared to over 99\% of \( ^{216}\text{Po} \) atoms. Assuming that the collisional cross sections of \( ^{218}\text{Po} \) and \( ^{216}\text{Po} \) will be very similar, the difference in collection efficiency between the two isotopes would be due to their differences in in-flight decay. We expect the efficiency of \( ^{218}\text{Po} \) collection to be higher based on this fact.

As mentioned earlier, all \( \alpha \) decays subsequent to \( ^{218}\text{Po} \) are also detected. As Po atoms on the surface of the photodiode decay, the daughter products are likewise deposited on or near the surface. Po atoms that were either neutral after Rn decay, neutralized in a collision with the gas, or decayed in flight, may decay into charged daughters, especially through \( \beta \) decays, which will then be attracted to the photodiode. There will be a greater probability of collecting the daughters of \( ^{216}\text{Po} \) and \( ^{218}\text{Po} \) since there is more time for these daughters to collect on the surface of the photodiode. Using
Figure 19: Fraction of Po ions deposited on the photodiode surface, neglecting losses due to collisions, as a function of vessel voltage.
$^{214}\text{Po}$ α counts instead of $^{218}\text{Po}$ α counts results in a higher efficiency of Rn detection for this reason, while the same is true for using $^{212}\text{Po}$ α counts instead of $^{216}\text{Po}$ α counts. Also for this reason, one significant concern for the long-term viability of a radon detector is the fact that $^{210}\text{Pb}$, with a half-life of 22.2 years, will build up on the surface of the detector and contribute to a growing activity of $^{210}\text{Po}$. Over time, a high $^{210}\text{Po}$ activity may diminish the efficiency of the photodiode by increasing the dead time of the detector. Fortunately, the 5.41 MeV energy of $^{210}\text{Po}$ is small enough to be outside the region of interest of $^{214}\text{Po}$ decay, 7.83 MeV, so that lead build-up will not directly interfere with Rn detection. Further, this effect can be mitigated by avoiding exposing the photodiode to high Rn concentrations or samples with high U or Th content.
5 Detector Efficiency Measurements

5.1 Calibration and Collection Efficiency

The Rn collection efficiency of the MAJORANA detector was measured using the RAD7 COTS Rn detector. The efficiency is calculated by measuring the Rn activity of a sample of unknown activity and comparing that to the activity measured by the RAD7, which has been calibrated for its own efficiency [47]. The MJD detector efficiency is thus defined as the ratio of the detected activity to that of the RAD7. Besides environmental conditions such as temperature and humidity, the differences in measured activity between the two detectors can be attributed to the efficiency of the photodiode to detecting radon and the vessel voltage, which will affect the electric field strength. Additionally, there will be a small to moderate difference in actual Rn activity as the gas flows from one detector to the other. As mentioned earlier and shown in Figure 19, the efficiency is predicted to depend strongly on the vessel voltage for low voltages but will asymptote to a constant value at high voltages. The difference in actual activity rate is due to the fact that radioisotopes decay between measurement at one detector and the other. Specifically, the activity rate is a function of time:

\[ A(t) = \lambda N(t) = \lambda N_0 e^{-\lambda t} = A_0 e^{-\lambda t} \]  

(26)

where \( N_0 \) and \( A_0 \) are the number of radioisotopes and activity at \( t=0 \). For \( t \ll t_{1/2} \) \( A(t) \) is approximately constant. As long as the gas flows from one detector to the other on a small timescale, there will be a negligible difference in actual activity between the two. This is certainly feasible for \( {}^{222} \)Rn since the half-life is more than 3.8 days. There may certainly be a significant difference for \( {}^{220} \)Rn since it has a half-life of just 56 seconds.
Given this fact, an efficiency measurement for $^{222}\text{Rn}$ can be generally accurate, though the same measurement for $^{220}\text{Rn}$ may not be.

The RAD7 operates under a similar principle to the MAJORANA detector, albeit at a smaller scale. The RAD7 uses electrostatic collection of radioisotopes in a 0.7L hemispherical cell, charged to a 2KV-2.5KV, onto a passivated ion-implanted planar silicon (PIPS) detector [47]. PIPS detectors have advantages over other detector technologies due to low dark current and leakage current, increased ruggedness, and good energy resolution [48]. The RAD7 has demonstrated utility in various applications, including Rn monitoring for mitigation in homes and scientific research [47]. Contributing to this utility are a broad operating range (4 to 750,000 Bq/m$^3$), versatile modes of operation, rugged and easily portable case, and integrated data analysis.

The RAD7 can be operated using a variety of preset and custom protocols with different cycle time, recycle number, analysis mode, and internal pump duty load. The cycle time determines the length of time that the RAD7 takes data for a single reading. A longer cycle time results in lower uncertainty in the reading but also results in lower temporal resolution. The recycle number determines the number of data points that the RAD7 will take in a given test and is set to zero for continuous monitoring. The data analysis mode determines which Po peaks are used in the calculation of Rn activity. The NORMAL mode uses both $^{214}\text{Po}$ and $^{218}\text{Po}$ and has lower uncertainty due to better counting statistics but may not be accurate for short-duration tests since $^{214}\text{Po}$ may not have reached equilibrium with $^{222}\text{Rn}$. The SNIFF mode uses solely $^{218}\text{Po}$, giving better accuracy for short-runs but higher uncertainty for long runs due to a lower efficiency of $^{218}\text{Po}$ collection. Another mode, AUTO, uses SNIFF mode for the first three hours of the
test and NORMAL after that time. Finally, the internal pump may be set to provide flow through the RAD7 either continuously, at some interval, or not at all (if an external pump is used). The AUTO pump setting provides flow during the first four minutes of a test to ensure a good initial sample and then for one minute every five minutes thereafter.

The operating protocols for the MAJORANA PIN photodiode and RAD7 are set using an ORCA script. The script sets a binning time, \( m_{\text{time}} \), and total test duration, \( \text{totaltime} \), for the MAJORANA detector, which then continuously takes data over \( \text{totaltime} \) and prints the results to a unique text file every \( m_{\text{time}} \). The text file contains the number of counts collected over \( m_{\text{time}} \) in each channel of the MCA, with each channel corresponding to a small energy bin. Since data is taken continuously, \( m_{\text{time}} \) is chosen to be short enough to allow for sufficient temporal resolution while reducing the total number of data files and the total file size of each test. For most tests, the binning time was set at 15 minutes.

The script also sets the cycle time, \( m_{\text{rad}} \), and other operating conditions for the RAD7. The RAD7 cycle time is chosen to balance higher counting statistics with better temporal resolution. An \( m_{\text{rad}} \) of 1 hour achieves this optimization and was used for most tests. We wish to obtain high-accuracy, continuous measurement during efficiency testing so the recycle number was set to 0 (continuous measurement until the end of the script at \( \text{totaltime} \)), the analysis mode was set to NORMAL, and the internal pump duty load was set to AUTO. The Orca script logs the last reported output of the RAD7 to a single text file every \( m_{\text{time}} \) during the run, with the RAD7 again reporting every \( m_{\text{rad}} \). The output of the RAD7 is in the following format:

\[
\text{YYYY-MM-DD HH:MM:SS } +0000 \text{ GMT index RH Rn RnUnc}
\]
where the date and time correspond to the beginning of the time bin, the index number

\text{totaltime}/\text{m_time}), \text{RH} \text{ is the relative humidity measured in RAD7, and Rn and}

\text{RnUnc} \text{ are the radon level (A) and uncertainty (\delta A) measured by the RAD7 in units of}

\text{picocurie per liter (37 Bq/m^3)}.

As mentioned above, the efficiency of our detector is measured by taking the ratio

of the average activity of \text{^{214}Po} and \text{^{218}Po}, separately, measured by the radon chamber to

the average Rn activity measured by the RAD7. The activity measured by the radon

chamber is simply the total count in the \text{^{214}Po} or \text{^{218}Po} peak divided by the total time of

the run, in seconds. The average activity of the RAD7 is taken as the maximum

likelihood mean of each RAD7 measurement \text{A}_{\pm \delta A} \text{ in the same time period as that used}

in the radon chamber activity measurement [49]:

\[ \bar{A} = \frac{\sum_{i=1}^{n} A_{i} (\delta A_{i})^{-2}}{\sum_{i=1}^{n} (\delta A_{i})^{-2}} \pm \sqrt{\frac{1}{\sum_{i=1}^{n} (\delta A_{i})^{-2}}} \]  \text{ (27)}

The significance of using this form of the mean is that it accounts for the fact that

the RAD7 measurements are themselves an average measurement taken over a time

period, \text{m_rad}. The result of this mean is converted from units of pCi/L to Bq (counts per second) by multiplying by a factor of 0.037 Bq/pCi·195 L. 195 L is the approximate

total internal volume of the system while doing emanation measurements, including the

vessel, RAD7, all tubing, and in later runs the sample/emanation chamber. Once the

RAD7 activity is determined, the efficiency is given by:

\[ \varepsilon = \frac{A_{PD}}{A_{RAD7}} \pm \left( \frac{A_{PD}}{A_{RAD7}} \sqrt{\left( \frac{\delta A_{PD}}{A_{PD}} \right)^{2} + \left( \frac{\delta A_{RAD7}}{A_{RAD7}} \right)^{2}} \right) \]  \text{ (28)}
where PD represents the activity measured via the photodiode, and $\delta A_{PD} = \sqrt{A_{PD}}$ is variance of $A_{PD}$ due to ordinary counting statistics.

### 5.2 Room Air Measurements

Initial efficiency measurements were done for varying vessel voltage using ambient room air as a source. The bias voltage of the detector was kept constant at 50V, the temperature of the air was approximately constant over the time scale of a run but varied approximately ±1K in a diurnal cycle, and the humidity of the air was minimized by passage through a dehumidifier. The dehumidifier consists of either a desiccating column of Drierite, anhydrous calcium sulfate impregnated with cobalt chloride as a moisture indicator [50], or a DRYSTIK dehumidifier produced by Durridge, which works by moisture exchange between sample gas and exhaust. By controlling all environmental conditions except the vessel bias potential, we are able to determine the Rn collection efficiency as a function of potential.

![Diurnal Room Temperature Cycle](image)

*Figure 20: Average Room Temperature vs Time of Day, averaged over 6 months*
Between runs, some changes were made to the overall system. These changes included replacing the tophat, inserting a metal inlet pipe, and modifying the system to recirculate air. The tophat was replaced because the initial tophat was constructed of 3-D printed plastic and, though advantageous for ease of manufacturing, the radon content and structural properties of the plastic were unknown and suspected to be inferior to the material which replaced it, acrylic. The inlet pipe was installed to provide more uniform gas mixing within the vessel while gas flows. The stainless-steel pipe connects to the vessel via a KF flange and is bent to follow the contour of the vessel to the bottom. By bringing the incoming gas to the bottom of the vessel and having the outlet at the top of the vessel, it is more likely that gas will mix well within the vessel. Whereas, before it was likely that there could be some laminar flow from an inlet and outlet both at the top of the vessel. Placing an object within the vessel will disrupt the electric field slightly, but this effect is mitigated by having the conductive pipe as close as possible to the side of the vessel. Finally, creating a closed system, capable of recirculating gas, is imperative to obtaining accurate sample Rn emanation measurements since the gas within the system must come to radioactive equilibrium with the sample, which is impossible if new gas is continually being added. While a closed system is not necessary for runs using room air as a source, and in fact is not desirable if one wishes to observe variations in room air Rn content, it was nonetheless useful to prove the capability using this simple case.

Figures 21 and 22 shows the measurement efficiency as a function of vessel voltage for $^{214}\text{Po}$ and $^{218}\text{Po}$, respectively. We see that the efficiency is small at low voltage but rises approximately linearly up to 5KV. This is consistent with Equation 25, which suggests some degree of linearity near the voltage $V = \frac{1}{2}V_0 = \frac{\gamma^2}{4K\eta_{1/2}} \ln 2$, though we
<table>
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<tr>
<th>Vessel Bias (KV)</th>
<th>$^{214}$Po Efficiency</th>
<th>$^{214}$Po Efficiency Uncertainty</th>
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</table>

*Table 1: Rn Collection Efficiency - Room Air*
Figure 21: Collection efficiency from $^{214}$Po, using room air as a source

Figure 22: Collection efficiency from $^{218}$Po, using room air as a source
do not observe a significant plateau in efficiency as Equation 25 also predicts. As expected, we observe a larger efficiency for $^{214}$Po collection due to the larger probability of $^{214}$Po being swept to and decaying near the surface of the photodiode. Table 1 shows the efficiency measurements for room air as a source.

5.3 U/Th Ore Rock Measurements

In addition to room air, a sample of a rock with high uranium and thorium content, similar to an ore, was also used as a source. The rock was a sample of the mineral thorite with inclusions of uranium pyrochlorate from the MacDonald Mine in Hybla, Ontario, Canada [51]. The rock naturally had much higher activity, resulting in better counting statistics and easier identification of specific decay peaks. Figure 23 demonstrates the difference in activity rate of $^{218}$Po (6.002 MeV), $^{214}$Po (7.833 MeV), and $^{212}$Po (8.954 MeV) between two similar runs of equal length, with the primary difference being that one used room air as a source and the other used the rock sample. We see in this figure that the rock sample run, in green, indeed has a higher activity in all observed Rn decay chain Po isotopes. The difference between the two sources is particularly notable in the $^{212}$Po alpha peak, consistent with the fact that the rock sample is similar in atomic composition to a thorium ore. The higher activity of the rock results in better measurement of the efficiency, especially at low to moderate voltages, as well as lower uncertainty at a given voltage due to higher count rates and a smaller relative fraction of Rn daughters that were removed or neutralized.
Comparison of Activity with Air vs Rock Sample

Figure 23: Room Air vs Rock Sample Spectra - Both runs taken at 5KV Vessel bias over a time period of 12 hours; energy bins are approximately 12 keV
As with the room air runs, the runs using rock as a source kept all environmental parameters constant except for the vessel bias potential. Three major changes were made to the system while performing efficiency measurements using the rock sample. The first was that a new high voltage power supply was installed to provide higher bias voltages to the vessel. The power supply which was used previously was the same power supply that provided the 50V reverse bias to the photodiode, through a different channel, and supplied a maximum bias of 5KV. The new power supply, Spellman Model SL20P150, instead provides a maximum bias of 20KV. This change allowed higher electric fields within the vessel, and thus better Rn collection efficiencies to the extent predicted by Figure 19. One issue related to the new power supply was that the higher voltage began to cause breakdown sparking in the air between the lid of the vessel and the photodiode mount ground wire. This issue was mitigated by placing a small amount of high voltage putty on the exposed portion of the mount ground wire.

The second change was that the gas flow was modified slightly to remove the Drystik dehumidifier, ensure a proper gas seal in the system, and change the order in which gas flowed between the various elements. Silicon putty was placed on the inlet and outlet holes in the lid of the 1-gallon paint can that was used as a sample chamber for the rock sample. This change helped to ensure that the gas flow system was indeed a closed loop, and that any radon measurement in the gas was due to the rock sample and not the room air. The Drierite desiccant alone is sufficient to maintain low humidity in a closed system. The gas flow was modified to send the gas from the sample chamber first to the desiccant then to the RAD7, and then to the vessel, rather than going to the vessel first and RAD7 last. Our goal was to minimize the transit time between the RAD7 and the
vessel to ensure that the air has the same activity in both chambers, so this new gas flow provided better accuracy in the efficiency measurement.

Figures 24 and 25 show the collection efficiency as a function of vessel voltage, again for $^{214}$Po and $^{218}$Po, during and following the changes mentioned above. We observe a relation between efficiency and vessel bias that much more closely resembles Equation 25 and Figure 19, with a steep rise in efficiency at low voltages and an approach toward a constant value at high voltages.
<table>
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<tr>
<th>Vessel Bias (KV)</th>
<th>$^{214}\text{Po}$ Efficiency</th>
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<th>$^{218}\text{Po}$ Efficiency</th>
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Table 2: Rn Collection Efficiency- Rock Sample, Photodiode #1
Figure 24: Collection efficiency from $^{214}\text{Po}$, using a rock sample as a source

Figure 25: Collection efficiency from $^{218}\text{Po}$, using a rock sample as a source
The second major change during the efficiency trials with the rock sample was that the photodiode was replaced. The original photodiode was replaced with a larger one, with 28mm x 28mm photosensitive area versus 18mm x 18mm. This change was done for two reasons: the first of which being that the larger surface area may allow for an increased efficiency by allowing a greater area to collect Rn daughter decays, and the second being that copper photodiode mount was designed for the larger photodiode. The mount held the smaller photodiode in a diagonal orientation, with points of contact only at the corners of the photodiode and was held in place simply by clamping action on the corners. The larger photodiode sits squarely within the mount, with contact along all outer edges of the photodiode, and is held in place by the secure fit which eliminates rotation, and by clamping.

The new photodiode initially had a high amount of electrical noise, which was determined to be due to shorting between leads of the photodiode and the top inner edge of the copper mount. This noise was mitigated by placing a small layer of Kapton tape between the leads of the photodiode and the mount. After this change was made, the new

![Photodiode Mount Geometry](image)

*Figure 26: Photodiode Mount Geometry a) with initial 18x18mm² Hamamatsu S3204-09 Si Pin Photodiode; b) with 28x28mm² Hamamatsu S3584-09 Si Pin Photodiode*
photodiode had a response very similar to the previous, as demonstrated by Figure 28, which compares two similar runs of equal length, source, and operating conditions except for the size of the photodiode.

The efficiency response in the new photodiode was slightly higher than the smaller photodiode, as shown in Figures 33 and 34. These plots show the ratio of efficiencies of the larger photodiode to the smaller. The lines plotted on Figures 33 and 34 represent the most likely ratio at all voltages for $^{214}$Po and $^{218}$Po, respectively. This suggests that the difference of greater surface area did indeed have a marginal effect on improving efficiency. Due to the increased efficiency and correct geometry, we use the second, large photodiode (PD2) henceforth.

Figure 27: Diagram of modifications to diode housing unit: a) addition of HV putty to ground wire to reduce electrical breakdown; b) placement of Kapton tape between leads of the photodiode and the mount
Figure 28: MCA Spectrum of two similar runs with photodiode #1 (green) and photodiode #2 (blue)
Figure 29: Photodiode in Cu mount; note the HV putty around the mount ground wire connection as indicated in Figure 27, also note the nylon screws.

Figure 30: Photodiode sitting flush Cu mount; note the Kapton tape across the photodiode leads.
<table>
<thead>
<tr>
<th>Vessel Bias (KV)</th>
<th>$^{214}$Po Efficiency</th>
<th>$^{214}$Po Efficiency Uncertainty</th>
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*Table 3: Rn Collection Efficiency-Rock Sample, Photodiode #2*
Figure 31: Collection efficiency from $^{214}$Po, after replacing the photodiode

Figure 32: Collection efficiency from $^{218}$Po, using a rock sample as a source
**Figure 33:** $^{214}$Po efficiencies using a larger photodiode vs the first photodiode

**Figure 34:** $^{218}$Po efficiencies using a larger photodiode vs the first photodiode
Having determined our detector's efficiency, we can convert the average $^{214}$Po or $^{218}$Po activity of a gas sample into a Rn activity. For example, an observed $^{214}$Po activity of 1 Bq while operating the vessel at 10 kV using PD2 would correspond to a $^{222}$Rn activity of 3.63±0.20 Bq since the efficiency at this voltage is 27.53±1.43%. A more meaningful quantity for emanation studies is the activity per unit surface area (Bq/m$^2$) or per volume (Bq/m$^3$). The former is used for determining Rn emanating from solid objects, whereas the latter is used for measuring Rn concentration in gases.

Whereas gas volume is relatively easy to calculate or measure, surface area is often not straightforward to calculate for real objects. The macroscopic surface area of objects in the emanation chamber may be estimated by approximating the object as a combination of standard geometric shapes such as spheres, cylinders, and cuboids. Alternatively, the macroscopic surface area of an object may be more precisely determined by creating a detailed model of the object in some computer-aided design software that has a function for numerical surface area calculation, such as AutoCAD [52]. As mentioned in Chapter 3, the microscopic surface area, considering small ridges, pits, and other imperfections, is much larger but may be mitigated by surface finishing techniques such as electropolishing.

For the MJD Rn Detector itself, the vessel activity per unit surface area is the measured activity of either $^{214}$Po or $^{218}$Po divided by the respective efficiency, $\varepsilon$, and divided by the interior surface area, 1.766 m$^2$. Similarly, the volumetric activity rate is the measured activity divided by $\varepsilon$ and the internal volume of the system, approximately 0.191 m$^3$ for the vessel alone or 0.195 m$^3$ with the RAD7, emanation chamber, and tubing included.
It is important to note that inferring the $^{222}\text{Rn}$ activity from the $^{214}\text{Po}$ or $^{218}\text{Po}$ activity in this manner assumes radioactive equilibrium between Rn and its daughters. While this is true even over time scales on the order of a few half-lives of the daughter, it will not be true for shorter time scales.

On a related note, an accurate measurement of the emanation of a particular sample must be taken after the entire system has been closed for enough time for $^{222}\text{Rn}$ to build-up within the sample gas such the radioactive equilibrium approximation is valid. Given the 3.8-day half-life of $^{222}\text{Rn}$, this build-up time corresponds to roughly 3 half-lives or 11.5 days. After 3 half-lives the $^{222}\text{Rn}$ activity is greater than 87.5%, depending on the initial gas Rn activity, of the activity of its precursor, $^{226}\text{Ra}$. 
6 Intrinsic Background Characterization

6.1 Motivation for Detector Background Characterization

With the relation between efficiency and vessel bias voltage known, it is then possible to measure the Rn activity of an arbitrary gas. However, in order to correctly infer the amount of radon emanating from a particular sample, it is necessary to fully characterize the intrinsic radon background of the vessel and all other components that come in contact with the gas. In a similar fashion to the very same motivation of this project, the need for a low-background radon detector is directly tied to the sensitivity of measurements. A Rn background with a low intrinsic Rn emanation rate from all interior surfaces coupled with a low initial Rn activity in the system will be capable of measuring much lower activities in samples of interest. Meanwhile, a detector system with a high initial Rn activity, or high Rn emanation from detector subsystem components, will not be sensitive to samples of low activity.

6.2 First Vessel Background Estimate

The first background run we made was done during room air efficiency measurements, just before installing the rock sample. We expected the background activity of the vessel would be less than the activity of room air. Based on this, we expected that the measured activity in a sealed vessel would decay from some initial value, close to the activity of room air, to some final value, approaching the steady-state activity of the vessel itself. The run was performed by completely sealing the vessel filled with room air and operating for 332.8 hours at a vessel bias of 5KV. The detector thus
had a $^{222}$Rn collection efficiency of 20.012±1.421% using $^{214}$Po activity and 11.929±0.862% using $^{218}$Po activity.

In the steady state, the amount of radon that decays in the vessel would be equal to the amount emanated by the vessel’s inner surface. The activity in the vessel will eventually reach a steady state after multiple half-lives of $^{222}$Rn, when it comes into radioactive equilibrium with $^{226}$Ra. $^{226}$Ra is very long lived, and thus will have an activity that is functionally constant over the time scale of our runs. Once sealed, radon from the room air will decay away while the vessel walls will generate new radon, eventually reaching some constant activity. We would then expect an expression for net Rn activity as a function of time to be of the following form:

$$A(t) = A_{air} e^{-\lambda t} + A_{BG} \left(1 - e^{-\lambda t}\right) \quad t \ll t_{1/2}^{226Ra}, \quad \lambda \gg \lambda_{Ra}$$

where $A_{air}$ and $A_{BG}$ are the activities of room air and the vessel Rn background, respectfully, and $\lambda$ is the decay constant for $^{222}$Rn, with a half-life of 3.8235 days. Figure 35 shows the measured $^{214}$Po activity as a function of time, with a fit to Equation 29. The activity starts at some large initial value of 1648±41 counts per hour or 457.8±11.3 mBq and falls to 41.11±3.38 mBq after 3.62 half-lives. Assuming the background emanation rate is constant, and using $\lambda=\ln2/3.8235$ days, we can use the fit on Figure 35 to infer a background $^{222}$Rn rate, adjusted to efficiency, of approximately 8.55±1.09 mBq/m².

This measurement of the background demonstrates the agreement between the measured activity and that predicted by radioactive decay over a reasonably long time period. However, this method has a high level of uncertainty due to the fit being sensitive to assumptions of the initial air activity, background activity, and decay constant. Taking this measurement over a longer time period, perhaps 10 half-lives in total, may yield a
better estimate of the background activity by minimizing the difference between the inferred background and the likely actual background. Yet, obtaining an accurate value of the background activity using this measurement may take a prohibitively long time.
Figure 35: Plot of $^{214}$Po activity for a background run of approximately 333 hours, the activity falls with a half-life of 3.82 days, consistent with radioactive equilibrium with $^{222}$Rn.
6.3 Improved Background Measurement- Nitrogen Gas Flush

To better estimate the intrinsic background of the vessel, it would be more expedient to start from a much lower initial Rn activity. In fact, the fastest possible measurement of the background would be to start from an initial activity that is very close to the background. In practice, since the background is not known a priori, it would be better to start from as low of an initial Rn activity as possible and build-up to the background level. Additionally, building up to the background level helps to ensure that the measured activity can be more fully attributed to the background, and not to remaining radon from room air or some other source.

In order to achieve this low background by evacuating the detector system of existing radon, we sought to purge air from the system with a clean, dry gas with low intrinsic radon content. Boil-off liquid nitrogen (LN) gas was chosen due to its intrinsic purity, ease of employment, and demonstrated success in past studies [27, 53, 55]. The boiling point of LN is 77.355 K, higher only than hydrogen, helium, and neon [54]. This means that most gas contaminants, including water (boiling point 373.15 K) and radon (boiling point 211.45 K), will remain in the solid or liquid phase at the boiling point of LN. One experiment found that the radon concentration in boil-off LN was roughly 0.5 mBq/m³, though additional reduction in concentration was achieved by passing the boil-off gas through charcoal filters [53]. The low boiling point of LN makes it very easy to use as a boil-off source since it boils at room temperature and can be controlled by submerging a variable-power heating source in the LN. Additionally, LN is relatively ubiquitous and economical, with use in research and development in many fields of physics, chemistry, and biology as well as several commercial uses. For these reasons,
many experiments have used boil-off LN gas to purge experimental environments of radon [1].

Our initial boil-off LN system consisted of a 25L Taylor-Wharton LN dewar with a gas port, which was connected to approximately 1.5 m of ¼” copper tubing followed by approximately 1 m of ¼” vinyl tubing connected to the inlet tube of the vessel. The vinyl tubing was used since it is flexible enough to allow it to be placed inside the plastic safety tank with the lid closed and allowed a connection to the inlet tube simply by fitting snugly over the inlet. The copper tube was used since the boil-off gas is initially very cold and may make vinyl brittle. The section of copper tubing allowed the gas to warm before reaching the vinyl section. Figure 36 shows the output of the dewar, connected to the Cu tubing via a Swagelok fitting.

Figure 36: Boil-off LN dewar, on the left is a liquid port, on the right is a gas port connected to our Cu tubing, center is a pressure gauge atop two pressure relief valves
The LN boiling was not supported by an external heat source in this configuration, and gas flow of boil-off nitrogen gas was achieved by allowing pressure to build-up in the closed dewar, and then opening the gas port valve to allow gas to flow into the vessel. The pressure in the dewar was limited to approximately 10 psi via a safety relief valve. Once pressure built up to the maximum value, the gas port was opened, and boil-off gas flowed until the pressure in the dewar reached atmospheric pressure. Since the rate of flow in this configuration depends on the pressure difference between the dewar and the detector vessel, the rate of flow gradually decreases from a maximum value at 10 psi to nearly nothing when the dewar is at the same pressure as the vessel. Figures 37 and 38 shows the activities of $^{214}$Po and $^{218}$Po, respectively, as a function of time during the first run of boil-off LN purging. Further, Figure 39 shows the qualitative utility of the MCA scatterplot of counts versus time versus energy. In Figure 39 we observe that the frequency of $^{214}$Po and $^{218}$Po counts decreases with time while the frequency of $^{212}$Po appears to be more constant. As mentioned earlier, this type of plot is also very helpful in identifying periods of high electrical noise, which can be observed as a dense line of counts at low- to mid-range energies in a particular time bin.

We can see that the activities of these two isotopes begin to decrease sharply at approximately one hour, when boil-off LN gas began to flow. The activity of $^{214}$Po drops by a factor of ~28 while $^{218}$Po drops by a factor of ~33 in the span of 4 hours. At the end of the run, the vessel had a $^{214}$Po-derived $^{222}$Rn activity, again adjusted for efficiency, of $7.99\pm2.18$ mBq/m$^2$ and a $^{218}$Po-derived activity of $7.01\pm2.37$ mBq/m$^2$, both taken over the last hour of the run. It is imperative to note that the efficiencies measured in Chapter 6 were performed using air dehumidified to approximately 1-2% relative humidity at the
Figure 37: $^{214}$Po activity during the initial boil-off LN flush
Figure 38: $^{218}$Po activity during the initial boil-off LN flush
Figure 39: MCA events vs time and energy during the initial boil-off LN flush
average atmospheric pressure of Albuquerque, NM, USA, ~630 Torr [56]. While pure nitrogen gas has a similar composition to air, which is 78% nitrogen [54], and close to zero humidity, the efficiency values using pure nitrogen may be slightly different than those measured using air, especially at pressures other than the standard atmosphere of Albuquerque. However, not having made the efficiency measurements in nitrogen gas, we will use the values for efficiency determined in Chapter 5 for all Rn measurements hereafter.

The reduction in activity below even the background level interpolated by the background run without a flush, the boil-off LN purge is proven to be beneficial. However, the activity rates of $^{214}$Po and $^{218}$Po continued to decrease after flushing concluded at 4 hours of run time. This is indicative of remaining radon from room air in the vessel, which is continuing to decay away. Thus, we concluded that a second flush was necessary to reach a concentration of radon below the emanation rate of the vessel.

The vessel was sealed by clamping the vinyl tube and placing a blank on the outlet flange, while the pressure in the dewar built back up to 10 psi. This waiting period also allowed an opportunity to observe the vessel in a sealed state, similar to the first, air-only, background run. Figures 40-43 show the time evolution of four Po peaks, $^{210}$Po, $^{212}$Po, $^{214}$Po, and $^{218}$Po, during the sealed operation and a second flush. In the first few hours we see a rapid decay of $^{212}$Po since it has a short half-life of 299 ns and there is no longer a strong source of $^{220}$Rn.

$^{210}$Po is the daughter of the long-lived $^{210}$Pb and we observe it to slowly build-up, as seen in Figure 40. This is consistent with the fact that $^{210}$Pb is known to plate-out on the detector surface [57]. This plating-out is useful because it has an activity that is nearly
Figure 40: $^{210}$Po activity during the 2\textsuperscript{nd} LN flush
Figure 41: $^{212}$Po activity during the 2\textsuperscript{nd} LN flush
Figure 42: $^{214}$Po activity during the 2\textsuperscript{nd} LN flush
Figure 43: $^{218}$Po activity during the 2$^{nd}$ LN flush
constant over moderate time scales of a few days (half-life of 138 days), and thus can be used as a reference to the performance of the detector itself, independent of immediate changes in radon concentration in the vessel. On the other hand, the activities of $^{214}$Po and $^{218}$Po decay at a constant rate until 114 hours into the run, when the dewar valve was re-opened and boil-off gas entered the system. During purging we see the activity of $^{214}$Po reduced by a factor of 9 and $^{218}$Po by a factor of 4, indicating that additional $^{222}$Rn is being swept out of the vessel. The boil-off gas flowed for approximately 1.5 hours before the flow rate became negligible and the vessel was again sealed in the manner described above. After being sealed, the activity rates of $^{218}$Po and $^{214}$Po began to grow as Rn was emanated from the vessel to a $^{214}$Po-derived final value of 4.33±0.33 mBq/m$^2$ and $^{218}$Po-derived value of 4.38±0.036 mBq/m$^2$.

Past values for the emanation rate of stainless steel, the major component of our vessel, are on the order of 5-10 $\mu$Bq/m$^2$ [58, 59]. Further, a similar detector developed by the Super-Kamiokande Collaboration, using an 80L collection vessel and Si PIN photodiode, was measured to have an intrinsic background of 0.33±0.07 mBq/m$^3$ [60], compared to our measured background of 40.03±2.95 mBq/m$^3$ (using $^{214}$Po). Thus, our measured background is nearly three orders of magnitude larger than what these other experiments measured. Sources of additional background activity above that expected may include vessel and photodiode components that have a high intrinsic radon emanation rate due to high uranium or thorium content, debris within the collection vessel, or an air leak in the system.
6.4 External Heat Source-Supported Boil-off

Allowing the LN to boil solely by heat transfer from the ambient air through the dewar, did not produce a sufficient LN boil-off rate for purging. The dewar is thermally insulating and, by design, maintains the LN in its liquid state for as long as possible to transport and store the LN for longer periods of time. In order to have some control over the boil-off rate, and thus gas flow, as well as to sustain the gas flow for longer periods of time, we sought to place an external heat source in the LN.

Our first system for external heating involved submerging a resistive heating element in the LN. The heating element is designed to be placed in a cup of liquid, such as water for tea or coffee, to heat the liquid for consumption. Marketed as an “instant” beverage heater, the element is rated to provide a heating power of 300W at 120V \[\text{[61]}\]. The heater was powered by an outlet extension cord fed through a large rubber stopper. The stopper also held a gas port and was placed atop the dewar. The Cu and vinyl tubing were replaced with a single 1.5 m section of \(\frac{3}{8}\)” PFA tubing, chosen for its combination of both thermal and chemical stability as well as pliability. The length of the heater power cord was fixed such that the combined length of the outlet extension inside the dewar, and the heater power cord was equal to the depth of the dewar from its mouth to the bottom of the inner portion. Figure 44 shows the layout of the heater within the dewar, while Figure 45 is the assembled dewar. The stopper was not fixed in place by anything other than wedging action. Ostensibly, if the pressure in the vessel rose above some unsafe value, the stopper would dislodge from the dewar and release the pressure. We avoided any potential overpressure issue by only operating the heater when the gas port valve was open and flowing into the vessel.
Figure 44: Beverage heater for LN boiling. Note tape around heater base. Length from the bottom of the stopper to the end of the heater is 56 cm.

Figure 45: Stopper placed on LN dewar and connected to PFA tubing
In order to control the power delivered by the heater, we used a Variac variable
transformer to control the voltage. Since the heater works by resistive heat dissipation,
the heating power scales quadratically with voltage for a given resistance of the heater.
The actual power output, however, was not known. The manufacturer specified value of
300W was given for a voltage of 120V, likely at or near room temperature. The
resistance of the metal in the heater has a temperature dependence and may vary in time
as the metal heats by the power delivered and cools from the cryogenic nature of LN.

The result of an LN flush with this configuration of external heater was an order of
magnitude more effective than a single flush in the previous configuration using ambient
heating only. The higher boil rate due to the power dissipated by the immersion heater
leads to a greater volume of boil-off gas produced per unit time. Further, the additional
quantity of gas results in a sustained pressure sufficient for purging over a longer period,
limited only by the quantity of LN.

Figures 46 and 47 demonstrate the effectiveness of this flush. As with the
previous runs, the vessel was left sealed for a period to determine a baseline for the initial
Rn activity before the flush. 37.7 hours into the run the heater was emplaced and
activated. Both figures show that the activity promptly began to fall and continued to
decrease for approximately 18 hours. Again using $^{214}$Po counts and efficiency, the
calculated Rn concentration fell from $787\pm42$ mBq, equivalent to $446\pm26$ mBq/m$^2$,
during the first 12 hours to $2.18\pm0.44$ mBq, or $1.24\pm0.25$ mBq/m$^2$, during the final 12
hours.
Figure 46: Reduction in $^{214}$Po activity during LN flush using immersion heater, flush begins at 37.7 hours of run time and ends at 55.7 hours

Figure 47: Reduction in $^{218}$Po activity during LN flush using immersion heater, flush begins at 37.7 hours of run time and ends at 55.7 hours
However, the operation of the immersion heater was not entirely successful. Upon the conclusion of this flush, the heater failed to function. An inspection determined that thermal stress caused the base the heater to fracture, exposing wires inside to cryogenic liquid and causing an electrical short circuit. This heater was designed only for casual use for a few minutes at a time and was not intended to be fully submerged.

6.5 Second Immersion Heater Design

We desired to use a heater that is better designed for our intended operation. We chose to use a flexible polyimide film heater. The heater consists of an etched foil heating element between two layers of Kapton film. Figure 48 shows the layout of the foil within the film. As with the previous heater, this heater operates via resistive heat dissipation in the foil, with the Kapton providing structure and electrical insulation. The heater was a 4” by 4” square and had a power density of 10 W/in² for a total power output of 160 W [62].

Figure 48: Omega KH-404/10P Kapton heating film [62]
The power and fluid feedthroughs of this new configuration has similarities with the previous, and a few key differences. Specifically, the new configuration does not use a stopper but rather uses a cap that is affixed to the dewar mouth by four 1 ¼” hex-head screws and sealed by an O-ring. Four feedthroughs are bored in the cap. One feedthrough hosts a gas port tube controlled by a quarter-turn valve, another hosts an additional gas tube with a 15-psi safety pressure relief valve, and a third is sealed with a blank fitting. The power cord for the heater passes through the fourth feedthrough and is sealed with epoxy. Figure 49 shows the layout of the dewar cap. The heater is again powered through a Variac to provide control over the boiling rate. Additionally, in order to prevent cold gas from entering the vessel, the boil-off gas was first passed through approximately 10 m of tubing coiled in a 5-gallon bucket filled with water.
We implemented the revised LN heater design to perform another run with a boil-off LN flush. This design has better durability in the extreme environment of ohmic heating in a cryogen. Accordingly, we were able to perform a sustained N₂ flow nearly until the amount of LN in the dewar, 31 L, has entirely evaporated. We avoid operating the heater until the LN has completely evaporated for two reasons. The first is to avoid a potential fire hazard and damage to the heater or dewar by excessive heating. The second is to maintain purity of the purge gas by avoiding introducing any impurities that may rapidly boil-out when the LN has evaporated.

The vessel was flushed for 70 hours. Assuming a depleted LN volume of 30 L and an expansion ratio of 700 [54], the total quantity of boil-off gas produced is approximately 21,000 L, or 5 L/min. After the flush we stopped the flow and sealed the vessel by closing a quarter-turn valve on each of the vessel inlet and outlet.

Through the first 158 hours of this run we experienced continued high electrical noise in the Po peak ROIs. We determined that the Faraday cage was not sufficiently grounded. Contributing to this was the fact that the Al extrudate framing had an anodized finish that is electrically insulating. In order to create a robust grounding, we ensured that all sides of the cage were connected with grounding strap and that the cage and vessel/diode electronics shared a common ground, that of the electronics crate.

The high noise precluded determination of Po activity rates in multiple portions of the run, and thus these portions were removed from the run data. Figure 50 shows both the magnitude of noise before and after modifying the grounding (at t=157.8 hours) as well as the periods that were removed due to excessive noise.
Figure 50: Measured MCA events during the first LN flush with the new heater system. a. Flush stopped and vessel sealed at $t=70$ hours. b. Faraday cage grounding modified at $t=157.8$ hours. Blinded regions correspond to time bins removed for excessive noise.
Figure 51: $^{214}$Po activity during the first LN flush with the new heater system. a. Flush stopped and vessel sealed at $t=70$ hours. b. Faraday cage grounding modified at $t=157.8$ hours. Blinded regions correspond to time bins removed for excessive noise.
Despite the large amount of noise and blinded time bins, we were still able to observe the effects of the purge and estimate a vessel background activity. The activity of $^{214}$Po is plotted as function of time in Figure 51. The sharp reduction in activity due to the flush was contained within a period of noisy data, but it is evident that the activity prior to sealing is much lower than room air. The average $^{222}$Rn activity during the 24 hours of quality data prior to sealing the vessel was 1.85±0.29 mBq.

Again, due to noisy data, the growth of $^{222}$Rn activity due to emanation from the vessel is not shown, however we can see the final emanation level clearly especially after the Faraday cage was modified. The final activity rate of this run was 3.40±0.42 mBq, corresponding to an emanation rate of 1.92±0.24 mBq/m², still higher than the goal background of 10s of μBq/m².

6.6 Background Activity Measurement with LN Flush & Moderate Vacuum

Having a moderate vacuum in the vessel has the dual benefits of allowing us to monitor the pressure in the vessel to test for any leaks as well as ensuring an additional amount of leak-tightness in the system. Further, as mentioned in Chapter 4, the detection efficiency is reduced by collisions of Rn daughters with gas or contaminant molecules in the vessel. Reducing the pressure inside the vessel inherently means that there will be fewer gas molecules to collide with.

Accordingly, we performed a run with an LN flush immediately followed by pumping on the vessel before sealing. The vessel was sealed at approximately 400 Torr, 130 Torr below local atmospheric pressure. The first flush of this run was intended to last 24 hours but was ended prematurely because the LN became depleted. As the LN evaporated, the flow rate dropped, and some air was able to creep back into the vessel
through the outlet valve. We sealed the vessel for approximately 72 hours to obtain additional LN and then re-flushed for 20 hours. At the conclusion of the second flush, we pumped the vessel down to $P=413.5$ Torr and sealed by closing the inlet and outlet valves.

Figures 52 and 53 note the results of this run. In the first plot, $^{214}$Po activity vs time, the effects of the two flushes and the build-up of $^{214}$Po due to $^{222}$Rn emanation are clear. The activity falls from the room air level of $\sim 3.9$ Bq/m$^3$ to 0.498 mBq/m$^3$ during the first flush, from 2.75 to 24 hours, before rising sharply due to evaporation of the LN and possible air backflow. The purging activity of 0.498 mBq/m$^3$ is consistent with previously measured values of 0.5 mBq/m$^3$ for the Rn concentration of boil-off LN gas [53]. This indeed suggests that our LN flush has displaced room air from the system.

After the second flush, from 97 to 117 hours, the $^{222}$Rn activity steadily rises to a final value of $1.94\pm0.24$ mBq/m$^2$. Consistent with the previous run without vacuum pumping, it suggests that the measured vessel background activity is indeed on the order of mBq/m$^2$, much larger than the goal of 10s of $\mu$Bq/m$^2$.

A clue to the high background may lie in the activity of $^{212}$Po, indicative of the presence of $^{232}$Th in the vessel. The $^{212}$Po activity falls from $96.45\pm19.29$ $\mu$Bq to $50.15\pm13.61$ $\mu$Bq over the 735.25-hour duration of the run. The falling activity, not a steady state, suggests that there was some higher initial quantity of $^{232}$Th that was decaying. Further, the average $^{212}$Po activity of similar runs using room air as a source was 46.77 $\mu$Bq. This fact, and the fact that the longest-lived daughter of $^{224}$Ra is $^{212}$Bi with a half-life of 10.64 hours and we did not observe significant activity of $^{212}$Po in room air runs, makes it unlikely that air is the source of the $^{212}$Po.
Figure 52: $^{214}$Po activity during first run with pumping to approximately 400 Torr after an LN flush. The first flush was unsuccessful due to LN evaporation faster than expected.
Figure 53: Falling $^{212}\text{Po}$ activity rate during the first nitrogen+vacuum run
We assessed that it was more likely that the source was either debris in the vessel or thorium content in some component of the vessel’s construction. Since the thorite rock sample that was used for efficiency measurements had a high thorium content and a granular consistency, an immediate concern was that dust or a grain of the rock flowed into the vessel and was causing an elevated $^{212}\text{Po}$ activity. Alternatively, it is possible that one or multiple components of the vessel had a large Rn emanation rate.
7 Investigation of Background Sources

7.1 Vessel Leak Investigation

In order to determine if a leak existed in the vessel, we left it sealed after an LN flush and observed the activity. The room air was measured to have a much higher Rn content than that of boil-off LN gas or of the measured intrinsic background of the vessel. If a major leak existed, the Rn activity would increase as air entered the vessel. Figures 54-57 depict the results of this leak test run. $^{214}$Po and $^{218}$Po activities are statistically constant (within standard counting error), during the sealed run. At 217 hours of runtime, the inlet side of the vessel was opened by unclamping the vinyl tube to simulate a leak in the vessel. Both $^{214}$Po and $^{218}$Po responded strongly to the simulated leak, both growing by over an order of magnitude. During both the sealed run and the simulated leak $^{212}$Po remained nearly constant, rising from 63.66±19.19 μBq during the first 48 hours of the run to 75.23±20.87 μBq, indicating that the simulated leak rate was still slow enough to prevent $^{220}$Rn daughters from reaching the detector due to their short half-lives compared to $^{222}$Rn daughters. This suggests that there was not a large leak in the vessel during sealed runs, however it was still not possible to tell if there was a smaller leak.

In order to mitigate against the possibility of a leak, all flanges were checked to ensure a tight seal, including ensuring a proper fit of all O-rings. Additionally, 9 C-clamps were placed around the vessel lid to supplement the three bolts which secure the lid. Since the vessel was originally designed as a bell jar vacuum chamber, it was expected to have an additional amount of force due to the pressure differential between the interior and exterior to secure the lid. The clamps and bolts were spaced equidistant around the perimeter of the lid, precisely 30° apart, in order to achieve a uniform force
Figure 54: MCA Scatterplot during the vessel leak trial run
Figure 55: $^{212}$Po activity during the vessel leak trial run. The error bars denote standard counting error of the square root of the number of counts.
Figure 56: $^{214}$Po activity during the vessel leak trial run. At 217 hours of run time one side of the vessel was opened to simulate a leak.
Figure 57: $^{218}$Po activity during the vessel leak trial run. At 217 hours of run time one side of the vessel was opened to simulate a leak.
around the lid. To this end, the fasteners (bolts and clamps) were tightened in an alternating pattern, tightening opposing sides around the lid. Figure 58 shows the lid emplaced with all fasteners. A future design of a radon detection chamber similar to ours would have additional holes bored through both the lid and the vessel in order to ensure a more consistent and stronger seal between the two.

Figure 58: Assembled vessel with C-clamps installed
7.2 Vacuum Pumping- Leak investigation

Concerned that there may still be some small leak in the vessel which was contributing to a higher than expected emanation rate, we planned to perform a series of tests involving pumping down to moderate vacuum. We choose a testing pressure of ~400-500 Torr since the tophat was not designed for high vacuum applications yet the pressure difference from atmosphere would still be sufficient to determine if there is any leak. Specifically, if the pressure in the vessel rose significantly above the pressure it was pumped down to, we could conclude that air was entering the vessel.

The vacuum pump system was implemented by replacing the outlet flange of the vessel with a bellows-sealed angle valve to maintain the capability to seal the vessel while also providing an interface to standard vacuum fittings. The opposite side of the valve was connected to a tee with a pressure gauge and a second valve. The second valve...

*Figure 59: Vacuum pumping components. Bellows hose leads to the vacuum pump*
is used to seal the vessel with the pressure gauge attached, when closed, and to pump
down the vessel, when open. The electronics in the pressure gauge may be destroyed by
high voltage so all pumping and pressure check operations were done only after
unbiasing the vessel and photodiode. Figure 59 shows the vacuum pumping system.

The first vacuum pressure test was done with an initial pressure of 412.7±2.1 Torr.
The uncertainty in pressure is due to the uncertainty of the pressure gauge, ±0.5% of the
reading [63]. We observed a pressure change of 1.9 Torr in 117 hours, 1.1 Torr of which
was over the first 24 hours and likely due to some outgassing. A pressure change of 0.8
Torr over 93 hours does not conclusively indicate a leak since it is below the sensitivity
of our gauge, however even a leak rate of $4.56 \times 10^{-4}$ Torr·L/s (given the 190.97 L volume
of the vessel) may be acceptable for just a moderate vacuum.

Figure 60: Pressure rise test of possible vessel leak, no significant leak indicated, inlay
boxes focus on trials at ~414 Torr and 500 Torr
Since it is possible that the very act of pumping to ~414 Torr sealed a leak that would otherwise exist at 630 Torr, we also tested the vessel at 500 Torr. The result of this test remained inconclusive of evidence of a leak, with the pressure remaining constant (±0.5 Torr) over nearly 3 days. Figure 60 is a plot of the vessel pressure as a function of time, for both the 414 Torr and 500 Torr tests. While these tests cannot rule out that there was a leak at zero or positive pressure relative to atmosphere, they can conclude that there is no appreciable leak at a moderate vacuum.

7.3 Electrical Noise Investigation- Faraday Cage

Prior to performing a boil-off LN flush with the second heater configuration, we observed a high amount of electrical noise in the photodiode signal. Previously, the electrical noise was primarily at low channel numbers, and hence low energies. Occasionally the noise would extend to higher channels for short durations. In either case, except in the rectified cases mentioned in Chapter 5, the noise previously did not interfere with Po α counting. The noise began to become detrimental for Rn detection operation as the noise, though diminishing in magnitude in high channel numbers, was present in a larger range of channels and extending into the region of interest (ROI) for $^{222}$Rn and $^{220}$Rn decay chain α’s. For runs with a high Rn activity a small amount of noise in the ROI may not be significant, however any amount of noise in the ROI will reduce the sensitivity of the detector.

A particularly interesting feature of the noise was that it seemed to increase when the fluorescent lights in the laboratory room were switched on as well as when other appliances were running. We suspected that the photodiode and the signal feed cable were picking up electromagnetic interference (EMI), resulting in high noise.
To mitigate the effect of EMI on the photodiode signal, we built a Faraday cage surrounding the plastic safety tank containing the vessel. The cage was comprised of six 0.032” thick 3003H14 aluminum panels. Four of the panels measure 42 ½”x52” and comprise the side walls of the cage, while the other two are 40 ½”x40 ½” and are the top and bottom of the cage. The panels are supported by a frame of 6105-T5 aluminum t-slotted extrudates and are fastened to the framing using heavy-duty tape. Additionally, sections of grounding strap are fastened between adjacent sides of the cage as well as between the cage and the crate containing the MCA electronics and HV power supplies to provide adequate grounding for the cage to properly shield from EMI.

Figures 61-64 note the performance of the Faraday cage towards mitigating EMI, even though the grounding was initially not as robust. Figure 61 is a clear indication of intensity and extent of the noise before and after installation of the cage, which was installed at 69 hours of run time. Before the cage was installed strong sources of interference would cause noise nearly across the entire spectrum of the MCA. After the cage was installed strong sources of noise persisted yet were confined to low channel numbers so as to prevent noise in the region of interest to Rn measurement. Figure 62 demonstrates the performance of the Faraday cage to reducing the amount of electrical noise that extended to high channel counts, above 10 MeV, where we normally do not observe many events. We see that prior to the cage being installed, there were many time bins where the number of counts at high energy was much higher than usual. This indicates that the number of noise events in the energy ranges of our several Po peaks is likewise high.
Figures 63 and 64 show the effect of noise on $^{214}$Po and $^{210}$Po counts. The activity in these two peaks should be nearly constant in time since $^{210}$Po is very long lived and $^{214}$Po is in radioactive equilibrium with $^{226}$Ra during the run. The activity in these two peaks have spikes near times that coincide with high noise from Figures 61 and 62. Further, we see that the noise after installation of the Faraday cage does not hugely affect the expected count rates of $^{210}$Po and $^{214}$Po.
Figure 61: MCA events before and after installation of a Faraday cage at $t=69$ hours, periods of high noise are noted by a high density of event markers.
Figure 62: Histogram of events above 10 MeV, showing the effect of electrical noise across the entire MCA spectrum, most notably before the Faraday cage was installed at t=69 hours.
$^{210}$Po Activity vs Time - High Electrical Noise

Figure 63: $^{210}$Po activity as affected by high electrical noise, particularly before installation of the Faraday cage at $t=69$ hours
Figure 64: $^{214}$Po activity as affected by high electrical noise, particularly before installation of the Faraday cage at $t=69$ hours
8 Reducing Background Activity

8.1 Cleaning Vessel Interior

Concerned that ore dust may have flowed into the vessel during efficiency measurements, we removed the lid and cleaned the interior with Kimwipe laboratory wipes and isopropanol (IPA). The IPA was used as a solvent for any oils inside the vessel, while the wipes were used to collect any debris. The cleaning was done by placing the plastic safety tank, containing the lidless vessel, horizontally and wiping inside the vessel with IPA-moistened Kimwipes. Due to the noxious fumes of IPA, a small fan was used to ventilate the working area. Also, the steel inlet pipe was removed and the exterior was wiped with IPA while the interior was flushed with IPA.

The Kimwipes were stored after cleaning and were subsequently analyzed in a gamma spectrometer. A 5cm x 5cm portion of the used wipe contained a level of $^{212}$Bi slightly above that of a clean, bare wipe, however the increased quantity was not high enough to conclusively state whether there was any debris collected on the wipe. It is possible that the sample tested in the gamma spectrometer did not have a large concentration of particulates since it was just a small portion of just one of several large Kimwipes used.

A flush with vacuum pumping was again performed after cleaning. The results of the post-clean run are shown in Figures 65-67. The MCA spectrum indicates qualitatively that the activities of $^{214}$Po and $^{218}$Po are actually increased after cleaning, while the activity of $^{212}$Po is constant within error. Since the cleaning did not involve the photodiode, or what is plated-out on it, we did not expect the activity of $^{210}$Po to change and indeed we observed nearly the same activity after cleaning.
Figure 65: MCA spectrum during the final 40 hours of the runs before (blue) and after (red) cleaning the vessel. Note that the activities of $^{214}$Po and $^{218}$Po are increased yet the activity of $^{210}$Po remains constant, verifying detector performance.
Figure 66: $^{212}$Po activity after cleaning the vessel. There is an elevated activity relative to before cleaning.
Figure 67: $^{214}\text{Po}$ activity after cleaning the vessel. There is an elevated activity relative to before cleaning.
The time series plots of $^{214}$Po and $^{212}$Po also show that the activities of these isotopes are higher after cleaning the vessel. Whereas just prior to cleaning the $^{212}$Po activity was 50.15±13.61 μBq, immediately after cleaning it is 106.7±9.5 μBq. For $^{214}$Po, the Rn emanation rate after flushing, pumping, and sealing was 1.94±0.24 mBq/m² before the clean, and 6.77±0.82 mBq/m² after.

The cause of this increase in activity after an operation that was intended to have the opposite effect is an interesting question that may hold clues to the origin of our higher-than-anticipated Rn emanation. It is possible that the IPA wipe dissolved and removed a layer of oxidation on the electropolished stainless steel which previously had inhibited Rn emanation. The wiping action could have dislodged particulates or spread particulates over a larger surface area. Also, the fan used to ventilate the work area from IPA fumes could have blown additional dust and debris into the vessel.

### 8.2 O-Ring Replacement

Some component of the vessel may have contributed to a high emanation rate, and we sought to identify components for replacement. The first we tried were all O-rings exposed to the interior of the vessel. We replaced these O-rings, which were made of Viton and Buna-N rubber, with solid PTFE. Other experiments [64, 65] have utilized PTFE O-rings for low background physics since PTFE has excellent chemical and physical properties as well as low a Rn diffusion coefficient.

In addition to replacing the O-rings, we also removed the aluminum centering rings that held the O-rings on the vacuum fittings and flanges. Due to the stiffness of PTFE, the new O-rings would not stretch to fit on the centering rings. As a result, the O-rings that required a centering ring were instead manually centered and then fixed in place.
Figure 68: MCA Spectrum during the first run after cleaning (blue) and after installing new O-rings (red). There is little difference between the two except for a slightly higher activity after installing the new O-rings.
All fasteners required a larger clamping force in order to ensure that the PTFE O-rings maintain a proper seal since the material is not compressible like rubber O-rings. We again checked the vessel for any leaks due to poorly-centered O-rings or inadequate sealing and found that the vessel was indeed adequately sealed. Following this pressure check, we again performed a run with a 25.5-hour long LN boil-off and pumping the vessel to 403.3 Torr before sealing. The results of this run indicate that Teflon O-rings did not reduce the Rn background. In fact, the effect was a small rise in $^{222}$Rn activity to $8.25\pm0.98$ mBq/m$^2$. This rise is perhaps due to the fact that we removed the lid in order to install a large O-ring between the lid and vessel. Despite this small rise, we retained the PTFE O-rings due to their proven performance in low background studies.

8.3 Low Vessel Bias Voltage Test

To better isolate the source of the increased background activity, we performed a series of runs at relatively low vessel bias voltage. We have established that Rn detection efficiency is proportional to the bias voltage, however, it is also proportional to the path length that a Rn daughter must travel. At low bias, Rn decays that are very far from the photodiode will have a smaller probability of detection, while those that are near will be less affected by a lower electric field. This is especially true of the $^{220}$Rn decay chain since the first daughter, $^{216}$Po, has a half-life of just 0.145 seconds.

We observed the activities of $^{222}$Rn and $^{220}$Rn between the following voltages, in KV: 0.1, 0, 0.5, 5. Through these voltages we see no change in $^{210}$Po activity, which verifies the notion that $^{210}$Pb is plated out on the photodiode surface. $^{214}$Po responds as we would expect from efficiency measurement runs, with very little $^{214}$Po collected at 0 and 0.1 KV and a fairly rapid rise in collection starting at 0.5 KV.
Figure 69: $^{210}\text{Po}$ activity during checks at various voltages (red)

Figure 70: $^{214}\text{Po}$ activity during checks at various voltages (red)
However, we noted that the low voltage had a modest effect on reducing the $^{212}\text{Po}$ activity. We can use $^{212}\text{Po}$ as a signature of excessive background within the vessel due to its very short lifetime and low activity in previous runs. The difference between the average activity at 0 KV and that at 5 KV was $20.06\pm16.98$ μBq, or the 0 KV activity is $67.5\pm24.9\%$ of the 5 KV activity. This indicates that the source of thorium may be close to the photodiode, either in a component of the photodiode or in the tophat mounting.

### 8.4 Re-electropolish Vessel and Clean Lid

Continued concerns of some sort of debris or other contamination in the vessel led us to re-electropolish the vessel. Electropolishing serves two purposes for reducing Rn emanation rate a material. The first is that it may remove contaminants embedded on the surface of the material. The second is that it results in lower Rn emanation rates by producing a smoother surface finish. Additionally, the Al lid was cleaned with an acidic solution to remove any contaminants from the surface. Finally, we obtained two 0.5 μm

![Figure 71: $^{212}\text{Po}$ activity during checks at various voltages (red)](image-url)
Figure 72: Vessel activity prior to (solid blue) and after (dashed red) electropolishing the vessel and cleaning the lid. $^{214}$Po and $^{218}$Po are reduced while $^{212}$Po and $^{210}$Po are unaffected.
in-line air filters, which is fine enough to filter most course aerosol particles [66] from flowing into the vessel and should mitigate further dust collection inside the vessel.

After reassembling the vessel and performing a pressure rise test for leak tightness, we performed another LN flush and vacuum pump run to test the effectiveness of the electropolish. The results of this run indicate that the electropolishing and acid wash reduced the background of $^{222}$Rn by 41% to $5.04 \pm 0.62$ mBq/m$^2$, compared to the activity after installing the PTFE O-rings. Electropolishing did not reduce the background of $^{220}$Rn. $^{210}$Po is again an excellent diagnostic of the performance of the detector its activity is constant to within ~1% before and after electropolishing.

### 8.5 Photodiode and Brass Screw Replacement

The low voltage runs suggest that there may be some source of radon close to the photodiode. The fact that the electropolishing and acid wash did not reduce the activity of $^{220}$Rn as it did $^{222}$Rn suggests that this source is located in either the photodiode itself, the photodiode mounting hardware, or the tophat assembly. Two potential contamination sources in the proximity of the photodiode are dust that was electrostatically collected on the photodiode surface, housing, and mount, and Th content in the brass screws that hold the photodiode mount.

To mitigate these possible sources, we replaced the photodiode with the same model, thoroughly cleaned the Cu mount with IPA and polyester cleanroom wipes, replaced the two brass screws that mounted the photodiode housing to the tophat with 4 equivalent nylon screws, and removed two brass screws that held the mount together. We again performed a background activity run after these modifications were made.
Figure 73: Comparison of similar runs before (blue) and after (red) replacing the photodiode, cleaning the photodiode mount and replacing brass screws.
Figure 74: $^{212}$Po Activity after replacing the photodiode, cleaning the photodiode mount, and replacing brass screws
Figure 75: $^{214}$Po Activity after replacing the photodiode, cleaning the photodiode mount, and replacing brass screws
Figure 73 demonstrates the effectiveness of the modifications made to the photodiode and mounting. As with the previous photodiode change, the presence of $^{210}\text{Po}$ has disappeared, though the tail of $^{218}\text{Po}$ and some electrical noise persists in the ROI of $^{210}\text{Po}$. The changes also resulted in a significant decrease in $^{218}\text{Po}$ and $^{214}\text{Po}$, a 74.4% reduction in $^{222}\text{Rn}$ background to $1.35\pm0.20 \text{ mBq/m}^2$. Figure 75 also demonstrates that the background of $^{214}\text{Po}$ is remarkably stable over the run, after coming to radioactive equilibrium with the background emanation. The changes did not, however, reduce the background of $^{212}\text{Po}$.

### 8.6 Removing the Stainless-Steel Inlet Pipe

It is perhaps possible that a small amount of dust or debris was trapped within the inlet pipe that was not flushed out when the pipe was cleaned with IPA. To test this possibility, we removed the inlet pipe and performed a background run without it.

![Figure 76: $^{214}\text{Po}$ activity during a background run with no inlet pipe. The inlet pipe is critical to an effective LN flush](image)

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A LN flush and subsequent background run proved that the inlet pipe is necessary for an effective LN flush, and efficient gas mixing in the vessel. As shown in Figure 76, the flush did not reach as low of an $^{214}$Po activity as previous flushes and came to a steady state at $5.47\pm0.67$ mBq/m$^2$, about a factor of four higher than the previous run.

### 8.7 Replaced Tophat and Additional Brass Screws

After re-installing the inlet pipe, we replaced the acrylic tophat with one made out of polycarbonate. We also replaced the two remaining brass screws that held together the photodiode mount with four nylon screws. Both acrylic and polycarbonate have similar chemical physical properties, so the replacement should be functionally equivalent. However, the emanation and permeability rates of radon through acrylic and polycarbonate may differ slightly.

Replacing the tophat and screws resulted in a slightly higher $^{222}$Rn activity compared to the previous run, when we replaced the photodiode with a new one (Section 8.5), with an activity of $1.83\pm0.25$ mBq/m$^2$. However, the activity of $^{212}$Po was reduced, at $57.44\pm9.71$ μBq compared to $74.01\pm5.93$ μBq in Section 8.5. Figure 77 compares the first run with the new photodiode to the run with the new tophat and brass screws.
Figure 77: Comparison of activities before (blue) and after (red) replacing the tophat and the remaining brass screws.
8.8 Replaced Electropolished Stainless Steel Inlet Pipe

Following the success in reducing the background rate of the vessel by electropolishing and establishing that the inlet pipe is critical to a low-background measurement, we obtained a new electropolished stainless steel inlet pipe in the same shape and design as the previous inlet (Figure 12). This did indeed reduce the $^{222}\text{Rn}$ background to $1.17 \pm 0.18 \text{ mBq/m}^2$, the lowest measurement yet for the intrinsic $^{222}\text{Rn}$ background of the vessel. The $^{212}\text{Po}$ activity was slightly higher than previously, at $81.52 \pm 11.09 \mu\text{Bq}$.

After replacing the inlet tube the only components unchanged from the original design of the detector and exposed to the interior of the vessel are the Cu photodiode mount housing, the photodiode wires, and the tophat D-SUB feedthrough flange. Persistent background activity could originate in those components or elsewhere such as in electrical solder above the photodiode or the vessel wall welds.

8.9 Background Activity Measurement with Emanation Chamber

In the final background measurement run, we connected the empty 2.95L emanation chamber and an 8 L/min [67] diaphragm pump to the vessel to measure the background of the emanation chamber and pump in addition to the vessel. The chamber is intended to hold samples for measurement. The pump is to circulate gas in the system, or more specifically to flow Rn-bearing gas emanated from a sample inside the emanation chamber, to the detection vessel. The results of that run, and a summary of all previous background runs are shown in Table 4.
<table>
<thead>
<tr>
<th>Run Name</th>
<th>Duration (hours)</th>
<th>$^{222}\text{Rn}$ Background (mBq/m$^2$)</th>
<th>$^{210}\text{Po}$ Activity (mBq)</th>
<th>$^{212}\text{Po}$ Activity ($\mu$Bq)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Air. Sealed</td>
<td>332.8</td>
<td>8.55±1.09</td>
<td>N/A*</td>
<td>30.88±5.08</td>
<td>Derived by interpolation</td>
</tr>
<tr>
<td>LN Flush</td>
<td>414.75</td>
<td>4.33±0.33</td>
<td>0.616±0.020</td>
<td>86.06±7.59</td>
<td>Based on efficiency in air</td>
</tr>
<tr>
<td>LN Heater Design 1</td>
<td>79.4</td>
<td>1.24±0.25</td>
<td>1.09±0.11</td>
<td>179.3±25.1</td>
<td>Heater damaged after run</td>
</tr>
<tr>
<td>LN Heater Design 2</td>
<td>397.8</td>
<td>1.92±0.24</td>
<td>1.26±0.04</td>
<td>62.16±6.59</td>
<td>Instituted Kapton heater</td>
</tr>
<tr>
<td>LN+Vacuum</td>
<td>735.25</td>
<td>1.94±0.24</td>
<td>2.18±0.09</td>
<td>50.15±13.91</td>
<td>1st run with slight vacuum</td>
</tr>
<tr>
<td>Vessel IPA Wipe</td>
<td>330.75</td>
<td>6.77±0.82</td>
<td>2.19±0.05</td>
<td>106.7±9.5</td>
<td>Vessel+Lid wiped with IPA</td>
</tr>
<tr>
<td>Replaced O-Rings</td>
<td>328.75</td>
<td>8.25±0.98</td>
<td>2.49±0.05</td>
<td>59.99±7.12</td>
<td>Installed Teflon O-rings</td>
</tr>
<tr>
<td>Re-Electropolish</td>
<td>262.5</td>
<td>5.04±0.62</td>
<td>2.82±0.05</td>
<td>71.96±8.73</td>
<td>Also cleaned lid w/ acid solution.</td>
</tr>
<tr>
<td>New Photodiode</td>
<td>585.5</td>
<td>1.35±0.20</td>
<td>N/A*</td>
<td>74.01±5.93</td>
<td>Also replaced/removed brass screws</td>
</tr>
<tr>
<td>Removed Inlet Pipe</td>
<td>606.5</td>
<td>5.47±0.67</td>
<td>N/A*</td>
<td>84.27±6.21</td>
<td>Pipe is critical to flush</td>
</tr>
<tr>
<td>Replaced Tophat</td>
<td>169.25</td>
<td>1.83±0.25</td>
<td>0.028±0.007</td>
<td>57.44±9.71</td>
<td>Also replaced remaining brass screws</td>
</tr>
<tr>
<td>Replaced Inlet Pipe</td>
<td>184</td>
<td>1.17±0.18</td>
<td>0.057±0.009</td>
<td>81.52±11.09</td>
<td>Electropolished SS inlet</td>
</tr>
<tr>
<td>Emanation Chamber +</td>
<td>246.75</td>
<td>2.30±0.30</td>
<td>0.097±0.010</td>
<td>126.1±11.9</td>
<td>Instituted 2.95L emanation chamber +circ. pump</td>
</tr>
</tbody>
</table>

*\text{N/A} indicates that the $^{210}\text{Po}$ activity was below the noise level*
9 Emanation Measurement

Once the efficiency of collection and intrinsic radon background of the vessel is known, it is possible to make accurate measurements using the detector. These measurements are performed by placing samples within the emanation chamber. Radon that is emanated from the sample is carried from the emanation chamber to be detected in the vessel. Examples of objects that may be desirable for measurement in support of MAJORANA, other $0\nu\beta\beta$ searches, or ultra-low background studies in general are detector construction materials such as metals and polymers, specific items such as cables and fasteners, and gloves and tools that may come into contact with detector components during construction.

While many objects may have complex shapes or textures, it is much simpler to determine the emanation rate per unit surface area for an object with a known surface.

![Image of Emanation Chamber with Quarter-turn Valve]

*Figure 78: Emanation Chamber with Quarter-turn Valve*
area. As mentioned in Chapter 5, the surface area is easiest to compute for an object with a simple geometry or well-defined computer-aided design model.

The emanation chamber consists of a tube with interior length 25 cm and diameter 12.25 cm. It is sealed on either end by a DN125 Conflat flange with a DN40 Conflat to \( \frac{1}{4}'' \) Swagelok tube adapter. The chamber is then connected to the vessel and circulation pump via \( \frac{1}{4}'' \) PFA tubing. Two 0.5 μm filters are placed downstream of the chamber to avoid debris transfer into the detector vessel. The emanation chamber is shown in Figure 78.

A diagram of the gas flow is shown in Figure 79. The solid lines denote the gas flow during a typical emanation measurement, while the dashed lines show the gas flow while integrating the RAD7 and while flushing with LN. Use of the 8 L/min circulation pump is not required while the RAD7 is connected to the system since the RAD7 has an internal pump. The two valves on either side of the emanation chamber enable the rest of the system to be sealed while changing samples.

![Diagram of the gas flow](image)

*Figure 79: Gas Flow Diagram of the Radon Detector System*
9.1 First emanation run- Granite Sample #1

The first sample tested with the emanation chamber was a section of decorative granite, typically used in home countertops. Although granite is a popular decorative material, it has been reported to release radon [68]. All varieties of rock emit some amount of radon due to naturally-occurring deposits of uranium and thorium in the crust of the Earth. However, granite indeed may contain elevated concentrations of uranium and thorium due to the manner in which granite is formed [69]. Specifically, granite is formed from magma that has cooled to a relatively low temperature after many other minerals have solidified out of the magma during cooling. Due to their high ionic valence numbers, uranium and thorium are less likely to crystalize out of hot magma and thus are preferentially concentrated in cooler-formed minerals such as granite. While this does not indicate that all granite will have a high uranium or thorium content, it does explain why granite may have a higher than normal radon emanation rate. Further, since that
emanation rate is likely to be much less than that of our thorium/uranium ore sample, it provides us a useful test of our detector with minimized risk of contamination.

Our first granite sample was $13.6 \pm 0.1 \text{ cm} \times 10.3 \pm 0.5 \text{ cm} \times 3 \pm 0.05 \text{ cm (LxWxH)}$, for a surface area of approximately $423.56 \pm 14.19 \text{ cm}^2$. It is ground to a smooth matte finish on four sides, polished with a resin-like sealing compound on one side, and unfinished on the remaining side. The sealed side was gently sanded to expose a portion of the granite beneath.

The first emanation measurement run started immediately upon completion of the final background run by closing the valves on either end of the emanation chamber to seal it in order to place the sample within. After placing the sample in the chamber, the valves were reopened and the circulation pump started to start the run. The results of the emanation measurement with this sample are shown in Figures 81-85. In Figure 81 we see the energy spectrum of detected $\alpha$’s. Most notably, we can see a peak in the vicinity

![Granite Sample #1 Activity](image)

*Figure 81: Granite Sample #1 Activity. Note the peak around 6.78 MeV, corresponding to $^{216}$Po, as well as the strange shape of the $^{212}$Po peak*
of 6.78 MeV. This peak corresponds in energy to $^{216}$Po, which we did not see in earlier runs due to its short half-life as discussed in Sections 4.4 and 8.3. Further, we note that the $^{212}$Po peak has a unique tail toward higher energies; the phenomenology of this tail is unknown and will require additional study. In Figures 82 and 85 we see that the $^{212}$Po and $^{218}$Po activities build-up to an equilibrium with the emanation activity of the granite from a lower initial activity, which was attributed to the background activity of the vessel in addition to a small amount of room air that was introduced to the emanation chamber when the sample was emplaced.

The measured $^{212}$Po emanation activity of the sample is 190.28±1.03 mBq, three orders of magnitude higher than the background activity of the vessel, indicating a high level of thorium in the sample. The short half-life and unknown efficiency fraction preclude any possibility of accurate determination of the $^{220}$Rn emanation rate of the sample.

*Figure 82: $^{212}$Po Activity vs Time for Granite Sample #1*
Figure 83: $^{214}$Po Activity vs Time for Granite Sample #1

Figure 84: $^{216}$Po Activity vs Time for Granite Sample #1
The activity of $^{214}\text{Po}$, in Figure 83, seems to continue to rise over the entire duration of the run. There is some expected delay in the observance of a $^{218}\text{Po}$ decay and the subsequent decay of $^{214}\text{Po}$ from that same nuclei, however the delay is on the order of minutes to tens of minutes, driven by the ~20-27-minute half-lives of $^{214}\text{Pb}$ and $^{214}\text{Bi}$. The cause of the plateaus to equilibrium in $^{212}\text{Po}$ and $^{218}\text{Po}$ but not $^{214}\text{Po}$ may lie in the rate in which gas flows through the system.

Since $^{214}\text{Po}$ did not come to an equilibrium valve over the course of this run, we used $^{216}\text{Po}$ activity to measure the $^{222}\text{Rn}$ activity in the vessel. Using $^{218}\text{Po}$ and its efficiency at 5KV, the background-subtracted $^{222}\text{Rn}$ emanation activity of the granite is $20.21\pm2.35\text{ Bq/m}^2$, though the efficiency with the continuously operating circulation pump may differ than that determined with the RAD7 pump, which operates on an intermittent schedule and an average flow rate of 1 L/min. [47]
9.2 Gas Flow Characterization of Emanation Chamber

Following the run with the first granite sample, we intended to flush with LN and do a follow-up measurement of the background activity of the system. This plan was precluded by a damaged vacuum pressure gauge yet allowed us an opportunity to characterize the system using room air as a source.

We opened the system at inlet of the emanation chamber and flushed with room air for 26.75 hours. We then closed the system by re-connecting the inlet of the chamber in order to observe the expected exponential decay in activity of the radon in the enclosed air. At approximately 75 hours into the run the circulation pump was inadvertently turned off for 3 hours. After 156 hours, the circulation pump was again turned off, intentionally, to observe the response of the system. Finally, at 174 hours, the system was again re-opened to the room air to flush out the system.

Figure 86 shows the $^{214}$Po and $^{218}$Po activity during this run. Three distinct features of this plot are evident, the first being that activity in the air falls at the rate we expect, with a half-life of ~3.82 days, while the vessel is sealed.

The second feature is that the $^{214}$Po activity seems to promptly rise while the circulation pump is not operating but then returns to a normal slope of decline. This behavior is not reflected in $^{218}$Po or $^{212}$Po (Figure 87), which suggests that the gas flow rate in the vessel has a strong effect on $^{214}$Po activity but not on other Po nuclides in the decay chain. It is likely that the high gas flow is pushing out uncharged daughters of radon before they can decay and be collected on the photodiode surface. $^{218}$Po would not be affected by this phenomenon since it depends only on one isotope, $^{222}$Rn. $^{212}$Po is
likewise not affected by this phenomenon, perhaps since the $^{220}$Rn decay chain has much shorter half-lives than $^{222}$Rn.

The final distinct feature is that there is a strong diurnal cycle in the $^{222}$Rn activity in the room air within our laboratory. This is likely caused by the natural emanation of radon from rock and soil, which is temperature and pressure dependent and as such may result in a diurnal cycle. Also, from this diurnal cycle we observe a slight delay in the arrival $^{214}$Po relative to $^{218}$Po. The delay is about one hour, which is consistent with the mean time between $^{218}$Po decay and $^{214}$Po decay predicted by the half-lives of the intermediate daughters, $^{214}$Pb, $^{214}$Bi, and $^{214}$Po. The mean time between the two decays is given by the sum of half-lives of the three divided by ln2 and is equal to 67 minutes.

Finally, Figure 87 shows the decline in activity of $^{212}$Po from the high activity of the granite. The decay rate of this decline is consistent with the 10.64-hour half-life of $^{212}$Pb. Since $^{212}$Pb is the longest-lived daughter of $^{224}$Ra, it will be the isotope that $^{212}$Po would be in radioactive equilibrium with, a further verification of the system.
Figure 86: Activities of $^{214}\text{Po}$ and $^{218}\text{Po}$ during the room air characterization run. Room air flushing from 0-26.75 and 174-263 hours, sealed from 26.75-174 hours, and circulation pump off from 75-78 and 156-174 hours.

Figure 87: $^{212}\text{Po}$ Activity vs Time. Decay constant ($p_1$) corresponds to 10.78±0.11 hours, near the 10.64 half-life of $^{212}\text{Pb}$.
9.3 Granite Sample #2

Following the room air flush run, we placed a new sample of granite into the chamber. Like the first sample, the second was a showroom sample of a decorative granite. The second sample originates from a different source than the first due to differentiation in color and arrangement of crystals (Figure 88), suggesting a different mineral composition. The source locations of both granite samples are unknown.

The second sample test began with the system sealed with room air. The count rate of $^{218}$Po and $^{214}$Po, in Figures 89 and 90, initially followed an exponential decline due to the decay of the high Rn content of room air. After an abbreviated LN flush of 6 hours, the activity of $^{214}$Po and $^{218}$Po rose to an equilibrium due to the emanation rate of the granite sample. Accordingly, the $^{222}$Rn emanation rate of the granite was determined to be $6.62\pm0.78$ Bq/m$^2$ using the activity rate of $^{214}$Po with background subtracted. The $^{214}$Po activity was once again used since it indeed reached an equilibrium. Additionally, the activity of $^{212}$Po was $31.25\pm0.42$ mBq, which is about a third of the first granite sample but still much higher than the background rate of the system.
**Figure 89:** $^{218}$Po Activity during Emanation Measurement of Granite Sample #2

**Figure 90:** $^{214}$Po Activity during Emanation Measurement of Granite Sample #2
The results of the two granite sample tests demonstrate the capability of the Rn detector system to measure the Rn emanation rate of samples of interest. Combined with efficiency measurements using a calibrated source and efforts to reduce the intrinsic background level of the vessel, we are able to make an accurate measurement of objects within the emanation chamber. Using the granite samples as a proof of concept, we are able to develop a standardized procedure to measure an arbitrary sample.

Figure 91: $^{212}\text{Po}$ Activity during Emanation Measurement of Granite Sample #2
10 Future Work and Recommendations

Future work on this project will include continued emanation measurements of granite samples as well as materials relevant to the construction of the MAJORANA and LEGEND experiments, including a rubber glovebox glove that will be used for assembling $^{76}\text{Ge}$ detector components.

Future work must also include renewed efficiency measurements done with LN boil-off gas and a slight vacuum in the system. Both of these modifications may result in an increased efficiency due to increased likelihood of collecting charged Rn daughters on the photodiode surface. The LN flush may do so by reducing humidity in the system and the vacuum may do so by reducing the density of gas in the system. Renewed efficiency measurements in this configuration will result in better accuracy of Rn emanation measurements. Re-calibration of the RAD7 will result in more accurate efficiency measurements and is recommended if possible.

The matter of high background activity compared to similar experiments is not fully understood and requires further investigation. Besides the stainless-steel vessel itself, potential sources that could contribute to the excess could be the polycarbonate tophat and the Cu photodiode mount. Replacing the acrylic tophat with the polycarbonate one resulted in a decreased $^{212}\text{Po}$ activity, potentially due to debris plated out on the acrylic surface, however it resulted in a slightly higher $^{222}\text{Rn}$ emanation activity. The alloy of the Cu mount is not known and may have higher than desired Th and U content. Additionally, welds and solder joints in the vessel may also contribute to the high Rn emanation.
11 Summary

The goal of this research project was to develop a high-sensitivity radon detector to measure the radon emanation of materials for use in the Majorana Neutrinoless Double Beta Decay Experiment and Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay. These experiments seek to find evidence of a very rare nuclear decay process called neutrinoless double beta decay ($0\nu\beta\beta$). Evidence of this process necessarily implies that the neutrino is its own anti-particle, a type of particle called a Majorana particle. Evidence that the neutrino has a Majorana nature implies violation of lepton number. Observation of $0\nu\beta\beta$ and determination of its lifetime would shed light on the fundamental properties of the neutrino such as mass and mixing angles, the weak nuclear process, and dynamics of the early universe. While one group has claimed to observe this process, the claim has yet to be conclusively verified.

Any experiment that seeks to measure such a rare process requires great care to be taken in understanding and mitigating the amount of background nuclear radiation in the experiment. Very sensitive detectors are required to observe $0\nu\beta\beta$ and any amount of background radiation may result in a diminished sensitivity of the detector to the expected energy signature of $0\nu\beta\beta$. One advantage of the search for $0\nu\beta\beta$ is the energy signature. Single beta decay and two-neutrino double beta decay have a range in the spectra of energies for the outgoing electrons, since neutrinos will have a variable share of the net energy and momentum of the decay. The two electrons of $0\nu\beta\beta$, however, will have a combined energy that is constrained to a single value, the Q-value of the decay.

Efforts to reduce background radiation involve avoiding naturally-occurring and man-made sources of radiation. The surface of the Earth has a relatively high amount of
radiation coming from extraterrestrial sources, as well as from anthropogenic and primordial radioisotopes. Most sensitive nuclear detector experiments are placed deep underground to shield from much of the radiation at the surface. Primordial radioisotopes are persistent underground, however. Radon coming from $^{238}$U and $^{232}$Th specifically provide a persistent source of background radiation, both on the surface of Earth and underground.

Radon is the only daughter in the uranium and thorium decay chains that is gaseous. It is able to escape rock, soil, and other material by flowing, or diffusing, through pores and fissures in the material. Radon is most known as a health hazard in homes and businesses since respiration of radon leads to a source of alpha and beta particles in the lungs, which may cause cancer. Those same alpha and beta particles may also decay near sensitive detectors, producing signatures similar to those being searched for.

This project used a radon detector that consists of a 191L electropolished stainless steel vessel to collect radon-bearing gas and a high electrostatic field to collect charged radon decay products on a Si PIN photodiode. Radon daughters that collect on the photodiode will subsequently decay and, in the case of alpha-decays, produce an alpha particle that may be detected. $^{214}$Po is the primary $^{222}$Rn daughter collected due to an increased likelihood of collection, while $^{212}$Po is the primary daughter of $^{220}$Rn for the same reason. Radon concentration in the gas is determined from the measured $^{214}$Po activity by scaling it by an empirically measured collection efficiency value. The collection efficiency was determined using room air and uranium- and thorium-bearing rock as sources and a Durridge RAD7 commercial radon detector as a calibration.
standard. Using the RAD7, the efficiency was determined as a function of the vessel bias voltage, ranging between 0 kV and 10 kV.

In addition to the efficiency, it is also important to understand the background Rn activity of the detector vessel itself. A lower background enables sensitive measurements of Rn emanation. Background activity tests were performed by observing the fall in activity of room air sealed in the vessel, by using boil-off liquid nitrogen (LN) to purge all room air from the vessel and observing a rise in activity to the background level, and by combining a boil-off LN flush with a moderate vacuum in the vessel. The boil-off LN system used ambient heat transfer from the room to boil the LN as well as two external heating designs, one using an immersion heater designed to boil water, and another using an etched-foil heating element covered with Kapton film.

Higher than expected background activity measurements led us to replace or modify several components of the vessel. Replacements included: solid PTFE O-rings for the original rubber ones; a new, clean SiPIN photodiode replacing an identical model; nylon photodiode mounting screws for brass ones; a tophat made of polycarbonate replacing an acrylic one; and a clean, electropolished stainless-steel inlet pipe for one that was not electropolished. Modified components included re-electropolishing the vessel, cleaning the aluminum vessel lid with an acid solution, and installing two 0.5 μm in-line air filters.

Samples were measured for emanation by placing them in a 2.95L cylindrical emanation chamber connected to the detector vessel by plastic polymer tubing and an 8 L/min circulation pump. Utilization of this detector in the construction and operation of MAJORANA, LEGEND, or any other ultra-low background search, provides valuable quantization of ambient radon backgrounds.
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