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**CHARACTERIZATION OF PARTIAL CHARGE
COLLECTION INDUCED BY NEUTRON DAMAGE IN
HIGH-PURITY GERMANIUM DETECTORS**

by

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B.S. Nuclear Engineering, The Pennsylvania State
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THESIS

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ABSTRACT

This paper investigates the correlation of damage induced by neutron interactions and degradation in the spectra of HPGe detectors. As neutrons kinetically interact with germanium crystals, they create interstitial and vacancy defects within the lattice. These defects then interfere with the charge migration of electron-hole pairs and reduce resolution in the observed energy spectrum. The partial charge collection produces observable spectral changes by increasing the peak width and reducing resolution (full width half maximum). A detailed characterization using various check sources was performed before and after iterations of neutron exposure in order to observe the effects of the neutron damage. An additional set of measurements was performed along with characterizations to show the detector's response at discrete locations on the HPGe crystal. This was done to observe how the spectrum changes when the gamma rays are isolated to regions of various thicknesses of germanium. In order to impart damage, the detector was placed inside a californium shuffler with the face of the detector against the guide tube for the ^{252}Cf source. For irradiation of the HPGe, the source was then

positioned in front of the face of the detector using the stepper motor of the shuffler. The neutron exposure time intervals were recorded and increased based on the initial damage observed. An MCNP simulation was performed to estimate the amount of interactions that occurred in the germanium crystal to ensure enough damage had occurred. Studying the effects that neutron damage imparts on a bullet-type HPGe detector can help provide necessary data to estimate total neutron exposure limits, reduce the likelihood of decisions made on suspect data, and aid in diagnostics of a damaged detector.

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Introduction

HPGe-based gamma-ray spectroscopy systems are the workhorse to gather accurate spectral data for gamma- ray emitting radionuclides and materials. The reliability of HPGe detectors are vital in safeguards applications, the ability to accurately categorize waste, and the determination of isotopics of unknown materials [Reilly]. Since HPGe detectors are susceptible to neutron damage, it is important to understand neutron exposure limits and the mechanisms in which the damage will occur, and how the damage might affect the detector's ability to collect usable spectral data [Knoll]. Recognizing the effects of neutron damage on HPGe spectroscopy is particularly important for those who operate the detectors for high-risk applications. Understanding the effects that neutron damage imparts on a detector can help prevent the propagation of incorrect data and aid in diagnostics of a damaged detector.

This paper will discuss and explore the methodology and data necessary to understand how neutron damage imparted to an HPGe will affect the detector's signal processing ability to accurately interpret the signals that represent the energy of discrete gamma rays. The reduction in accuracy will be observed as a decrease in resolution (larger value of FWHM) through increases of low energy tailing and through an observed peak centroid shifting towards lower channels. These effects most likely occur because of the neutron damage causing incomplete charge collection of the electron-hole pairs created when gamma radiation ionizes the germanium as it passes through the crystal. Both the gamma-ray energy and the effective area of germanium between the diodes effect the detector's response to the damage [Knoll]. A high-energy gamma ray will produce more electron-hole pairs, which increase the amount that can be subjected to a

loss of signal carrying charge because of the neutron damage in the crystal. The effective area between the diodes describes the distance the electron-hole pairs need to travel through the crystal in order to produce a signal for processing. The distance between the anode and cathode in an HPGe detector also correlates to the spectral effects observed in the measured spectrum. When gamma ray passes through a larger portion of germanium, the distance the electron-hole pair needs to travel to produce a signal is increased. The longer the distance between the anode and cathode is for the electron-hole pair, the greater the likelihood that the pair will encounter damage.

The Theory section, Chapter 1, will outline the mechanisms and physics necessary to explain how the HPGe is used to measure gamma rays to produce spectra. Chapter 2, Experimental Setup, will describe the methodology of gathering the necessary data to observe the damage's effects. Data and Observations, Chapter 3, will review the preliminary analysis and present the data in a more malleable form. Results and Discussion, Chapter 4, will relate all the data to how the neutron damage effected the ability of the detector to interrupt the correct energy and how the quantity of damage is proportional to both the energy of the gamma ray and the effective area to which the electron-hole pairs need to migrate. The Conclusion, Chapter 5, will review the results and reinstate the thesis. Chapter 6, Future Work, will outline the next steps to better understand the observations outside of the scope of this paper.

Chapter 1: Gamma-Ray Interactions with High-Purity Germanium

This section presents a summary of pertinent information regarding the physical properties that make HPGe function as a gamma-ray detector. A high purity germanium crystal's properties as a semiconductor and its ability to transmit electrical charge are important to understand in normal operating conditions. Later, this chapter will discuss how the electrical signals are disrupted and how neutron damage creates further interference.

Semiconductor Properties

HPGe is a highly desired material for gamma-ray detection because of its particular semiconductor properties. Semiconductors are ideally suited for gamma-ray detection, which results from their crystalline structure and bandgap characteristics. How these traits differ between a semiconductor, conductor, and insulator began with the basic atom and how the atomic structure conducts charge.

In an atom, electrons are distributed in precisely determined energy levels. Combining atoms to form a solid structure broadens those energy levels into energy bands. The lower band is called the valence band and corresponds to those outer-shell electrons that are to the specific lattice sites within the crystal [Knoll]. The higher band is called the conduction band and represents the electrons that are free to migrate through the crystal. Electrons in the conduction band contribute the conductivity of the material. In a conductor (metal), the valence band is not completely filled with electrons and in effect is continuous with the conduction band [Gilmore]. Therefore electrons can easily migrate throughout the material because they need achieve only small incremental energy to migrate from the valence band to the conduction band [Knoll]. The lack of boundary

between the valence band and conduction band is what gives metals their high electrical conductivity. The presence of an energy boundary does exist in semiconductors and insulators. The boundary creates energy regions that are “forbidden” to electrons known as the bandgap [Gilmore].

In a semiconductor or an insulator, the number of electrons within the crystal is just adequate to fill completely all available sites within the valence band and the conduction band is completely empty. The two bands are separated by a forbidden region known as the bandgap. The size of the bandgap will determine whether the material is a semiconductor or an insulator [Knoll]. For an electron to migrate through a semiconductor/insulator material, it must gain sufficient energy to jump from the valence band across the bandgap into the conduction band [Gilmore]. In the absence of thermal excitation, at 0 K, both insulators and semiconductors would theoretically show no electrical conductivity.

The value of the bandgap is not constant, but changes slightly with temperature. For germanium, the bandgap initially increases linearly as temperature decreases, but at very low temperatures it reaches a constant value [Tsoulfandidis]. Cooling the HPGe reduces the number of electrons in the conduction band, thereby reducing the background current from thermal noise and make it much easier to detect the extra excitation caused by gamma-ray interactions [Gilmore]. As a gamma ray passes through the detector, it will excite the electrons of the germanium and create an electron-hole pairs.

P-N Junction

Further detail is needed when describing the how semiconductors can be used as radiation detectors. In an absolutely pure semiconductor the thermal excitation would

promote an amount of electrons from the valence band and leave behind an equal amount of holes [Gilmore]. Since there are always some amount of impurities present, this equal exchange of electrons and holes is not possible. When impurities are present they dictate the conductivity of the semiconductor and therefore are responsible for a semiconductor's type. When the impurities leave behind holes in the electronic configuration of the lattice, the impurities are referred to as acceptor impurities. When the acceptor impurities are distributed throughout the semiconductor material give rise to extra energy states just above the valence band called acceptor states. Germanium with acceptor states is called p-type germanium: 'p' for positive acceptor impurities [Gilmore].

On the other end, if the impurities inject additional electrons into the electronic configuration, the impurity is considered a donor atom and will introduce donor states just below the conduction band [Gilmore]. Germanium with donor states is called n-type germanium: 'n' for negative donor impurities [Gilmore].

The semiconductor gamma-ray detector depends up the curious electronic redistribution that takes place when the two different types mentioned above are placed in contact with each other [Gilmore]. The p-type germanium has an excess of holes and the n-type has an excess of electrons. As they diffuse together, the holes and electrons migrate together, combine, and mutually annihilate. This creates a region around the physical junction of the two types and the excess charge carriers have cancelled each other out [Gilmore]. This is known as the depletion region.

The depletion region is the active element in an HPGe detector. This region is very thin, but when a positive voltage is connected to the n side of the junction, the width of the depletion region increases as the electrons are withdrawn from the semiconductor.

The negative voltage is applied to the p side and withdraws holes. Because the positive voltage is connected to the negative type semiconductors, this is called a reverse bias [Gilmore]. In HPGe crystals, this is achieved by doping a small layer of the germanium so that it becomes the opposite type of the original crystal. When the high voltage is applied for operation, the depletion region grows to occupy the entire crystal, birthing the active detector region.

Electrons and Holes

When radiation interacts in a semiconductor, the energy deposition always leads to the creation of equal numbers of holes and electrons [Knoll]. Interactions of gamma rays and detectors occur in three different processes: photoelectric, Compton scattering, and pair production. In the photoelectric absorption, the gamma ray loses all of its energy in a single interaction with the germanium. In Compton scattering, the gamma ray loses only part of its energy in one interaction [Reilly]. Lastly, a gamma ray with an energy of at least 1.022 MeV can create an electron-positron pair [Reilly]. As a gamma ray passes through HPGe, each of these interactions contribute to the cascading shower of electron-hole pairs.

The interaction of a gamma ray with the semiconductor material will produce primary electrons with energies considerably greater than thermal energies, though it is possible for electrons to gain sufficient thermal energy to be elevated from energy bands below the valence band and into the conduction band [Knoll]. Physically, this process simply represents the excitation of an electron that is normally part of the covalent bond such that it can leave the specific bonding site and drift throughout the crystal [Knoll]. The excitation process not only moves the electron to the conduction band but also leaves

a vacancy called a hole in the valence band. The combination of the two is called an electron-hole pair [Knoll].

After their formation, both the electron and the hole take part in random thermal diffusion away from their point of origin [Knoll]. In times of the order of 10^{-12} seconds (1 ps), the electrons that populate higher states in the conduction band deexcite towards the bottom of the conduction band. In the same way, the holes concentrate near the top of covalent band. Because of this multistep process, the average energy necessary for the creation of one electron-hole pair is much larger than the bandgap [Tsoulfandidis]. In the absence of an applied electric field, the thermally created electron-hole pairs ultimately recombine. An equilibrium is established in which the concentration of electron-hole pairs observed at any given time is proportional to the rate of formation and saturating due to the rate of destruction through electron-hole recombination. The number of electron-hole pairs produced will be related directly to the gamma-ray energy absorbed [Gilmore]. The important factor is being able to measure the electron-hole formation, which depends on electric field, charge mobility, and carrier lifetime.

Charge Mobility

In an HPGe detector, an electric field is applied to induce the mobility of the electrons and holes. Both the electrons and holes will undergo a net migration. The electron in the conduction band will move towards the anode in the opposite direction of the electric field vector. In the valence band, electrons will begin to move to the highest energy band to fill the hole left by the electron [Luke]. The continuous filling of the vacancies is what propagates the hole, net positive, towards the cathode in the same

direction of the electric field vector [Knoll]. This can be seen in the following figure [Gilmore]:

Figure 1: Electron-hole migration

All the types of the charge carriers present in a medium contribute to the conductivity. In the case of semiconductors, both electrons and holes should be taken into account when the conductivity is calculated; the conductivity changes if the mobility of the carriers or their concentration, or both, change [Tsoulfandidis].

In a perfect crystalline structure, the electron-hole pairs would migrate without interruption from their place of origin within the HPGe crystal directly to the electrodes. The charge motion induces signals on the electrodes and the detector is then be able to relate the amount of electron-holes to a single energy count. Imperfections in the crystalline structure would inhibit either the electron or the hole, or possibly both, to not be accounted for during the migration/signal processing. These imperfections are known as traps and can arise from a variety of issues within the crystal.

Trapping of Charge Carriers

In a detector crystal there is likely to be a small population of traps. These might be a consequence of crystal imperfections, interstitial impurities, or radiation damage. If a charge carrier migrates to one of these traps, it may be held until thermal excitation releases it again [Knoll]. If the trapping time is on the order of the charge collection time, charges will be lost and incomplete charge migration will occur [Leo]. The mean lifetime that the charge carriers live without being trapped is as important as the mobility for the

induced charge on the electrodes. Structural defects in the lattice will contribute to the number of trapping sites within the crystal [Leo]. Any loss of the charge motion will reduce the signal the detector can observe for a single event. Loss of pair migration will result in the detector system recording a smaller pulse and therefore a lower energy than what actually occurred. As more low-energy events are recorded in the histogram, the observed peak will broaden on the low-energy spectrum and therefore decrease the resolution. Interestingly, when there is a substantial amount of charge migration loss, the entire histogram of the peak observed will shift to lower energy. Since the detector being used in this experimentation has an established baseline for resolution, any loss in the resolution or centroidal shifts towards a lower energy are a direct result of the imperfections created by radiation damage.

Charge Induction Efficiency

The motion of the charges in the electric field is what induces the pulses on the electrodes that are read out. For a perfect detector, this charge induced equals the charge that is liberated within the detector material, so the charge induction efficiency (CIE) = 1. In a real detector, slower motion of the charges and trapping leading to decreased lifetime reduces the CIE. This can be related to the product of the carrier mobility (μ) and lifetime (τ), $\mu\tau$. As both electrons and holes may be moving, the CIE is a function of both electron $(\mu\tau)_e$ and hole $(\mu\tau)_h$. Charge induction efficiency (η) is then expressed as:

$$\eta(x) = \frac{(\mu\tau)_e E}{D} \left[1 - \exp\left(-\frac{D-x}{(\mu\tau)_e E}\right) \right] + \frac{(\mu\tau)_h E}{D} \left[1 - \exp\left(-\frac{x}{(\mu\tau)_h E}\right) \right] \quad [1]$$

Where D is the detector thickness, E is the electric field intensity, and x is the distance from the cathode of the radiation interaction and ionization. The relationship described in Equation 1 is called Hecht's relation and describes the behavior of charge transport as a

function of distance the holes need to travel to the cathode [Hecht] If there are any imperfections the CIE will be non-uniform and the detector's resolution will be compromised.

Radiation Damage

Gamma radiation liberates electrons but does not cause atomic displacements. Irradiation of germanium detectors by neutrons, particularly fast neutrons, can give rise to the displacement of atoms from their lattice, leaving a vacancy in the now-empty lattice position. That atom displaced to a different location, forming an interstitial vacancy pair called a Frenkel defect. These defects are particularly effective traps; if germanium detectors are in a neutron field for any length of time the spectrum will deteriorate because of the increasing proportion of these defects [Gilmore].

The neutron-induced damage can be classified into two categories: bulk and surface effects. The most fundamental type of bulk-radiation damage is the Frenkel defect, produced by the displacement of an atom in a semiconductor material from its normal lattice site. The vacancy left behind, together with the original atom now at an interstitial position, constitutes a trapping site for charge carriers. These defect sites are sometimes called point defects to distinguish them from more complex "clusters" of crystalline damage that are formed along the track of a primary "knock-on" neutron-atom interaction if sufficient energy is transferred [Knoll].

The severity of damage to be anticipated is a strong function of the neutron radiation involved. When enough of the defects have been formed, carrier lifetime and charge collection efficiency are reduced and the energy resolution of the detector is degraded because of fluctuations in charge lost [Knoll]. Semiconductor detectors are

relatively sensitive to performance degradation caused by damage created within the detector by incident neutron radiation. The large-volume and long-charge collection paths in co-axial HPGe detectors make them more susceptible to such degradation than the much thinner silicon diode detectors typically applied to gamma-ray detection [Knoll]. The principal consequence of neutron damage is an increased amount of hole trapping within the active volume of the detector. In a damaged detector, the amount of charge collected is subject to a loss caused by this trapping. The trapping will cause a smaller pulse which will be observed as tailing or complete peak shifting toward the low energy side [Knoll]. See Appendix 7 for a visual representation of the induced pulse and how the MCA operates under both normal and damaged conditions.

Dependence on Detector Geometry and Configuration

The detector geometry selected for this experimentation was closed coaxial [Ortec]. This simply means that the HPGe crystal is cylindrical in shape with a hole bored out 20 mm from the bottom of the central axis. This is done to allow the cathode to be inserted into the crystal. See Figure 2 below for more detail on bullet-type crystals.

Figure 2: Diagram depicting internal well of a bullet-coaxial HPGe crystal

In coaxial detectors, the specific detector configuration can have a strong influence on the measured spectral effects. In HPGe coaxials fabricated from high-purity p-type germanium, holes are the carrier type that are drawn inwards to the p⁺ contact,

because of the reverse bias, near the cylindrical axis. For HPGe coaxials made from high-purity n-type germanium, the electrode polarity is reversed; holes are instead collected at the p⁺ contact fabricated on the outer cylindrical surface. These n-type HPGe detectors show much less performance degradation from radiation damage when compared with the more common p-type detectors. In one study of similar coaxial detectors of both types, the n-type detector was able to withstand 28 times the neutron fluence before showing the same peak broadening as that observed from the p-type configurations [Knoll]. The explanation for this difference lies in the fact that the damage sites preferentially trap holes rather than electrons.

Because of the cylindrical geometry and attenuation of the incident gamma rays, more interactions occur at large values of the detector radius than at small values. For such locations, the rise of the signal pulse is dominated by the species that drifts inward toward the detector center. If these are holes, the corresponding pulse is much more likely to be affected by hole trapping than if the holes must only travel the shorter distance to the outer electrode [Knoll]. This effect can also be seen if the incident gamma ray interacts at varying locations within the active volume of the detector. If the electron hole pair is created near the edge of a p-type detector, it will be more affected by the hole trapping when compared to an interaction closer to the center well. As a result of their superior performance in the presence of damage, n-type HPGe coaxial detectors have become the configuration of choice for applications in which exposure to fast neutrons may occur over time [Knoll].

Since a p-type detector will have 7000 μm n⁺ layer on the outer surface, it cannot be used for gamma-ray energies less than 40 keV [Gilmore]. These low energy effects

can be avoided with the use of an n-type detector since the outer layer requires less attenuating material [Gilmore]. Most applications do not call for much detection under the 100 keV limit and therefore the increased cost and difficulty in manufacturing of n-type detectors is not necessary for standard HPGe applications.

Resolution of a Gamma Spectrum

Resolution within an energy spectrum is described as the width of the energy peaks. Width is measured by the full width at half maximum (FWHM), which is defined as the width of the distribution at a level that is just half of the maximum ordinate of the peak. The terminology for “high resolution” refers to a small FWHM and “low resolution” refers to a large FWHM. This definition assumes that any background or continuum on which the peak may be superimposed is negligible or has been subtracted away. It should be clear that the smaller the FWHM for the energy resolution, the better the detector will be able to distinguish between two energies that are near each other [Knoll]. For examining a tail on a distribution, which occurs with neutron damage, it is common to observe another quantity, the full width tenth maximum (FWTM). In the current work, the damage is extreme enough that the FWHM changes drastically so the FWTM is not needed. Figure 3 below shows the 662-keV peak before and after irradiation. The figure is in linear scale to show the difficulty of analyzing a FWTM.

Figure 3: Details of the 662-keV peak before (black) and after (blue) neutron damage.

This study is focused on the change in resolution as a function of neutron damage imparted on the detector. Resolution was chosen because it is an observable spectral characteristic that can be related to the amount of damage. Using the FWHM and typical data acquisition techniques also reduces the amount of specialized equipment needed to observe the effects of the damage and relates the damage to typical operations of HPGe detectors.

The FWHM resolution, R , of an energy spectrum can be described through the physical terms involved. For a single energy, E , it can be expected that the average amount of generated pair events can be described as N [Leo]. For a Gaussian peak shape the FWHM is 2.35 times the standard deviation [Leo] The energy dependence of the resolution can then be seen to be:

$$R = \frac{2.35}{\sqrt{N}} \quad [2]$$

This expression shows how the resolution will change if the number of ionization events changes at a given energy. The Fano Factor is used to describe the departure of statistical fluctuations in the number of charge carriers and is defined by [Knoll]:

$$F = \frac{\sigma^2}{N} \quad [3]$$

This can then be expressed in terms of resolution by:

$$R = 2.35 \sqrt{\frac{F}{N}} \quad [4]$$

Furthermore, the resolution of a given energy peak will affect the minimum detectable activity (MDA); this relationship is shown by:

$$MDA(E) \propto \frac{\sqrt{R(E)B(E)}}{\varepsilon(E)} \quad [5]$$

Here $R(E)$ is the resolution of the detector as a function of energy; $B(E)$ is the background counts per keV as a function of energy, and $\varepsilon(E)$ is the absolute efficiency of the detector as a function of energy [Ortec]. The relationship between the MDA and the resolution shows how the resolution can impact the detector's ability to detect and identify low intensity gamma rays or work in a high-noise environment.

Chapter 2: Experimental Setup

To make measurements of resolution decrease as a function of neutron dose, a well characterized HPGe detector was placed inside of ^{252}Cf Shuffler and exposed to the neutron source. The detector was then used for a series of measurements after each interval of neutron exposure. The following chapter gives details about this process.

Shuffler Setup

A californium shuffler is an instrument that measures delayed neutrons induced by fission in order to quantify the amount of uranium [Rinard]. This is done by introducing a ^{252}Cf source in the measurement chamber that is attached to a teleflex cable so that it can shuffle up and down the height of the item. For this experiment, the shuffler was placed into a maintenance mode to move the source to a set height for the duration of the detector exposure [Rinard]. Since the shuffler's source manipulation only takes commands in steps of the stepper motor, the correct number of steps needed to be calculated and confirmed. A ^3He tube with a digitizer was placed in the shuffler against the guide tube relative to where the detector would be later placed; see Figure 4. The source was then moved to different positions by inputting various step values until the ^3He detector counts per second reached a maximum, indicating that the source was in the proper position for irradiation of the HPGe detector.

Figure 4: Image of the californium shuffler (left); Image of the detector orientation inside of the californium shuffler (center); Cut away diagram of the internals of the californium shuffler (right).

Data Acquisition and Processing

All HPGe data was taken with the same equipment and configuration. This was done to ensure consistency and to ensure that all changes were because of the damage done to the detector and not systematic variations. The HPGe detector was a Canberra GC2518, which has a built-in cryostat-cooler. The detector was connected to an Ortec DSPEC Pro (multichannel analyzer) through an Ortec Detector Interface Module. The multichannel analyzer internally stored the settings for the pulse shaping and gain settings. These settings were kept constant throughout the measurements and were not modified after each irradiation so as to optimize resolution and to not interject other systematic uncertainties that would be difficult to quantify. The MCA memory made the consistency between measurements much easier. The MCA was connected to a laptop and Ortec's Maestro (version 7.01) was used to record the spectra [Ortec]. Once collected, all spectra were processed through PeakEasy (version 4.86). PeakEasy has capabilities for data processing beyond that of Maestro [Rooney]. First, PeakEasy allows for batch processing in order to extract pertinent data from multiple spectrum files.

PeakEasy also performs a Gaussian fit when regions of interest are established. By performing an actual curve fit, more accurate data can be extracted for the FWHM compared to the simple processing done by Maestro. Although PeakEasy does allow for the batch processing, the peak data extracted from spectra in this thesis were all done individually. A full list of models and serial numbers of the equipment used can be found in Appendix 6.

Initial HPGe Characterization Setup

First, the detector was characterized using an array of different gamma-ray sources to establish a baseline prior to any neutron exposure and damage. In general, characterization is performed to understand how an individual detector responds to various energies of gamma radiation as to generate an intrinsic efficiency curve and FWHM baseline. Five sources and six peaks were used to establish a wide range of energy response, seen in Table 1. Identifications and activities of these sources can be found in Appendix 5.

Table 1: List of Nuclides

Isotope	Centroid [keV]
Cd-109	87.78
Ba-133	383.67
Cs-137	661.52
Mn-54	834.79
Co-60	1173.32
Co-60	1332.66

Another motivation for characterizing the detector is to understand how efficient the detector is at various energies. Efficiency is described as the amount of counts a detector is able to record in the full energy peak versus the amount of radiation coming from a known source activity (total counts recorded/total counts emitted). At both low

(<200 keV) and high (>600 keV) energies, an HPGe detector is less efficient than at 200-300 keV. This is because at lower energies the gamma rays get absorbed before they are able to reach the detector by either the detector's housing or even the detector in its outside dead layer. At higher energies the gamma rays have enough energy to pass through the detector without interacting.

Two similar but separate classes of efficiency are used to describe a detector's response: absolute and intrinsic. Absolute efficiencies are defined as number of pulses recorded over the number of radiation quanta emitted by the source. They are dependent not only on the detector properties but also on the details of the counting geometry (primarily the distance from the source to the detector). The intrinsic efficiency is defined as the number of pulses recorded over the number of radiation quanta incident on the detector.

$$Intrinsic = \frac{(Net\ Counts/Livetime)4\pi}{Activity_{Adj}.\Omega} \quad [6]$$

$Activity_{Adj.}$ accounts for the branching ratio (B_r) of the gamma ray and the transmission factor (T_f) quoted from the source manufacturer and Ω is the solid angle detector seen from the actual source position:

$$Activity_{Adj.} = N_0 e^{-\lambda t} B_r T_f \quad [7]$$

Absolute efficiency no longer includes the solid angle subtended by the detector as an implicit factor [Knoll]. The two efficiencies are simply related for isotropic sources by:

$$Absolute = Intrinsic \left(\frac{\Omega}{4\pi} \right) \quad [8]$$

Since the geometry of the characterization measurements will remain constant for all the measurements in this experimentation, only intrinsic efficiency will be considered. The intrinsic efficiency for the detector used can be seen in Figure 5.

Figure 5: Detector efficiency before neutron damage.

The characterization measurements were taken with the source 25 cm from the face of the detector. To ensure accuracy with the repeated measurements, a source holder was designed and 3D printed to fit around the detector and position the source at the correct distance, as seen in Figure 6. The detector was placed upright and the source placed on top of the holder. The measurements were taken for as long as necessary to reach 10,000 counts within the peak of interest. This is done to reach a 1% statistical uncertainty.

Figure 6: 25-cm source holder used for characterization measurements.

Neutron Exposure

A p-type HPGe detector would start to show significant damage at a neutron fluence of 10^{10} n/cm² [Knoll]. Other studies have shown a 30% loss of resolution at 6×10^8 n/cm² incident on a detector [Leleux]. The ²⁵²Cf source emits neutrons at a rate of 8×10^7 neutrons per second into 4π . The calculated exposure time to achieve that fluence of neutron emission on the 30.19 cm² face of the detector at 1 cm was approximately 12,000 seconds. For a better approximation of the neutron fluence onto the detector, an MCNP input deck was written. This was done to assure that the detector would not undergo an excessive amount of neutron damage and to better understand the neutron interactions since the shuffler is designed to reflect neutrons.

During the first 3000 seconds of neutron exposure, the detector was placed into the shuffler, the source was moved to the face of the detector for 500 seconds, and the detector was removed from the shuffler in order to perform a source check. The exposure

time for the experiment was short enough that the detector was disconnected and the cooler was not running. Another facility concern was that the heat generated from the mechanical cooler might interfere or create a fire hazard. The source check used ^{226}Ra and ^{137}Cs to observe the effects of the damage at different energies. The source check showed that the damage was happening very slowly and that the time interval should be increased. The checks also showed resolution inconsistencies and indicated that the resolution improved after some exposures which drastically defies the theory behind HPGe neutron exposure. Source checks were performed after each neutron exposure and before the first exposure of each day to establish a baseline.

The time interval was increased to 1,000 seconds until the total exposure reached 10,000 seconds. A wiring port on the shuffler was utilized in order to keep the detector cold during the longer exposure intervals. Attention was given to the temperature of the shuffler chamber to determine whether a longer interval could be used. After each exposure the detector was removed and source checked with the same ^{226}Ra and ^{137}Cs sources and distance. It was concluded that the heat would not be an issue and the final time interval was increased to 2,000 seconds to bring the total exposure to 12,000 seconds. The same inconsistencies in resolution improvement arose during the longer time intervals and needed to be investigated. Buffer time was allowed after each neutron exposure before measurements to allow the activated aluminum to decay away so that the gamma rays emitted would not interfere with measurements. This later became a concern with longer neutron fluence and activation, that the buffer time was increased to 48 hours.

As mentioned above, when conducting the source checks with ^{226}Ra and ^{137}Cs , the FWHM and centroids of the 351-keV and 662-keV peaks were being observed as a

measure of resolution. The resolution followed a pattern of degradation throughout the intervals of exposure, which was consistent with the theory. But then the resolution seemed to have recovered between days of experimentation. This was originally thought to be the detector “self-healing” or “self-annealing,” but this was not convincing because the detector was being kept at its operating temperature of -190° Celsius. Upon further investigation, it was found that the inconsistencies aligned with the high-voltage bias. When the detector was being positioned and left unattended, the high voltage was set to zero. Once it was reapplied, the resolution showed an improvement to the previous measurement. This was most commonly observed when measurements were performed on different days. This led to separate experimentation to further investigate the high voltage bias and worsening resolution.

High Voltage Biasing Resolution Degradation

Once the 12,000 second irradiation was completed, the detector was set up so that a ^{133}Ba source was six inches from the face of the detector. A .JOB file was then created in Ortec’s Maestro so that the detector would collect a spectrum for 30 minutes live time, stop the data collection, save the spectrum, and then repeat the process. It was found that once the high voltage was applied, the resolution would start to degrade until it reached an equilibrium and would then stabilize. To further test this phenomenon, the source was moved directly in front of the detector (zero inches) and then further away at six inches. When the source was closer the equilibrium point was reached faster, but when it was further away the equilibrium was reached more slowly. This showed that the equilibrium point was dependent on the count rate seen by the detector, suggesting time to equilibrium was dependent on the amount of charge migration. Others have found a

similar occurrence when AlGaN semi-conductors have known dislocations/damage in the lattice [Khalil]. The theory is that as the traps, created by the dislocations, fill, they create a disturbance in the electric field; once they are filled, the resolution will reach equilibrium. Once at its equilibrium, the detector's resolution would remain stable as long as the high voltage was continuously applied; refer to Figure 7. Further investigation also showed that it only took a few minutes of the high voltage being disabled for the resolution to return to its better original value.

Figure 7: Resolution degradation at the 608-keV energy peak as a function of time length of the high-voltage bias.

This phenomenon had a few separate outcomes. First, all of the data taken as source checks between the first 12,000 seconds of neutron damage is suspect because any changes in the resolution could have been because of the detector not being at an equilibrium as described above. In order for the remaining measurements to be consistent, the detector must be at equilibrium. To ensure this, before the calibration measurements, all of the sources being used were placed directly in front of the detector for one minute. The combined count rate was sufficient for the detector to reach its

equilibrium point. This will be investigated further and findings will be documented in a future publication.

HPGe Characterization

Once the data was analyzed from the first 12,000 seconds of neutron exposure, it was evident that the spectra's resolution had begun to degrade. According to Ortec's website, a detector may not begin to show any signs of damage or its full extent of the damage until it is thermal cycled. Therefore the detector was brought to room temperature and then cooled down back to operating temperature. When the characterization was performed after the thermal cycle, the FWHM increased further. The increase in FWHM (decrease in resolution) indicated that characterization measurements would be needed before and after the thermal cycles to evaluate the damage. It was also evident that crucial data was potentially lost during the first exposure since the measurements before and after thermal cycling were drastically different.

The first 12,000 seconds of neutron exposure uncovered some initial flaws in the experimental setup. First, the amount of time per exposure could be increased with the ability to power the detector's cooler. Second, the detector needs to be in a state of equilibrium to ensure the validity of the characterization measurements. Last, thermal cycling the detector reveals the true extent of the damage done to the HPGe crystal. The last two neutron exposures were performed with a duration of 6,000 seconds each. While the detector was undergoing the last two neutron exposures, it was continuously kept cool because of the effects the temperature can have on neutron damage seen in other studies [Seabury]. This was done to double the amount of damage and to have an intermediate

data point. It was also done to ensure that a damage did not reach a saturation point before the full 24,000 seconds of neutron exposure.

HPGe Survey of Discrete Crystal Locations

Knowing that the neutron damage would create dislocations in HPGe lattice, it was of interest to investigate if the damage would be worse based on the location in the crystal. The motivation was to observe if the amount of damage was dependent on the distance the electron-hole pair must travel to be recorded. The theory presumes that the greater the distance of electron-hole migration, the greater likelihood that some events would be lost due to damage. Damage has a greater effect on the holes than the electrons [Knoll]. Therefore the further the interaction of an incident gamma ray is away from the negative diode, the greater the full peak resolution will be affected.

Figure 8: 2-mm hole bored into the lead brick used for detector sweeping.

To observe the changes in charge migration as a function of diode distance, an additional series of experiments was performed. A 2-mm hole was bored into a lead brick (2" x 4" x 8") in order to collimate the gamma rays emitting from a ^{57}Co source; see

Figure 8 for more detail. The check source was carefully placed over the hole and then the opposite side of the brick was placed against the detector. The brick was then placed onto a lab jack and moved in 2-mm increments. The first two series of sweeping moved along the full length of each axis. One “sweep” was performed across the face of the detector (left to right) and another was performed on the side of the detector (tip to base). See Table 2 for detector orientation and notation. Tape was placed on the center lines of the two paths to ensure accuracy and repeatability. The sides of the detector were also labeled so the orientation could be noted and repeated:

Table 2: Detector Orientation and Notation

Side of the Detector in reference to it upright and facing the observer	Notation
Left	A
Right	B
Top	C

The first two sweeps (baseline and after 12,000 seconds of neutron damage, before the thermal cycle) were performed along the entirety of their respective axis until no counts could be recorded. See Figure 9 for detector orientation and direction of sweeping. These methods and results were quite similar to another study that sought to explore the actual active volume of an n-type HPGe detector in order to model it better in MCNP [Berndt] by applying their experimental methods, this study was able to observe different outcome entirely. Once the full series of sweeping measurements was complete, three points of interest for each axis were identified and measured when the characterizations were performed. See Figure 9 below for more detail about the sweeping directions and notation.

Figure 9: Radiography of the detector used in the experimentation. The red arrow depicts the direction of the face sweeping (Side A to Side B) and the blue arrow depicts the direction of the side sweeping (Front to Rear).

The points of interest across the face – see Figure 9 – were at 22 mm, 38 mm, and 54 mm from Side A of the detector. Since the casing surrounding the detector is 75 mm in diameter, the 38-mm measurement point was of interest because it represents the center of the HPGe crystal where the diode is located and therefore the thinnest point on the detector's face. The 22-mm and 54-mm measurement points were chosen as the mid-points to the radial dimensions and represent the thickest region of the detector without interferences caused by edge effects or the dead layer.

Figure 10: Sweeping of the detector face before (blue) and after (orange) neutron damage. The detector was surveyed from Side A to Side B. All measurements taken were with the ^{57}Co and within 1% counting error and therefore error bars are too small to be depicted. The dip in the middle is attributed to the co-axial geometry.

The points of interest across the Side A axis were at 16 mm, 26 mm, and 36 mm from the face of the detector, see Figure 11. Since the gap between the crystal and the case surrounding the detector is 4.88 mm, the 16 mm measurement represents the top third of the HPGe crystal. This is the thickest part of the crystal along the A axis. The 26 mm measurement point was of interest because it represents the center of the HPGe crystal where the diode is located and therefore the thinnest point on the detector's side. Additionally, there is a thicker aluminum band wrapped around the HPGe crystal casing that provides structural support for the set screws. This band causes an interference by attenuating the gamma rays. It is located between 20 mm and 24 mm from the face of the detector and therefore it was necessary to avoid. The 36 mm measurement point was of interest because it represents furthest third of detector and it is also along the diode.

Figure 11: Sweeping of the detector from front to rear before (blue) and after (orange) neutron damage. All measurements taken were with the ^{57}Co and were within 1% counting error and therefore error bars are too small to be depicted. The dip in the middle is because of the thick band of the aluminum casing.

Another study had shown similar dips in counting efficiency when a heavily collimated ^{241}Am was swept along the side of a detector [Haj-Heidari]. The dips seen in that study were much more pronounced since they used the 59.5-keV-peak from ^{241}Am which is more attenuated than the ^{57}Co source used in this study. The dipping is because of the varying thickness in the aluminum casing of the detector; see Figure 11. The varying counts per second in this region shows a dependency on the location of the gamma rays when characterizing a detector.

Chapter 3: Data and Observations

When discussing the resolution of an HPGe detector, the first metric to describe goodness is the full width half max (FWHM) observed within the spectrum. This is because the FWHM is a reliable expression for mostly Gaussian-like shapes. The FWHM metric begins to lose some of its credibility as the damage increases and the resolution degrades. The resolution begins to degrade as the number of dislocations in the germanium-crystal structure increase the time delay for the electron hole pair is increased causing an observed low energy tail. With the slower charge motion, some of the induced charge is not within the amplifier's time window for the pulse, resulting in lower pulse heights for those effected pulses. As this tail increase with the amount of damage done, the peak also becomes short as the counts are getting re-distributed to the lower energy region as seen in Figure 12. Appendix 2 contains the spectra for the remaining isotopes.

Figure 12: 662-keV peak before (black) and after (blue) neutron damage

The growing tail may also begin to distribute counts into a peak that is near the one being observed, causing an overlap of peaks in the spectrum. Each alteration drives the peak's shape further away from a Gaussian-like shape. The more skew the shape

becomes, the more difficult it is to analyze. FWHM is also dependent on the peak's energy. The higher the peak's energy the larger the FWHM will be. The relationship between FWHM and energy can be described by the following:

$$FWHM = a + b\sqrt{E} + cE^2 \quad [9]$$

FWHM is being expressed in energy (keV) and E is the energy (keV) in the spectrum.

The variables a, b, and c can be found by fitting this expression onto an Energy vs.

FWHM plot. The variables will be unique to a specific detector/ multichannel analyzer combination and should remain somewhat constant assuming the detector is not damaged and they system remains unchanged.

Figure 13: Full-width half maximum as a function of energy. The 0 depicts the baseline before neutron damage and the subsequent series are the 12,000, 18,000, and 24,000 seconds of neutron damage.

Figure 13 depicts the change in the FWHM based on the energy of the peak. There is also a slight shifting in the centroids, but because of the scale of the axis it is minuscule. The relationship between FWHM and energy, as seen in Figure 13, is more evident once the constants of the FWHM function are found, particularly the b and c parameters, for each spectrum of neutron exposure. By plotting the parameters, the changes per exposure are more evident seen in Figures 14 and 15.

Figure 14: The values of the b constant from Equation 9 as a function of neutron exposure (seconds).

Figure 15: The values of the c constant from Equation 9 as a function of neutron exposure (seconds).

These constants also help to indicate that the damage done to the germanium crystal is nearing a maximum and saturation. This flattening is shown through the constants changing less and the amount of fluence continues to be increased.

FWHM as a Function of Centroid Energy

Further observation of the above equation (Equation 9), reveals that there is another metric to be noted. At higher energies the FWHM change is more drastic as damage occurs. This trend is because of the relationship of FWHM and Energy but the higher the energies more electron-hole events are occurring, which allows more opportunities for charge mobility losses. The above figures also show a trend in which the incremental neutron exposure is affecting the FWHM less than the previous exposures. The deceleration of resolution loss shows how the damage is reaching a maximum. The full-energy spectrum comparisons of the baseline vs neutron exposures can be found in Appendix 4.

Thermal Cycling Effects for FWHM

The resolution changes that were observed before and after the thermal cycling also provide insight as to how much damage is occurring. It is known that thermal cycling a detector once damage has occurred will further degrade the resolution of the spectrum. Observing the magnitude of that intermediate degradation is of interest. Looking specifically at the 87-keV peak emitted from ^{109}Cd , not only does the FWHM begin to reach a maximum/saturation point with more neutron exposure, but the change in FWHM between thermal cycling lessens. The difference in the FWHM between thermal cycling is lessened until it is nominally zero indicates that the additional neutron flux through the detector is having less of an impact on the resolution since the thermal

cycling should be exaggerating the damage, see Figure 16. More graphs showing the exposure vs. resolution before and after thermal cycling of the remaining isotopes can be found in Appendix 2 and 3.

Figure 16: The changes in the ^{109}Cd 87-keV peak before (blue) and after (orange) thermal cycling. .

The effects of thermal cycling at the initial exposure interval have quite a large effect on the resolution. The magnitude of the effects of the thermal after the second exposure, 18,000 seconds, show that the equilibrium is being reached. The final exposure and thermal cycle show that the detector is reaching a maximum damage level.

Centroid Shift and FWHM of Sweeping Measurements

Observations were made of the sweeping measurements that were taken at the same time and thermal cycle intervals as the characterization measurements. The data from the heavily collimated gamma ray source measurements provide a different perspective on the effects of the damage imparted on the HPGe crystal. By collimating the emitted gamma rays to a small region and aiming it at distinct locations on the crystal, insight was given as to how the detector responds to radiation in certain areas. Since the

detector is not uniform in terms of the distance between the anode and cathode in the regions, any differences in the centroid shift or resolution will be magnified by neutron damage, as seen in Figure 17.

Figure 17: The 38-mm peak (black) compared to the 22-mm peak (blue). The 38-mm peak depicts the center of the detector directly in front of the diode well. The 22-mm peak depicts the thicker portion of the germanium crystal.

The full peak energy shift is because the damage will increase the amount of trapping of the electron-hole pairs; the difference can be seen by changing the distance they need to travel. The distance difference is seen in the centroid shift because the longer the incident electron-hole pair takes to travel induces a smaller pulse within the amplifier time window and is seen as a lower energy in the spectrum. Even before any intentional neutron damage, there is a slight but evident shift in the centroid between 22 mm/54 mm (sides) and 38 mm (center) on the face of the detector as shown in Figure 18.

Figure 18: Face sweeping of the detector depicts how the 122-keV centroid shifts to a lower energy as a function of location in the germanium crystal.

A similar effect can be seen when observing the centroid changes when the source is moved along the Side A axis. When the source only 18 mm from the face of the detector, the electron-hole pair had a slightly longer distance to travel, which the detector perceived as a lower energy. The two measurement points of 26 mm and 36 mm had mixed results. At first they were identical, which is expected since they should have the same distance between their anode and cathode. But as more damage was done to the HPGe Crystal, the 36mm centroid began to drift into a lower energy, seen in Figure 19. This result can either mean that the neutrons were having a penetrative effect and depositing their energy deeper in the crystal or, more simply, the cathode does not extend the full length of the well in the crystal. If the cathode is indeed smaller than assumed, it could be calculated from this data.

Figure 19: Side sweeping of the detector depicts how the 122-keV centroid shifts to a lower energy as a function of location in the germanium crystal.

Chapter 4: Results and Discussion

This section will discuss the analysis and results of the data collected. Each subsection will to explain how the trends seen in the data collected can be reduced and normalized. The FWHM increase as a function of energy normalizes and shows the damage does not affect higher energies more than lower energies but rather the factor of the change is the same. The discrete locations of the of ^{133}Ba source also show a similar effect. The damage is mostly uniformly distributed and the effects observed of low energy centroid shifting is actually because of the distance the electron-holes need to travel.

FWHM Changes as a Function of Energy

As seen from the changes in the FWHM vs. energy plots, it is evident that the relationship between energy and resolution (FWHM) changes is disproportional across the energy spectrum once damage has occurred. This disproportionalitiy was shown though the changing b and c parameters from the FWHM dependency on energy as a function. The functions show that the apparent worsening of the spectrum at higher energies. However, when observing the change in the FWHM from the baseline measurement as a function of the peak's centroid (energy), the bias no longer exists. This function is calculated using equation and the amended data appears in Figure 20

$$\frac{FWHM_{Damage}-FWHM_0}{E_{Centriod_0}} \quad [10]$$

The alternation to the FWHM data works because the change in the FWHM is proportional to the number of electron hole pairs that were lost because of the neutron damage. The change in the FWHM then accounts for all the lost electron hole pairs because the response of the detector moves events into lower energy bins.

Figure 20: Changes in FWHM normalized for centroid energy. Each series depicts the amount of neutron exposure in seconds and the results after the thermal cycle. Error bars are one standard deviation.

When this expression is graphed, as in Figure 20, this ratio is not energy dependent and that the spectrum endured, in fact, an equal change per energy. The average of these values for a given neutron fluence would represent the amount of damage done to the detector shown in Table 3.

Table 3: Average change in FWHM/Centroid

Neutron Exposure in Seconds	Average Change in $\Delta\text{FWHM/Centroid}$
12000	0.020
18000	0.023
24000	0.025

Figure 21: Changes in FWHM normalized for centroid of the original recorded energy. Each series depicts the amount of neutron exposure in seconds and the result both before and after the thermal cycle. Error bars are one standard deviation.

When the data is displayed as the change in FWHM as a function of centroid, as in Figure 21, it confirms the previous observations that the damage was reaching a maximum. With the change becoming less with each iteration of damage and subsequent thermal cycle, the damage is having less effect and reaching a maximum.

Centroid Shifts as a Function of Electron-Hole distance

The approach used when determining the amount of damage imparted on the HPGe crystal cannot be applied when observing the centroid shift in the discrete locations used in the sweeping experimentation. The peak does not necessarily lose resolution the same way the characterization measurements revealed; rather, the bulk of the counts are affected and so the full peak energy moves towards where the low energy tail would be located. This shift shows a greater effect the damage had on the detector's response when a gamma enters a region of further from the negative diode. The greater effect on spectrum as a function of distance from the negative diode is consistent with the theory that the holes are more affected by the damage [Knoll]. The full energy peak centroid shift is dependent on the path in which electron-hole pairs interact with the HPGe crystal. The further the incident interaction happens from the negative diode, the longer the incident hole takes to travel and induces a smaller pulse within the amplifier time window and is seen as a lower energy in the spectrum.

MCNP Simulation

An MCNP input was written and run to simulate the HPGe crystal 1 cm away from the ^{252}Cf source within the shuffler [Werner] [Werner et al.]. This simulation was done in order to get an approximation of how many neutrons interacted with the germanium. The f4 tally was used to see the amount of neutron flux that had passed through the detector. Then the ptrac module was used in order to extract the amount of energy the neutrons deposited in the crystal. In the beginning two models were created in order to observe how the neutrons would behave. The first model was built using a preexisting shuffler geometry. The HPGe crystal was oriented “inside” of the shuffler

with the source 1 cm away. A simpler model was developed to cut down computing time, in which the crystal was positioned 1 cm away from the neutron source with no additional geometry. Both simulations showed the same amount of flux onto the crystal and therefore the shuffler's geometry and reflections did not contribute to the flux.

The f4 tally revealed that approximately 27% of the neutrons emitted from the ^{252}Cf source passed through the face of the HPGe crystal. Since the half-life of the californium is 2.6 years, each exposure needed to be corrected for decay. These calculations were done to relate the neutron exposure time cited throughout the paper to the actual neutron fluence through the detector. See Table 4 below for neutron flux for each exposure interval.

Table 4: Decay correction for the ^{252}Cf source used.

Date of Exposure	Neutron Emission from Cf-252 (n/s)	Seconds of exposure	Neutrons on HPGe (n/cm ²)
9/5/2019	8.37E+07	12,000	8.19E+12
1/22/2020	7.57E+07	6,000	3.70E+12
2/1/2020	7.52E+07	6,000	3.68E+12

Chapter 5: Conclusion

The hypothesis that the neutron damage imparted on the detector would have observable effect in the resolution of the spectra collected holds true. The idea that the trapping caused by dislocations would create a low energy tail was observed and brought to an extreme by measuring the heavily collimated source at discrete locations on the crystal.

The results of the changes in FWHM were anticipated through experience in dealing with HPGe detectors, but the experimentation brought up a number of unexpected data points as well as results. It was not expected that by biasing the high voltage on the detector would lead a resolution degradation over time. Luckily, the high-voltage biasing effects were caught early on and corrections and alterations were able to be made in order to ensure accuracy in later measurements. The observation was also fortunate as another area for further study. Thermal cycling of the detector led to interesting observations and helped show how the detector was reaching its maximum damage. Without the thermal cycling, the changes in the FWHM would have been slow and then would have a greater magnitude of change once it was thermal cycled on the completion of the experimentation.

The methodologies used to observe the neutron damage imparted onto the HPGe crystal were successful once minor modifications were made. The characterization measurements provided an observable resolution degradation with increasing neutron exposure. The measurements also showed the response of higher energy peaks being more affected by the damage can be interrupted as a statistical dependency. The sweeping measurements were successful in quantifying the damage as a function of the path of the electron hole pairs; a co-axial detector will observe different pulses depending on where

they interact in the crystal because of the distance between the diodes. Both sets of measurements were also successful in indicating that the damage imparted onto the crystal was approaching a maximum. Furthermore, the drastic results of the early thermal cycling were crucial to establishing the true extent of the damage that may have gone unseen and aided in establishing the equilibrating of the damage.

Ultimately, the combination of initial setup and the unforeseen events that were corrected for led to a robust investigation of how neutron-damage-induced traps will inhibit an HPGe detector's ability to collect an accurate spectrum. The data, observations, and results all contribute to the overall knowledge needed for the operation of HPGe detectors in a high neutron environment. There is, of course, more to explore and consider in future studies of the effects of neutron-induced traps.

Chapter 6: Further Research

In performing this thesis work a number of areas were identified for improvements to the experimentation and other work that can expand the concept of electron-hole trapping. Some cases, such as the high voltage biasing, will need to be further examined, while other aspects simply need to be repeated in order to gain better insights.

Repeating Experimentation

Since there are regions of interest in which data was lost, it would be beneficial to repeat these experiments. The pitfalls seen from the high voltage biasing and the thermal cycling process did not reveal the true extent of the damage. Therefore, repeating the entire experimental process described in this paper would reveal many of the missing data points and provide further insight into electron-hole trapping.

Moving forward this experiment will be repeated with the intervals of the neutron exposure reduced in order to gather better data between the points taken in this paper. With the intervals shortened, a better established damage vs. resolution could be produced. Shorter time intervals will also help establish a minimum exposure to create observable damage as well as more realistic field conditions that operators may encounter. It would be greatly beneficial to establish a more accurate curve to represent the damage as a function of neutron fluence.

Additionally, a digitizer will be utilized instead of a multichannel analyzer. A digitizer would give great insight into the waveform being produced by the detector. The use of a digitizer will reduce doubt in the MCA's ability to process the information being received by the detector and provide more exact waveform data. The results of the

experimentation in this paper show that an MCA and its settings to interpret a waveform can heavily influence the amount of damage seen to the spectra they collect. Since these setting had to be kept constant for this work, it would be beneficial to see the actual waveform of the detector signal processing as opposed to the adulterated signal produced from the MCA's processing. Another observation that requires further investigation is that of the shift in the lower level discriminate. The lower level discriminate increasing with more neutron exposure is possibly from an increasing dead layer on the detector's surface but further research will need to be conducted.

Investigating the Loss of Resolution as a Function of Time in which the HPGe is Biased with High Voltage

Further investigation of the phenomena observed pertaining the building up of resolution lost will be conducted in conjunction with the repetition of the overall experimentation. Investigating the build-up of resolution degradation changes as a function of neutron damage will provide insight to the mechanisms at work. As the current study showed with the AlGaN, there should be a direct correlation between the amount of damage done and the time interval necessary for the high voltage bias to be enabled to reach to a FWHM equilibrium. If the theory of degradation vs. high voltage biasing holds true, additional research will be necessary in order to understand the complete phenomenon.

Since the high voltage biasing is an effect on the dislocations causing varying conduction throughout the crystal, this will require much more expertise in electronic field production within semiconductors. The information uncovered can potentially be

used to develop better models for how HPGe migrates change and as a metric for field testing neutron damage.

Annealing

The detector used to gather all of the data in this paper will be annealed in order to attempt to recover from some of the damage that caused the loss of resolution. By attempting to repair the detector, it will show whether or not the damage done will be recoverable, even if only a small portion. The same set of characterization measurements will be conducted with the same MCA settings in order to establish a new baseline and to determine how much damage was recovered using the resolution as the improvement metric. The same set of full sweeping of the detector along the face and the Side A axis will also be repeated. The initial sweeping of the detector will be used not only to investigate how much the dead layer changed but also to investigate the amount of damage recovered through centroid shifting.

Then, the detector will be damaged further and the full range of measurements that this paper outlines will be tested. The amount of damage needed to reach the equilibrium again will provide insight as to how much the germanium recovered and if it is more susceptible to further damage after the annealing process.

Appendix 1: Spectrum Comparisons Before and After First Thermal Cycle

This appendix shows the individual isotopes and peaks associated with the characterization measurements taken before and after the first thermal cycle. These peaks were chosen since they show the greatest magnitude of change in resolution for any one thermal cycle. Figures 22 through 26 show that the amount of damage has increased though the low energy tailing and shifting in the peaks. These spectra were taken after the initial 12,000 seconds of neutron damage both before and after the detector was thermal cycled.

Figure 22: Ba-133 388-keV peak, before (black) and after (blue) first thermal cycle (12,000 seconds of neutron exposure)

Figure 23: Cd-109 88-keV peak, before (black) and after (blue) first thermal cycle (12,000 seconds of neutron exposure)

Figure 24: Co-60 1173-keV peak and 1332-keV peak, before (black) and after (blue) first thermal cycle (12,000 seconds of neutron exposure)

Figure 25: Appendix I Figure 4: Cs-137 662-keV peak, before (black) and after (blue) first thermal cycle (12,000 seconds of neutron exposure)

Figure 26: Mn-54 835-keV peak, before (black) and after (blue) first thermal cycle (12,000 seconds of neutron exposure)

Appendix 2: Spectrum Comparisons from Baseline to 24,000 Seconds Neutron Exposure

This appendix shows the individual isotopes and peaks associated with the characterization measurements taken any intentional neutron damage occurred and the result of 24,000 seconds of neutron damage and thermal cycle. These energy peaks were chosen since they show the greatest magnitude of change in resolution from the beginning to the very end of the experimentation. Figures 27 through 31 show that the amount of trapping has increased though the low energy tailing and shifting in the peaks.

Figure 27: Ba-133 388-keV peak before (black) and after (blue) 24,000 seconds of neutron exposure and thermal cycle

Figure 28: Cd-109 88-keV peak before (black) and after (blue) 24,000 seconds of neutron exposure and thermal cycle

Figure 29: Co-60 1173-keV peak before (black) and after (blue) 24,000 seconds of neutron exposure and thermal cycle

Figure 30: Cs-137 662-keV peak before (black) and after (blue) 24,000 seconds of neutron exposure and thermal cycle

Figure 31: Mn-54 835-keV peak before (black) and after (blue) 24,000 seconds of neutron exposure and thermal cycle

Appendix 3: Changes in Peak's FWHM vs Neutron Exposure

This appendix shows the individual isotopes and resolutions associated with the characterization measurements taken before and after each thermal cycle. These plots were chosen since they show the change in resolution for each thermal cycle at each neutron exposure. Figures 32 through 36 show that the amount of damage increasing at each neutron exposure interval and the effect the thermal cycling has on increasing the amount of trapping. These FWHM were found using PeakEasy.

Figure 32: Ba-133 384-keV peak before (blue) and after (orange) thermal cycling at discrete neutron exposures.

Figure 33: Cs-137 662-keV peak before (blue) and after (orange) thermal cycling at discrete neutron exposures.

Figure 34: Mn-54 835-keV peak before (blue) and after (orange) thermal cycling at discrete neutron exposures.

Figure 35: Co-60 1173-keV peak before (blue) and after (orange) thermal cycling at discrete neutron exposures.

Figure 36: Co-60 1332-keV peak before (blue) and after (orange) thermal cycling at discrete neutron exposures.

Appendix 4: Comparison of Combined Spectra

This appendix shows the full spectra of isotopes and peaks associated with the characterization measurements taken at the three different levels of neutron exposures after the detector was thermal cycled. These full-energy spectra were created by adding all of the individual characterization measurements together from their neutron exposure measurements. Figures 37 through 39 show that the amount of damage has increased through the low energy tailing and shifting in the peaks. These spectra were taken after each interval of neutron exposure and after the detector was thermal cycled.

Figure 37: Full-combined spectra of the baseline (black) and 12,000 seconds of neutron exposure (blue).

Figure 38: Full-combined spectra of the baseline (black) and 18,000 seconds of neutron exposure (blue).

Figure 39: Full-combined spectra of the baseline (black) and 24,000 seconds of neutron exposure (blue).

Appendix 5: Source information

The below table provides all the known information of the sources used in this experimentation. The table also provides the necessary information that was used to calculate the intrinsic efficiency of the detector.

Table 5: List of Nuclide information used for intrinsic Efficiency. Note: These activities were “guaranteed” to be within 5% from the manufacturer.

Nuclide	Ba-133	Cd-109	Mn-54	Co-57	Co-60	Cs-137
ID	2036-42-6	2036-42-5	2036-42-2	2036-42-3	2036-42-4	2036-42-7
Energy (keV)	383	88	834	122	1332.5	662
Branching Ratio	8.94E-02	3.61E-02	1.00E+00	8.56E-01	1.00E+00	8.51E-01
Calibration Activity (Bq)	3.64E+05	3.43E+05	3.62E+05	4.02E+05	3.71E+05	3.65E+05
Calibration Date	11/1/2018	11/1/2018	11/1/2018	11/1/2018	11/1/2018	11/1/2018
Half life (Days)	3846.08	462.6	312.3	271.79	1925.598	11019.593
Lamda (1/Days)	0.0001802	0.0014984	0.0022195	0.0025503	0.00036	6.29E-05
Characterization Date	8/15/2019	8/15/2019	8/15/2019	8/15/2019	8/15/2019	8/15/2019
Transmission Factor	0.984	0.97	0.987	0.973	0.988	0.985
Adjusted Activity (Bq)	3.04E+04	7.80E+03	1.89E+05	1.61E+05	3.31E+05	3.01E+05

The below table contains the information used in order to decay correct the ^{252}Cf source:

Table 6: Source information for ^{252}Cf

Source	Manufacturer	Date of Initial Mass	Initial Mass (ug)
Cf-252	Frontier	27-Jan-05	574.9

The below table is the information for the sources used as intermediaries and during the high voltage biasing experimentation:

Table 7: Source information for non-characterization sources

Nuclide	Ba-133	Ra-226
ID	1066-5-2	1649-75-2
Energy (keV)	383.85	609.31
Calibration Activity (Bq)	3.69E+05	3.748E+04
Calibration Date	6/1/2004	3/1/2013

Appendix 6: Equipment Used

The following table provides the information of all of the equipment used to perform acquisition of the spectral data collected in this experimentation.

Name	Model/Description	Serial Number
ORTEC DSPEC PRO	Multichannel Analyzer	11238915
ORTEC Detector Interface Module	Positive High-Voltage Bias	11224101
CANBERRA Detector	GC2518	10954
CANBERRA CRYOSTAT	CP5-PLUS-SL	
CANBERRA PREAMP	7087068	
CANBERRA CRYO CONTROLLER	CRYO-PULSE-5 PLUS	0945

Appendix 7: Visualization of Induced Pulse under Normal and Damaged Conditions

Under normal operating conditions, a gamma-ray incident on an HPGe crystal will create electron-hole pairs. As the pairs migrate they induce a pulse, which is then seen by the multi-channel analyzer (MCA). Using the size of the pulse seen within the timing window, the MCA assigns an energy. But, when detector is damaged the electron-hole pairs take more time to induce a pulse. The delay then elongates the pulse and a portion is then outside of the timing window. Since the pulse was incomplete, the MCA records it as a lower energy. When a large amount of gamma rays are incorrectly recorded as a lower energy, the spectrum will show low energy tailing and in extreme cases a full energy peak shift. Figure 40 below depicts the normal vs damaged pulses and how they affect the spectrum.

Figure 40: The Normal (Green) and Damaged (Red) Induced Pulses and How the MCA's Timing Window Will Affect the Spectrum

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