THE USE OF GALLIUM NITRIDE AS A SCINTILLATOR IN A FAST NEUTRON SPECTROMETER

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By
Johnathan Wensman, B.A.

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THE USE OF GALLIUM NITRIDE AS A SCINTILLATOR IN A FAST NEUTRON SPECTROMETER

Johnathan Wensman, B.A.

Thesis Advisor: John F. Currie, Ph.D.

ABSTRACT

The use of Gallium Nitride (GaN) for a fast neutron spectrometer via elastic recoil induced scintillation is discussed. As a direct band gap semiconductor, GaN provides high radiative efficiency and high photon yield per deposited unit of energy, both desirable features for a scintillator. Additionally, when correctly doped, GaN exhibits both increased emission, and decreased self-absorption of emitted photons. This work presents initial experiments and modeling which explore the use of GaN as a novel scintillator material for use in a fast neutron spectrometer. These experiments include exposure to neutron, energetic ion, beta, and photon radiations with supplemental computational work explaining observed instrument performance.
I would like to thank my family and friends for supporting me, not only during this work, but throughout my life. I could not have even started this work without you.

I would also like to thank those who helped in the work, including Professors John Currie, Christopher Cothran, Joseph Serene, Amy Liu, and Jeffrey Vanhoy as well as Dr. Noel Guardala, Dr Veerendra Mathur, and a special thank you to Dr. Jack Price and the ILIR program for funding this research.

Finally I would like to thank Gizmo and Bear for reminding us of what is truly important.

Johnathan Wensman
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1 INTRODUCTION

Ionizing radiation detection and spectroscopy began in earnest with work by Wilhelm Röntgen in the late 1800s, and has evolved significantly since, employing many differing approaches\textsuperscript{1,2,3,4}. Ionizing radiation spectroscopy, and neutron spectroscopy in particular, find many applications in the fields of experimental nuclear physics, radiation safety, detection of radioactive materials, and many more.

Due to the charge neutrality of neutrons and the nature of neutron interactions with matter, neutron detection and spectroscopy is difficult. For comparison, looking at photon spectroscopy full energy transmission between a photon and transducer in a single interaction can be accomplished via the photoelectric effect, and many spectroscopic systems have been built around this mechanism. Neutrons do not have an equivalent energy transduction mechanism.

For this reason, neutron spectroscopy is performed by measuring characteristics of secondary charged particles created during neutron-nucleus interactions. The resulting ionization and subsequent charge carriers can either be collected directly, as in a diode spectrometer\textsuperscript{5,6,7}. Alternatively, in an appropriately engineered device, the charge carriers can create a photon signal which is then collected and analyzed\textsuperscript{8,9,10,11}. In general, the direct charge collection approach provides small instrument size coupled with fast timing characteristics, with some drawbacks including high susceptibility to performance degradation due to radiation induced damage.

There are two main approaches taken in order to produce the secondary charged particles. The first method of producing energetic charged-particles in the MeV energy range involves
incorporating nuclides such as $^{10}$B or $^{6}$Li into the structure of the active materials. These nuclides have high thermal-neutron capture cross sections, and via mass-energy equivalence release relatively large amounts of energy during the desired nuclear reaction. These reactions result in charged particles with MeV energies even for the lowest energy incident neutrons in the thermal energy range of $\sim$0.025 eV. Such an approach is adequate to detect thermal neutrons but is not very useful for neutron energy determination due to the large charged particle energy masking the initial neutron energy. Recently successful attempts to use cerium-doped cesium lithium yttrium hexa-chloride (CLYC) using the $^{35}$Cl(n,p) reaction for fast neutron spectroscopy have been reported, however, the dynamic range of these detectors is limited and complicated due to the capture cross section behavior of the $^{35}$Cl.

Another approach uses the recoil ions produced by neutron elastic scattering off atoms either composing, or in close contact with the transducer. In general hydrogen is the atom of choice for such recoil spectrometers due to the relatively simple partial differential cross section for energies below 10 MeV and the similar mass allowing for nearly full energy transfer at a 0$^\circ$ scatter angle, but in theory any atom can be used.

Proton recoil requires using transducers that contain a high hydrogen atom content, which can be found in the form of liquid scintillators or in situations such as the scintilant being dissolved in a hydrogenic solvent, scintillators incorporated into a polymerized hydrocarbon, polymeric material coated onto the front face of the detector or self-contained organic crystals (i.e. anthracene, stilbene). The drawback of these however is an intrinsically low-radiative efficiency, and self-absorption of the emitted light.
In order to solve the problems presented from the approaches described above, I have created a neutron spectrometer which uses Gallium Nitride (GaN) as the transducer with elastic recoil of the constituent atoms as the transduction mechanism. The direct band gap and other solid-state properties of GaN allow fast, efficient radiative electron-hole recombination making a scintillation-based device attractive.

Previous investigations into the use of GaN as a neutron spectrometer have been performed, focusing mainly upon the creation of a charge capture device due to the material properties of GaN rivaling or exceeding those of alternate similar devices. These include comparable carrier mobility to silicon and a higher breakdown field by an order of magnitude. Studies have shown however that in addition to the above-mentioned features which make a diode device attractive, GaN is also an efficient scintillator. Along these lines, GaN has been investigated for use in scintillation-based devices through non-elastic recoil of a converting nuclide. This is an unnecessary complication as the approach ignores the elastic recoil of the constituent ions. This is mainly because the atomic masses of gallium and nitrogen are well above other atoms considered for recoil-based spectrometers due to the reduced kinematic energy transfer in elastic recoil.

Because of the increased scintillation and relatively large elastic recoil cross sections of gallium and nitrogen, I have conceptualized, created, and characterized a scintillation based GaN neutron spectrometer using elastic recoil of the constituent atoms to produce secondary charged particles. In the following I will present the theory of a GaN based neutron spectrometer and the work completed in characterizing the scintillation response of GaN to various forms of ionizing
radiation. This work includes both experimental results and computational work explaining the resulting observations from neutron, energetic ion, beta, and photon irradiation of GaN. Future experiments are also recommended in order to further develop the theory and performance of a GaN based scintillation spectrometer.
2 BACKGROUND

2.1 Charged Particle Spectroscopy

When an energetic charged particle encounters matter, it interacts with both the nuclei and electrons through the Coulomb force, and, depending upon the particle and energy, it can also undergo nuclear reactions. In addition to these, while the particle is losing energy and accelerating, additional energy is lost through radiative emissions in the form of bremsstrahlung radiation. The amount of energy an incident particle loses to each of these paths depends upon a multitude of factors, including the charge, mass, and energy of the incident particle, as well as number density and atomic number of the material.

Each material has a stopping power of charged particles, or a rate of energy lost per unit distance in the material. For heavy charged particles the ionization stopping power is classically derived via the Bethe formula, given by

\[
-\frac{dE_i}{dx} = \frac{4\pi e^4 z_e^2 N Z}{m_0 v^2} \left( \ln \left( \frac{2m_0 v^2}{I} \right) - \ln(1 - \beta^2) - \beta^2 \right)
\]

where \( e \) is the electronic charge, \( z_e \) is the charge of the primary particle, \( N \) is the number density of the material, \( Z \) is the atomic number of the material, \( m_0 \) is the electron rest mass, \( v \) is the velocity of the incident particle, \( I \) the average excitation and ionization potential of the material, and \( \beta = \frac{v}{c} \). For electrons, due to the smaller mass requiring relativistic corrections, the ionization stopping power is modified to

\[
-\frac{dE_e}{dx} = \frac{2\pi e^4 N Z}{m_0 v^2} \left[ \ln \left( \frac{m_0 v^2 E}{2I\tau} \right) - \ln(2)(2\sqrt{\tau} - 1 + \beta^2) + \tau + \frac{1}{8}(1 - \sqrt{\tau})^2 \right]
\]

where \( \tau \) is \( 1 - \beta^2 \).
The stopping power due to bremsstrahlung radiation for electrons is given by

\[ -\frac{dE}{dx} = \frac{e^4NEZ(Z + 1)}{137m_0c^4} \left( 4 \ln \left( \frac{2E}{m_0c^2} \right) - \frac{4}{3} \right) \]

where \( E \) is the initial electron energy. These stopping powers alone reveal some important characteristics of charged particle interaction.

First, we see that the stopping power of heavy charged particles varies proportionally to the inverse square of the particle velocity, meaning that as the particle loses energy, the energy transfer increases. Additionally, the stopping power is proportional to both the square of the particle charge, and the electron density, \( NZ \), of the material, meaning higher particle charge, and higher density materials increase stopping power.

Second, the results of the electron ionization stopping power reveal generally the same behaviors, but by comparing the presented stopping powers, one can find

\[ \frac{dE_r}{dx} \frac{dE}{dx} \approx \frac{EZ}{700} \]

for \( E \) given in MeV. This shows us that the fraction of energy lost to bremsstrahlung radiation can be approximated by a function of only the atomic number of the absorbing material and the energy of the electron.

In the context of crystalline semiconductors, the predominant result of charged ionizing radiation impinging upon a material is excited electrons. Because of this, multiple charged particle spectrometers have been developed utilizing both diode and scintillation approaches mentioned in chapter 1.
For example, silicon diode detectors have become ubiquitous in the field of heavy charged particle spectroscopy due to various advantages including timing characteristics, thin entrance windows\textsuperscript{14,15}, and good energy resolution on the order of tens of keV FWHM for modern commercial devices\textsuperscript{16}. These detectors in general consist of silicon, doped in order to create a diode, being reverse biased. Charged particles which interact with the silicon diode through the above described processes and are stopped within the detector, depositing all their energy create ionization induced currents, which are detected and recorded. With the ionization current proportional to the particle’s initial energy, the current spectrum is representative of the particle spectrum.

Alternatively, due to availability of materials, simplicity of operation, and radiation specific characteristics such as stopping power for the radiation concern and backscatter percentage, charged particle spectrometers have been created out of various scintillating materials. Similar to diode detectors, charged particles interact with the scintillator creating ionization, but instead of collecting the current via biasing, the charge carriers are allowed to thermalize, and result in scintillation. The scintillators, chosen for the specific application, accounting for system and experiment constraints, range from bismuth germinate (BGO)\textsuperscript{17}, cesium iodide (CsI)\textsuperscript{18}, and sodium iodide (NaI)\textsuperscript{19}, to more exotic scintillators, such as anthracene\textsuperscript{20}, plastic scintillators\textsuperscript{21}, and liquid scintillators\textsuperscript{22}. In order to account for various phenomena and increase spectrometer performance, various device configurations can be used, such as combining dissimilar scintillators as in a phoswich detector\textsuperscript{23} or including multiple photosensitive elements in order to provide position sensing\textsuperscript{24}. 
2.2 Photon Spectroscopy

Ionizing photon radiation interacts with matter depositing energy in one of three ways, through photo-electric absorption, Compton scattering, or pair production. During photo-electric absorption an incident photon is absorbed entirely by an atom, ejecting a photoelectron from one of the bound shells with energy equivalent to the difference between the initial photon energy and the binding energy of the electron. As the atom is ionized in the process, the vacancy is filled either through free electron absorption or a rearrangement of bound electrons, leading to emission of characteristic x-rays with energy dependent upon the atom itself. Depending upon the characteristic x-ray energies, these can lead to a cascade effect with further photoelectric interactions. In the case of such a cascade, the photon energies decrease rapidly allowing us to say that after the initial photoelectric absorption, the remaining energy of the photon is carried away by the photoelectron.

Compton scattering occurs between the photon and an electron in the material where the incident photon is deflected from the original path by an angle \( \theta \). The angular distribution of scattered photons is predicted by the Klein-Nishina formula\textsuperscript{25} for the cross section, \( \frac{d\sigma}{d\Omega} \), given by

\[
\frac{d\sigma}{d\Omega} = Z r_0^2 \left( \frac{1}{1 + \alpha \zeta} \right) \left( \frac{\delta}{2} \right) \left( 1 + \frac{\alpha \zeta^2}{\delta(1 + \alpha \zeta)} \right)
\]

where \( Z \) is the atomic number of the material, \( r_0 \) is the classical electron radius, and \( \alpha, \zeta, \) and \( \delta \) are given by

\[
\alpha = \frac{E_{\gamma_0}}{m_0 c^2}
\]

8
\[
\begin{align*}
\zeta &= 1 - \cos(\theta) \quad (6b) \\
\delta &= 1 + \cos^2(\theta) \quad (6c)
\end{align*}
\]

with \( m_0 \) the rest mass of an electron, and \( c \) the speed of light. Additionally, assuming the electron was at rest the energy transferred to the electron, \( E_e \), can be determined through conservation of energy and momentum to be

\[
E_e = E_{\gamma 0} \frac{\alpha(1 - \cos \theta)}{1 + \alpha(1 - \cos \theta)}
\]

where \( E_{\gamma 0} \) is the initial photon energy.

Finally, pair production is possible when the photon energy exceeds two times the rest mass of an electron (~1.021 MeV), or the threshold. This process involves the disappearance of the photon and the creation of a positron-electron pair, with photon energy above the threshold distributed between the pair created as kinetic energy.

In the creation of a spectrometer the ideal case would be for each photon to deposit all energy in the transducer. Depending upon the photon energy though it is possible for photons to pass through material without interacting, or interacting, but not depositing all energy (i.e. small angle Compton Scattering in a thin transducer). Therefore, when discussing many photons incident upon a material the number transmitted without undergoing a reaction is important. For a beam of photons of energy \( E_{\gamma} \) this is determined by

\[
\frac{I}{I_0} = e^{-\mu_t(E_{\gamma})\ell}
\]

where \( I \) is the final photon beam intensity representing the amount of the initial beam which passes through a material without undergoing a reaction, \( I_0 \) the initial beam intensity, \( \mu_t \) the
linear attenuation coefficient of the material, and \( t \) the material thickness. Alternatively, the attenuation percent of a beam of photons of initial energy \( E_\gamma \) is given by

\[
A(E_\gamma) = 1 - e^{-\mu_t(E_\gamma)t}
\]

(9)

Additionally, the linear attenuation coefficient can be split into source terms for each of the interactions described above, or

\[
\mu_t = \mu_e(E_\gamma) + \mu_c(E_\gamma) + \mu_p(E_\gamma)
\]

(10)

where the subscripts e, c, and p correspond to photoelectric, Compton, and pair production. And the mean free path, \( \ell \), is simply the inverse of \( \mu_t \), or

\[
\ell(E_\gamma) \approx \frac{1}{\mu_t(E_\gamma)}.
\]

(11)

The importance of each process described above depends upon the energy of the photon and the atomic number of the absorbing medium. Generally, for low energy photons (\( E_\gamma \sim 0-0.2 \text{ MeV} \)) photoelectric absorption is predominant, with Compton scattering more important for mid-energy (\( E_\gamma \sim 0.2-6 \text{ MeV} \)), and pair production dominant for higher energy photons. As can be seen, in a similar manner to that of charged particles the result of photon radiation interacting with matter is the creation of energetic electrons.

As with charged particles, both diode and scintillation spectrometers have been developed for photon radiation. For example, the well-known method of photon spectroscopy, via sodium iodide (NaI) scintillation utilizes a doped NaI crystal which scintillates when exposed to high energy photon radiation, with the intensity being proportional to the amount of photon energy deposited in the crystal. By ensuring the crystal is thick enough to nearly completely absorb the
photon energy of consideration and coupling the crystal to a photo-detection system the
scintillation pulses can be recorded, and the initial energetic photon energy or energies can be
determined.
2.3 Neutron Spectroscopy

Neutrons undergo various types of interaction with matter\textsuperscript{28} depending upon the neutron energy. The most straightforward neutron interaction is elastic scatter, in which total kinetic energy is conserved. Next, during inelastic scatter a neutron is absorbed by a nucleus, then re-emitted at a lower energy leaving the nucleus in an excited state, which then emits a gamma ray. A specific type of inelastic scatter, called neutron capture can occur at low neutron energy where the neutron is captured and not-re-emitted, leaving the nucleus in an excited state. A non-elastic scatter involves a neutron being absorbed by a nucleus, which then emits another particle, or multiple particles. The cross-section of a reaction is the probability of the reaction as a function of energy and solid angle, or the probability of a neutron of a certain energy being scattered through a certain angle.

Due to the charge neutrality of neutrons removing the possibility of coulomb interactions, to perform neutron detection and spectroscopy the approach must account for the possible interactions and be tailored to the desired transduction mechanism. In the case of detection an indirect approach can be taken, designing the detector with a moderating layer around the counter which reduces the neutron energy via elastic recoils. This allows for neutron moderation, and detection when the neutron reaches the central detector. A single moderation-based device does not provide energy information but a spectrum can be reconstructed by utilizing concentric detectors, or multiple detectors with varying moderator thicknesses\textsuperscript{29}. Multiple assumptions must be made in order to begin determining a neutron spectrum using this method, including a constant neutron field during recording of data. Additionally, the algorithms and process’ to
retrieve the initial neutron energies from the recorded data, termed the unfolding process, introduce large uncertainties. As the assumptions cannot always be satisfied, and the uncertainty introduced can be unacceptable, these methods are more useful for detection versus spectroscopy.

In order to perform spectroscopy then, a more direct approach is generally taken by selecting the desired transduction interaction and building the device around it. This can be done by choosing a material with a large non-elastic scatter cross section and Q value and measuring the signal from a secondary particle. If a property of the particle is a function of neutron energy, such as the energy, and that property of the secondary charged particle can be measured efficiently, it is possible to reproduce the spectrum of incident neutrons. Alternatively, neutron spectroscopy via elastic scatter can be performed by first measuring the ion recoil spectrum due to neutron irradiation and unfolding the result to determine the initial neutron spectrum.
2.3.1 Non-elastic Recoil Transduction

As previously mentioned, neutron spectroscopy via non-elastic recoil transduction can be performed by selecting a material with a high non-elastic cross section in the neutron energy range of interest, and building a system around that material in order to measure the resulting reactions during neutron irradiation. Generally in these detectors in order to maximize the signal strength a reaction with a high Q value is selected. This has been done with nuclides such as $^{10}$B or $^6$Li, which have high thermal-neutron capture cross sections, i.e. kilo-barns, for low energy neutrons, and both have large Q-values. The result then is the emission of alpha particles with MeV energies even for the lowest energy incident neutrons, in the thermal energy range of ~0.025 eV. These reactions are well suited to detect neutrons, but neutron energy determination is difficult due to the large Q value masking the effect of neutron energy, especially at the low energies.

Recently successful attempts to use cerium-doped cesium lithium yttrium hexa-chloride (CLYC), using the $^{35}$Cl(n,p) reaction, for fast neutron spectroscopy have been reported, unfortunately the dynamic range of these detectors is limited and complicated due to the capture cross section behavior of the $^{35}$Cl.

Beyond these, various other materials have been discussed due to large cross section and Q value, such as $^{157}$Gd, $^{233}$U, $^{235}$U, and $^{239}$Pu. In the case of gadolinium, the reaction products are high energy gamma rays and electrons, complicating pulse processing techniques. Further, uranium and plutonium-based neutron detectors present unique problems in the form of security
and safety, as well as the massive Q value masking much of the initial neutron energy, like the boron and lithium-based detectors.
2.3.2 Elastic Recoil Transduction

Another approach to neutron spectroscopy uses the recoil ions produced by neutron elastic scatter, which are in close contact, or enclosed within, the active scintillator material. A generalized technique is to have a low-mass-nuclei rich target material in the active volume of the detector and determine the neutron spectrum by analyzing the energy spectrum of recoil nuclei, as governed by the partial differential cross section discussed above. As the energy transferred during elastic scatter is well defined via a kinematic conservation of energy and mass analysis, the recoil energy spectrum is dependent upon the target and projectile mass, as well as the scattering angle as given by

$$E_1 = E_0 \left[ \frac{m_1^2}{(m_1 + m_2)^2} \left( \cos \theta \pm \sqrt{\left( \frac{m_2}{m_1} \right)^2 - \sin^2 \theta} \right)^2 \right] \tag{12}$$

where $m_1$ and $m_2$ are the projectile and target mass respectively, $E_0$ and $E_1$ are the initial and final projectile energy respectively, and theta is the angle between the initial and final projectile direction of motion. Via conservation of energy, the energy transferred to the scatterer, $E_2$, is given by

$$E_2 = E_0 - E_1 \tag{13}$$

defining the ratio of scatterer mass to projectile mass as $A$, then we can see that the energy transferred to the scatterer via an elastic collision is given by

$$E_2 = E_0 \left[ 1 - \frac{\left( \cos \theta \pm \sqrt{A^2 - \sin^2 \theta} \right)^2}{(1 + A)^2} \right] \tag{14}$$
therefore, if the partial differential cross-section for a given reaction is known, then by matching the recoil spectrum to the known recoil probabilities, the initial neutron energy can be determined. The energy transfer to recoil nuclei is maximized for low mass scatterers, and for this reason, historically neutron spectrometers utilizing elastic recoil have minimized the recoil nuclei mass such that the energy imparted to nuclei during elastic scattering is maximized, allowing for a larger scintillation signal. Considering the ideal case for illustrative purposes then, if we assume an ideal hydrogen recoil-based spectrometer, as well as a constant partial differential cross section for hydrogen, the resulting recoil, and scintillation spectrum for a mono-energetic neutron irradiation would look like Figure 1 below.

![Figure 1. Idealized hydrogen recoil spectrum](image.png)
Where we have assumed identical neutron and hydrogen mass. In this idealized spectrometer then we retrieve the initial neutron energy based, for example, upon the endpoint of the spectrum.

The actual cross section of hydrogen is not constant. Regardless, much effort has gone towards creation of a hydrogen-based recoil spectrometer in order to capitalize on the energy transfer. In order to maximize the signal from hydrogen recoil, the desire is to use a scintillator with high hydrogen content, which can be found in the form of liquid scintillators, where the scintillant is dissolved in a hydrogenic solvent, where scintillators are incorporated into a polymerized hydrocarbon, a polymeric material is coated onto the front face of the scintillator (typically an inorganic one) or self-contained organic crystals (i.e. anthracene, stilbene)\(^3\). The drawback of these methods however is a relatively low-radiative efficiency, and self-absorption of the emitted light. The alternative to using a scintillator with high initial hydrogen content would be to implant a highly efficient scintillator with hydrogen. Unfortunately, it is not feasible to implant a scintillator with sufficient hydrogen in order for the signal from hydrogen recoils to overcome that which would be produced by inherent scintillator reactions to neutron radiation due to both the flux required and that upon implantation of massive amounts of hydrogen, the scintillation characteristics would be erratic\(^3\). Because of these difficulties with hydrogen-based recoil scintillation spectrometers, other light ions have been investigated.

Moving away from hydrogen, helium-3, and helium-4 have been used\(^3\). Unfortunately, these detectors present a problem in that a supply shortage of helium-3 and helium-4\(^3\) has led to difficulty in instrument creation. In addition to these issues, due to the dependence of neutron
interaction on detector volume and a relatively low reaction cross section leading to large detectors, any additional radiations present can create a signal, including high energy gamma. In the detectors mentioned above the solution to this issue comes in pulse shape discrimination (PSD), which introduces unwieldy processing requirements and equipment. Finally, to ensure adequate signal to noise ratio, some systems must be cooled, introducing complex cooling requirements to system design. To avoid the above-mentioned issues, I propose the use of GaN as the scintillator in a neutron spectrometer, utilizing the elastic recoil of the constituent gallium and nitrogen atoms to create the ion recoil signal.
2.4 Neutron Interactions with Gallium Nitride

To determine the suitability of GaN as a neutron spectrometer, I began by considering the neutron cross sections for reactions involving gallium and nitrogen. Doing this reveals 19 total reactions up to initial neutron energy of 20 MeV, listed below in Table 1.

<table>
<thead>
<tr>
<th>$^{14}$N reactions</th>
<th>$^{69}$Ga reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n,el)</td>
<td>(n,el)</td>
</tr>
<tr>
<td>(n,2a)</td>
<td>(n,np)</td>
</tr>
<tr>
<td>(n,np)</td>
<td>(n,p)</td>
</tr>
<tr>
<td>(n,p)</td>
<td>(n,a)</td>
</tr>
<tr>
<td>(n,nd)</td>
<td>(n,t)</td>
</tr>
<tr>
<td>(n,d)</td>
<td>(n,d)</td>
</tr>
<tr>
<td>(n,na)</td>
<td>(n,(^3)He)</td>
</tr>
<tr>
<td>(n,2n)</td>
<td>(n,2n)</td>
</tr>
<tr>
<td>(n,a)</td>
<td>(n,na)</td>
</tr>
<tr>
<td>(n,t)</td>
<td></td>
</tr>
</tbody>
</table>

Legend:

- n neutron
- el electron
- α alpha particle
- p proton
- d deuteron
- t triton

However, by narrowing these reactions down to the most likely and plotting the relevant cross sections results in Figure 2 below.
As can be seen, the most likely reaction over a large neutron energy range observed is elastic scattering either with nitrogen or gallium, by a factor of nearly ten. This is the reason that an elastic recoil based neutron spectrometer can be made using GaN. At higher energies the (n,2n) reaction also becomes prominent. As mentioned in the previous chapter, the energy imparted to a recoiling nucleus is dependent upon the neutron energy, and the angle through which it is scattered. Therefore, in addition to the elastic cross-section we must consider the partial differential elastic cross sections of nitrogen and gallium. To do this, we begin with the partial differential cross section for elastic neutron collisions with both $^{69}$Ga and $^{14}$N provided by the Evaluated Nuclear Data File database. The database provides the partial differential cross...
section in b/sr by incident neutron energy and neutron scatter angle, all in center of mass (COM) coordinates. To predict the response of GaN to neutron irradiation we assume only elastic scattering, convert the neutron energy to lab frame, and identify the relevant ion recoil energy in the lab frame for the incident neutron energy and scatter angle. The database neutron energy is converted to the lab frame using

$$E_L = E_{cm} \left( \frac{[m_1 + m_2]^2}{m_2} \right)$$

(15)

where the L and cm subscripts indicate the lab and center of mass frame respectively, m is the mass, and the 1 and 2 mass subscripts indicate the incident and scattered particle respectively. The ion recoil energy is then determined using equations (14) and (15). Performing these conversions on the relevant available data produces Figure 3 and Figure 4 below.
Figure 3. Nitrogen (n,el) ion recoil distribution as a function of initial neutron energy
Finally, looking at the partial differential cross-section for a single neutron energy, we can predict the ion recoil spectrum as a function of initial neutron energy. Doing so for various neutron energies produces Figure 5, Figure 6, and Figure 7 below.
Figure 5. Predicted cumulative ion recoil spectrum (gallium and nitrogen) from 2.3 MeV neutron irradiation
Figure 6. Predicted cumulative ion recoil spectrum (gallium and nitrogen) from 2.8 MeV neutron irradiation
Therefore, assuming a functional unfolding mechanism can be created in order to reconstitute or determine the initial neutron field based upon the recoil spectrum and ion energy dependent scintillation, a scintillation-based neutron spectrometer can be created utilizing GaN as the transducer and elastic recoil of the constituent atoms as the transduction mechanism. The first assumption can be justified by using the success of hydrogen recoil-based spectrometers as an example. Although the cross section is different for gallium and nitrogen, the same methods successfully used for hydrogen unfolding should produce similar results for nitrogen and
gallium. The second assumption is one of the main foci of this work, ensuring that GaN provides a linear scintillation response with varying ion energy over a range of ion species and energies.
2.5 Previous Gallium Nitride Work

Due to the advantages of GaN over silicon in the electronics industry\textsuperscript{41}, a bevy of studies have been performed characterizing the solid-state properties of GaN, ranging from scintillation studies to studies of the elastic constants. Beyond the base of work intended for the development of GaN to surpass silicon in the electronics industry, various studies have been performed evaluating the use of GaN as a radiation spectrometer, ranging from its use in x-ray and alpha detection and spectroscopy, to use in neutron spectroscopy systems. The first earnest use\textsuperscript{42} of GaN for radiation spectroscopy device was completed in 2003 using a double Schottky contact structure in order to create an alpha spectrometer. Further experimental alpha spectrometers were developed between 2009 to 2012, utilizing an ohmic contact and Schottky contact in varying configurations\textsuperscript{43,44}, as well as in a sandwich configuration\textsuperscript{45}.

Beyond alpha particles various investigations have been performed in evaluating the use of GaN in an x-ray detector. These studies used GaN in either a Schottky metal-semiconductor-metal (MSM)\textsuperscript{46}, or Schottky diode configuration\textsuperscript{47,48}. Due to difficulties in decoupling the photovoltaic and photoconductive currents, less successful tests were performed using a p-i-n structure\textsuperscript{49}, although presumably the limitation in these tests was due to the difficulty in fabrication of high quality materials.

Further, some documented work exists investigating the use of GaN as a neutron detector and spectrometer. All documented approaches taken involve either incorporation of a conversion isotope into GaN such as the previously mentioned boron or gadolinium\textsuperscript{50,51,52}, or utilizing the intrinsic $^{14}$N(n,p) reaction\textsuperscript{53}. As can be seen all previous work has been performed utilizing a
diode configuration. This can be explained both because of the general movement in the field of radiation spectroscopy to diode detectors due to the advantages previously mentioned, as well as the material properties important for diode operation of GaN rivaling or exceeding those of silicon. Most studies into the use of GaN as a diode detector however ignore the role that the direct band gap plays in increasing the probability of electron hole recombination. Few studies have emphasized this feature, among them, radioluminescence has been investigated for use in dosimetric devices\textsuperscript{54}, and .

To this point, zero investigations have been performed into the possibility of using GaN as a neutron spectrometer by utilizing the elastic recoil of the constituent gallium and nitrogen atoms. Additionally, heavy charged particle spectroscopy of energies below the $^{241}$Am alpha has not been investigated using GaN. Further, beyond GaN, no serious work has been performed investigating the utilization of elastic recoil of atoms heavier than helium as the elastic recoil transduction mechanism for a neutron spectrometer.
2.6 Proposed Gallium Nitride Spectrometer

Due to the direct band gap, gallium nitride (GaN) provides fast electron-hole recombination after electronic excitation from ionizing radiation with an increased probability of radiative recombination, and by performing n<sup>+</sup> doping GaN exhibits the Burstein-Moss shift<sup>55</sup>, effectively inducing transparency to self-emitted photons. Additionally, GaN has demonstrated the capability of direct epitaxial growth of photodetectors<sup>56</sup>, possibly obviating the need for a separate light detection mechanism. Further, assuming epitaxial growth is not utilized, with the band gap of 3.4 eV photon emission would be expected to be in the 365 nm range, which is advantageous to work in due to the multitude of photo-detection systems available for use in this range. In practice, due to bulk self-absorption and Levy flight, back side photoluminescence collection shows that the dominant peak is shifted to 380 nm<sup>57</sup>, still within the desired wavelength range. The GaN detector also is advantageous regarding both detector size and thermal properties. Due to the cross-sections and the wide band gap not only can a relatively small crystal be used, obviating the need for PSD due to increased probability of gamma and x-ray escape from the crystal, but operation can be performed at room temperature, avoiding cooling requirements. For these reasons GaN is a good candidate from the photon collection efficiency and signal contamination standpoint to create a scintillation-based radiation detector.

With the scintillation efficiency in mind, as well as the neutron cross section behavior discussed earlier, we propose the use of GaN as a scintillator for use in a neutron spectrometer utilizing the signal created by heavy ion elastic recoil during neutron irradiation. With regards to previously developed elastic recoil-based neutron spectrometers, gallium and nitrogen obviously
present much larger masses, and previous scintillators using elastic recoil as the transduction mechanism were not capable of using these ions. Due to the reduced recoil energy from a kinematic standpoint, the energy available for scintillation from a nitrogen or gallium ion is small compared to the alternative ions discussed in the scintillators currently being used. Additionally, for scintillators which did not exhibit high radiative efficiency, or did display any significant self-absorption, the small signal produced by such recoil would be insufficient for spectroscopic purposes. The advantage here presented by GaN comes from the large direct band gap, and solid-state properties brought on by doping.

A basic operating diagram of such a spectrometer is shown below in Figure 8.

![Figure 8. Gallium Nitride neutron spectrometer basic flow chart](image)

In this envisioned spectrometer an appropriately doped GaN wafer would be optically coupled to a light detecting device, for simplicity we use a photo-multiplier tube (PMT). The output of the PMT would then be routed through an appropriately chosen readout system. During neutron irradiation, neutrons would undergo elastic scattering with the wafer creating a spectrum of energetic ions with a distribution of energies determinable as shown above by using the partial differential cross-sections. The energetic ions would then deposit energy in the wafer, creating a scintillation signal with amplitude dependent upon the ion energy. This scintillation signal would then propagate to, and be read by the PMT, whose output would be processed by the
attached electronics giving a scintillation pulse height spectrum, related to the initial neutron
ergy by the partial differential cross section, as shown above.

As mentioned earlier, the physical properties of GaN allow for efficient scintillation and photon transport after creation. Additionally, as the signal is created by heavy ions, the large stopping powers involved allow for a relatively thin wafer to completely stop the energetic ions. This benefit comes with the caveat that higher stopping power intrinsically leads to lower scintillation efficiency. In addition, with an index of refraction of approximately 2.4 a large amount of the photon signal would be lost to internal reflection, unable to escape the crystal after creation.

Therefore, by utilizing the specific solid-state properties of n+ doped GaN and the inherent neutron interaction behavior, we have created a novel neutron spectrometer with a large dynamic range which utilizes easily procurable materials and off the shelf components through a method previously ignored due to a lack of conformation to typically successful methods. In the following work, initial experiments showing the operation of a prototype GaN based scintillation spectrometer will be presented and validated via computational analysis. First, to validate neutron detection, the developed spectrometer was exposed to multiple mono-energetic neutron radiations. Next, to affirm ion recoil producing a predictable scintillation signal the system was exposed to many monoenergetic beams of various ions. Finally, to evaluate the performance of the spectrometer under normal conditions the response to beta, gamma, and alpha radiations was investigated. For each experiment computational analysis and modeling was performed in order to validate the results. Through these experiments it has been shown that not only can doped
GaN perform neutron spectroscopy, but also charged particle spectroscopy and photon radiation detection.
3 EXPERIMENTS AND ANALYSIS

3.1 Detector Set-up

To validate the theory of a GaN based neutron spectrometer three iterations of the prototype detector were investigated, each conforming to a basic design, based on the typical scintillation detector design\textsuperscript{59,60} with changes made in each version. Each version was exposed to various forms of ionizing radiation to characterize the scintillation response. The basic detector design consisted of a wafer of GaN optically coupled to a photomultiplier tube (PMT), connected to a power source with the output run through Nuclear Instrumentation Modules (NIMs), into a computer for analysis as diagramed below in Figure 9.

![Figure 9. General detector setup](image)

Two distinct wafers of GaN were purchased from Kyma Technologies for use in the experimental investigations. The first wafer was 1 inch in diameter, 250 µm thick with a silicon doping level of approximately $1 \times 10^{17}$ atoms per cubic centimeter as determined by a secondary ion spectrometry experiment performed by Kyma on a representative wafer sample with results included in appendix 2. The second wafer was 2 inches in diameter, 1 mm thick with a lower silicon doping of approximately $5 \times 10^{16}$. The differing materials were purchased to investigate the effect of doping and wafer thickness on scintillation intensity of GaN. The doping
would be expected to influence the probability of radiative recombination resulting in scintillation, as well as the self-absorption of the crystal to emitted light\textsuperscript{61}. Higher doping increases the density of sites available for radiative recombination, decreasing the probability that an e-h pair created during ionization will terminate in a non-radiative manner. At the same time, increasing the doping leads to a change in the band structure, enabling self-absorption of photons emitted above the original band-gap due to a Burstein-Moss shift, leading to light loss which reduces overall scintillation collection by the PMT\textsuperscript{62}. For these reasons a balance must be achieved between increasing the initial scintillation intensity and decreasing the probability of self-absorption of emitted photons. Increasing the thickness of the crystal on the other hand would be expected to increase the probability of uncharged radiations interacting with the crystal, as well as increase the total energy deposition of charged particles that are energetic enough to pass through the wafer. This leads to a broader energy sensitivity, but also increases the amount of photon self-absorption.

As mentioned above, the wafer of GaN is optically coupled to the PMT via an optical couplant, and as the detector is a scintillation-based device, the optical coupling was of great importance. GaN itself has a high index of refraction\textsuperscript{63} of approximately 2.4, and considering reflectance of light at boundaries, the index of refraction of the couplant can have drastic effects on the transmittance of light from the GaN wafer to the vacuum of the PMT. To observe the effect and optimize the couplant to maximize the scintillation signal available for analysis we begin by considering the system optically, consisting of three boundary interfaces. First between the wafer and the couplant, second between the couplant and the PMT window, and third
between the PMT window and the vacuum of the PMT as illustrated below in Figure 10 with $n_x$ indicating the index of refraction of the respective material, given in Table 2 for predetermined values.

**Figure 10. Interface diagram of basic detector**

**Table 2. Pre-determined refractive indices of detector system**

<table>
<thead>
<tr>
<th>Material</th>
<th>Index label</th>
<th>Index value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN wafer</td>
<td>$n_1$</td>
<td>2.4</td>
</tr>
<tr>
<td>PMT window</td>
<td>$n_3$</td>
<td>1.5</td>
</tr>
<tr>
<td>PMT vacuum</td>
<td>$n_4$</td>
<td>1.0</td>
</tr>
</tbody>
</table>

To determine the overall transmittance between the wafer and the PMT we begin with the Fresnel Equations for reflectance for s and p polarized light respectively.\(^{64}\), given by
where $\theta$ is the angle of incidence away from normal, and $n_i$ and $n_f$ are the indices of refraction of the initial and final medium respectively, as shown in Figure 11 below.

**Figure 11. Fresnel Equations values**

With these values, the overall transmittance at an interface can then be estimated by
\[ T = 1 - \frac{1}{2} (R_s + R_p) \]  (17)

The total transmittance of a system with multiple interfaces is given by the product of the transmittance of each boundary. Applying equations (16a), (16b), and (17) for all angles between 0° and 90° at each interface, converting to transmittance, averaging over all angles for each interface, and multiplying to find the total average transmittance of the system for varying index of refraction of the couplant produces Figure 12.
As we can see the total overall transmittance is maximized by either matching the index of GaN, or the PMT window. As such, each version of the detector system used a silicon vacuum grease with index of refraction of approximately 1.5.

In all, the three versions of the detector setup utilized two different PMTs. The specification sheet of the initial PMT is unavailable but the PMT had a spectral response over a large range of photon wavelength between approximately 300-700nm with a relatively constant,
low sensitivity. Although the first PMT had a large range, to maximize the efficiency for the predicted scintillation of GaN, the PMT was replaced with a Hamamatsu R329-02 PMT. The specification sheet is included as Appendix 2 – . As indicated in the specification sheet the spectral response of the R329 PMT was excellent around the wavelength of the GaN bandgap, dropping off rapidly with increasing, and decreasing wavelength.

Finally, the portable stage of the NIM electronics setup remained constant throughout the experiments. This stage consisted of the PMT output being run through an Ortec 113A pre-amplifier to an Ortec 572A amplifier. The processing of the output of the amplifier was performed on the system available at each experimental location with system specific information not available. In general, the location specific components consist of an analog to digital converter (ADC) which outputs to a computer with varying software for signal processing. A diagram of the overall detector setup can be found below in Figure 13

![Diagram of detector setup](image)

* Indicates experimental location specific component

**Figure 13. Nuclear Instrument Module experiment setup**

Putting all these pieces together, the three detector versions are summarized below in Table 3.
Table 3. Versions of portable components of detector prototype

<table>
<thead>
<tr>
<th>Version</th>
<th>Wafer</th>
<th>Couplant</th>
<th>PMT</th>
<th>NIM Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250 µm</td>
<td>Silicon vacuum grease</td>
<td>Initial</td>
<td>Unavailable</td>
</tr>
<tr>
<td>2</td>
<td>250 µm</td>
<td>Silicon vacuum grease</td>
<td>R329-02</td>
<td>Ortec 113A/572A</td>
</tr>
<tr>
<td>3</td>
<td>1mm</td>
<td>Silicon vacuum grease</td>
<td>R329-02</td>
<td>Ortec 113A/572A</td>
</tr>
</tbody>
</table>

During transfer of the wafer between the original PMT and the R329 significant fracturing occurred due to the fragility of the 250 µm wafer. Because of this although the surface area and volume of the active volume of the detector remained approximately constant between detector versions 1 and 2, the integrity of the crystal was different.
3.2 Experiments Performed

To characterize the response of the GaN based scintillation radiation detector multiple original experiments were performed exposing the detector to various well characterized radiation spectra and analyzing the resulting scintillation spectra. To assess the response to neutron radiation the detector was exposed to effectively monoenergetic neutrons at both the Naval Surface Warfare Center, Carderock Division (NSWCCD) Positive Ion Accelerator Facility (PIAF), as well as the Army Research Laboratory (ARL) Neutron Generation Facility. Likewise, to evaluate the scintillation response to ions and validate the neutron response, the detector was exposed to energetic ions at the United States Naval Academy (USNA) Accelerator Facility. Finally, to determine the scintillation response from various other radiations probable to accompany a neutron radiation field, the detector was exposed to various hand-held gamma, beta, and alpha radiation sources both in vacuum and at atmosphere at the USNA Accelerator Facility. When describing each experiment in the following sections it will be made clear which detector version from Table 3 was used.
3.2.1 Neutron Experiments

Two main groups of neutron experiments were conducted. The first experiments conducted were performed at the NSWCCD PIAF which housed a National Electrostatics Corp. (NEC) 9SDH-2 Tandem accelerator capable of producing beams of positive ions. These experiments were performed with version 1 of the detector with a black plastic cap affixed over the crystal and end of the PMT to exclude ambient light. The second neutron experiments performed exposed version 2 of the detector to neutron radiation from a standard DT neutron generator at the ARL Neutron Generation Facility. These experiments also used the plastic cap to exclude ambient light.

For the purposes of the NSWCCD experiments, proton beams were accelerated into a thin beryllium target. Beryllium undergoes a (p,n) reaction given by

\[ p + Be^9 \rightarrow n + B^9 + Q \]  \hspace{1cm} (18)

A general diagram of this sort of reaction in the lab frame, assuming the target is at rest, is given below in Figure 14.
Figure 14. Diagram of general inelastic collision

With \( m \) indicating the mass of the respective particle, \( E_0 \) the initial energy of \( m_1 \), and \( E_3 \) and \( E_4 \) the energies of the respective outgoing particles. For consistency, we will consider \( m_3 \) to be the light product, and \( m_4 \) to be the heavy product, in this case the neutron and Be\(^7\) nucleus respectively. By accounting for the kinematics of the reaction\(^{66}\) the energy of the resulting neutron can be determined, beginning with the Q value using

\[
Q = (m_1 + m_2 - m_3 - m_4)c^2.
\]  

(19)

The total energy, \( E_t \), available for the products is given by

\[
E_t = E_0 + Q
\]

(20)

\( E_3 \) and \( E_4 \) can then be found to be given by
\[ E_3 = E_t B \left( \cos(\theta) \pm \frac{D}{\sqrt{B}} - \sin^2(\theta) \right)^2 \] (21a)

\[ E_4 = E_t A \left( \cos(\phi) \pm \frac{C}{\sqrt{A}} - \sin^2(\phi) \right)^2 \] (21b)

where A, B, C, and D are given by

\[ A = \frac{m_1 m_4 (E_0)}{(m_1 + m_2)(m_3 + m_4)} \] (22a)

\[ B = \frac{m_1 m_3 (E_0)}{(m_1 + m_2)(m_3 + m_4)} \] (22b)

\[ C = \frac{m_2 m_3}{(m_1 + m_2)(m_3 + m_4)} \left( 1 + \frac{m_1 Q}{m_2 E_t} \right) \] (22c)

\[ D = \frac{m_2 m_4}{(m_1 + m_2)(m_3 + m_4)} \left( 1 + \frac{m_1 Q}{m_2 E_t} \right). \] (22d)

Only the plus signs are used unless B>D and A>C respectively. In each of these cases the maximum angles possible are given by

\[ \theta_{max} = \sin^{-1} \left( \frac{D}{\sqrt{B}} \right) \] (23a)

\[ \phi_{max} = \sin^{-1} \left( \frac{C}{\sqrt{A}} \right). \] (23b)

This results in \( E_3 \) being given by
\[ E_3 = \frac{m_1 m_3 E_0}{(m_1 + m_2)(m_3 + m_4)} \left( \cos(\theta) \pm \sqrt{\frac{m_2 m_4}{m_1 m_3} \left( 1 + \frac{Q}{E_0} \right) \left( 1 + \frac{m_1 Q}{m_2 E_t} \right) - \sin^2(\theta)} \right)^2, \quad (24) \]

and \( E_4 \) given by

\[ E_4 = \frac{m_1 m_4 E_0}{(m_1 + m_2)(m_3 + m_4)} \left( \cos(\phi) \pm \sqrt{\frac{m_2 m_3}{m_1 m_4} \left( 1 + \frac{Q}{E_0} \right) \left( 1 + \frac{m_1 Q}{m_2 E_t} \right) - \sin^2(\phi)} \right)^2. \quad (25) \]

This shows us that for the Be\(^9\)(p,n)B\(^9\) reaction under consideration the neutron energy depends upon proton energy and the angle from the initial beam line at which the neutron is emitted. Evaluating equation (24) results in Figure 15 below, showing the neutron energy dependence upon proton energy and scatter angle.
For this reason, by selecting the angle between the initial proton beam and the detector and the proton energy at the point of the reaction we can determine the approximate energy of neutrons in our experiment.

The experiments performed at the ARL Neutron Generation Facility utilized a standard DT generator which utilizes the deuterium-tritium fusion reaction given by

$$D + T \rightarrow n + He^4 + Q$$  \hspace{1cm} (26)

Performing the same calculations as above for this reaction produces **Figure 16** below
Figure 16. D-T Fusion neutron energy at varying angle and D energy

The details for neutron experiments performed are provided below in Table 4

<table>
<thead>
<tr>
<th>Experiment location</th>
<th>Neutron energy [MeV]</th>
<th>Detector version</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSWCCD PIAF</td>
<td>2.3</td>
<td>1</td>
</tr>
<tr>
<td>NSWCCD PIAF</td>
<td>2.8</td>
<td>1</td>
</tr>
<tr>
<td>ARL</td>
<td>14.1</td>
<td>2</td>
</tr>
</tbody>
</table>
3.2.2 Ion Irradiation Experiments

Next, to assess the scintillation response of GaN to charged particles the detector was exposed to beams of various energies of protons and nitrogen ions at the USNA Accelerator Facility. The reasoning behind these experiments was twofold. First, the proposed GaN neutron detection is based in a predictable scintillation response from recoiling heavy charged particles from elastic recoil, namely nitrogen and gallium. For this reason, we would like to simulate ion recoil by impinging experimentally controlled energetic ions directly onto the detector to observe the scintillation response. Second, although the primary goal of developing this detector was to perform neutron detection and spectroscopy, GaN has been theorized to exhibit properties which would enable this detector to perform charged particle spectroscopy as well. To verify these capabilities, detector response to experimentally controlled energetic ions needed to be evaluated.

The accelerator used for these experiments was a NEC Pelletron 5SDH-1 particle accelerator housed at the USNA Accelerator Facility. The USNA NEC particle accelerator was specifically modified for these experiments. A general discussion of the NEC particle accelerator design is included in Appendix 3 – National Electrostatics Corporation Accelerator Overview.

Due to the coulomb interaction, energetic ions in atmosphere are slowed and stopped in short ranges. For protons and nitrogen ions the predicted range in dry air at sea level is shown below in Figure 17.
Figure 17. Ion range in dry air at sea level

Because of this, the beam line and experimental chamber for these experiments are held at high vacuum of approximately $10^{-6}$ torr. The basic experiment was performed by placing a scattering foil in the beam line in the experimental chamber at a selected angle, defined here as $\varphi$, and the detector within the experimental chamber at a selected angle from the beam line defined here as $\theta$. A diagram of this experimental setup can be found in Figure 18 below.
In the performed experiments, two separate scattering foils were used for various experiments, with a $\phi$ of 45° and a $\theta$ of 90° throughout. The first set of experiments, which consisted of the clear majority of those performed, utilized a 0.1 µm gold foil, while the remainder of the experiments were performed with a 152.4 µm nickel foil. The scatter foil was employed to both reduce the beam intensity incident upon the detector and allow for additional selection of the ion energy impinging upon the detector.

Typical currents of ions in the beam are hundreds of nA, therefore impinging the beam directly into the detector would lead to approximately $6.24 \times 10^{11}$ ions striking the detector per second, exceeding the time resolutions of the attached electronic analysis systems. As a figure of
merit, the fall time of the pre-amplifier used is listed as 50µs, therefore ideally, we would like to be seeing events below ~2000 per second.

Considering the scatter foil then, for each ion incident upon the foil there is a small chance it will be scattered, estimated by the Rutherford differential cross section

$$\frac{d\sigma}{d\Omega} = \left( \frac{Z_1 Z_2 \alpha \hbar c}{4 E_0 \sin^2 \left( \frac{\theta}{2} \right)} \right)^2$$

where $Z_1$ and $Z_2$ are the atomic number of the ion and target respectively, $\alpha$ is the fine structure constant, $E_0$ is the initial ion energy, and $\theta$ is the deflection angle. Additionally, the fraction of ions scattered $F_s$ can be determined to be approximately

$$F_s = \frac{N_A \rho \sigma}{A}$$

where $N_A$ is Avogadro’s number, $L$ is the foil thickness, $\rho$ the foil density, $\sigma$ the scatter cross-section, and $A$ the atomic number of the scatter material. The differential Rutherford cross-section is sufficient to provide a first order analysis of the experimental scatter system. For higher accuracy additional modeling can be performed, including using the screened coulomb potential which would account for the screening effects of atomic electrons.

Using equation (27) in equation (28), accounting for the solid angle of the detector from the scattering foil and evaluating for varying angles and energies assuming a beam of hydrogen on a gold target, we can determine the approximate fraction of ions scattered into the detector, shown below in Figure 19.
This shows a reduction in the number of ions striking the detector using the described setup to between $10^3$ and $10^5$ per second, depending upon the initial energy. These rates are much closer to the capabilities of the processing electronics, and to account for signal pile up due to events exceeding the system capacity, pile up rejection was employed to reject distorted signals. In this situation, the scattered fraction, and therefore event on detector rate varies as the square of the projectile and target Z product, meaning that for nitrogen projectiles with otherwise the same parameters the rate on the detector would be approximately 200 times larger.
To observe the energy transfer effect, we look at the ratio of $E_1$ and $E_2$ to the initial projectile energy for varying angles and mass ratios as determined by equations (12) and (14), seen below in Figure 20.

![Figure 20. Particle scattering energy distribution](image)

This shows us that for proton experiments where the mass ratio of hydrogen to gold is roughly 0.006, practically no energy is lost due to scatter. On the other hand, for nitrogen
experiments with a mass ratio of approximately 0.07, the scattered ion losses approximately 13.3% of its energy. This energy reduction was necessary as the accelerator was only capable of reliably producing nitrogen beams of between 600 keV to 3 MeV. Therefore, assuming a thin target which produces monoenergetic scatter we could investigate nitrogen energies down to approximately 520 keV. Relating this back to neutron/nitrogen elastic scatter, 600 keV nitrogen would correspond to the maximum energy transfer from a 2.4 MeV neutron, whereas a 520 keV nitrogen scatter would correspond to the maximum energy transfer from a 2 MeV neutron. Therefore, to first calculations, the use of a gold scatter foil provided 400 keV more neutron recoil relatable data.

Unfortunately, the energy reduction also affects the accuracy of the Rutherford approximation as a primary assumption is that the scattered particle does not lose energy to the scatterer, meaning that for increased energy transfer, the Rutherford cross section would be expected to be decreasingly accurate.

As mentioned earlier, during the ion experiments a second, thicker wafer of GaN became available which was doped to a much lower concentration. To investigate the effects of an increased thickness and decreased doping, proton experiments were performed utilizing the new wafer after both proton and nitrogen experiments had been completed with the thin wafer (detector version 2). Due to the unavailability of gold scatter foils after completing the experiments with version 2 of the detector, a 152 µm Å nickel scatter foil was used for these experiments with all other experimental factors the same. During the previously discussed experiments the maximum energy loss was 13.3%, reducing the reliability of the Rutherford approximation as a primary assumption is that the scattered particle does not lose energy to the scatterer, meaning that for increased energy transfer, the Rutherford cross section would be expected to be decreasingly accurate.
cross section, but not invalidating it. However, due to the mass difference between nickel and gold, the energy transfer from nitrogen to nickel is approximately 36% of the initial energy for 90° scatter whereas the energy transfer from proton to nickel is approximately 3.5%. For this reason, nitrogen scatter off nickel was not performed due to the unreliability of the scattering.

With all of this in mind, Table 5 below presents the ion, initial ion energy when entering the experimental chamber, scatter foil, estimated ion energy on detector after scatter, and detector version for the ion experiments performed at the USNA accelerator facility.

**Table 5. Ion experiments performed at USNA Accelerator Facility**

<table>
<thead>
<tr>
<th>Ion</th>
<th>Charge State at Magnet</th>
<th>Initial ion energy [MeV]</th>
<th>Scatter foil</th>
<th>Maximum scattered ion energy [MeV]</th>
<th>Detector version</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>+1</td>
<td>1.2</td>
<td>1000Å, Au</td>
<td>1.19</td>
<td>2</td>
</tr>
<tr>
<td>p</td>
<td>+1</td>
<td>1.4</td>
<td>1000Å, Au</td>
<td>1.39</td>
<td>2</td>
</tr>
<tr>
<td>p</td>
<td>+1</td>
<td>1.55</td>
<td>1000Å, Au</td>
<td>1.53</td>
<td>2</td>
</tr>
<tr>
<td>p</td>
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<td>1000Å, Au</td>
<td>1.78</td>
<td>2</td>
</tr>
<tr>
<td>p</td>
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<td>2</td>
<td>1000Å, Au</td>
<td>1.98</td>
<td>2</td>
</tr>
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<td>2.18</td>
<td>2</td>
</tr>
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<td>2.35</td>
<td>1000Å, Au</td>
<td>2.38</td>
<td>2</td>
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<tr>
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<td>2.66</td>
<td>1000Å, Au</td>
<td>2.63</td>
<td>2</td>
</tr>
<tr>
<td>N</td>
<td>+2</td>
<td>0.6</td>
<td>1000Å, Au</td>
<td>0.52</td>
<td>2</td>
</tr>
<tr>
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<td>2</td>
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<td>N</td>
<td>+3</td>
<td>1.5</td>
<td>1000Å, Au</td>
<td>1.3</td>
<td>2</td>
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<tr>
<td>N</td>
<td>+3</td>
<td>2.25</td>
<td>1000Å, Au</td>
<td>1.95</td>
<td>2</td>
</tr>
<tr>
<td>N</td>
<td>+3</td>
<td>3</td>
<td>1000Å, Au</td>
<td>2.60</td>
<td>2</td>
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<td>p</td>
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<td>2</td>
<td>152 µm, Ni</td>
<td>1.93</td>
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<td>p</td>
<td>+1</td>
<td>2.5</td>
<td>152 µm, Ni</td>
<td>2.42</td>
<td>3</td>
</tr>
<tr>
<td>p</td>
<td>+1</td>
<td>2.75</td>
<td>152 µm, Ni</td>
<td>2.66</td>
<td>3</td>
</tr>
</tbody>
</table>
As indicated in Table 5, selection of the ion charge state entering the experimental chamber was possible by tuning the steering magnet appropriately.
3.2.3 Other Radiations

Finally, as many of the environments containing neutron radiation that the GaN detector would be used in also have components of other radiations, we also tested the scintillation response to gamma, beta, and alpha radiations by placing hand-held sources a set distance from the unshielded detector and recording the resulting scintillation spectrum. These experiments were performed in the USNA Accelerator Facility, in the accelerator experimental chamber in vacuum for two reasons. First, due to the low penetrating power of beta and alpha radiations the experiments needed to be performed with an unshielded detector, necessitating a light free environment. Second, although the radiation spectra of the sources used is well characterized, to reduce environmental shielding effects the experiments needed to be performed in vacuum. To account for both requirements the accelerator experimental chamber was used with no ion beam being introduced into the chamber. The general experimental setup is presented below in Figure 21.
Figure 21. Radioactive source experimental setup

The sources used, type, and energy of radiation emitted, along with detector version are presented below in Table 6.
Table 6. Handheld sources experiments

<table>
<thead>
<tr>
<th>Source</th>
<th>Activity(^1) [µCi]</th>
<th>Radiation Type</th>
<th>Energy [keV]</th>
<th>Distance (d)</th>
<th>Detector Version</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{60}\text{Co}) (^{(2)})</td>
<td>18.093</td>
<td>Gamma</td>
<td>1332 (peak), 1173 (peak)</td>
<td>20 cm</td>
<td>2</td>
</tr>
<tr>
<td>(^{137}\text{Cs}) (^{(2)})</td>
<td>8.048</td>
<td>Gamma</td>
<td>662 (peak)</td>
<td>20 cm</td>
<td>2</td>
</tr>
<tr>
<td>(^{241}\text{Am})</td>
<td>1.417</td>
<td>Gamma/X-ray</td>
<td>59.54 (peak)</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>26.4 (peak)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>17.8 (peak)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13.9 (peak)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alpha</td>
<td>5486 (85%)</td>
<td>5 mm</td>
<td>2,3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5443 (13%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5388 (2%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{14}\text{C})</td>
<td>0.145</td>
<td>Beta</td>
<td>49.5 (average)</td>
<td>5 mm</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>156 (endpoint)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{99}\text{Tc})</td>
<td>0.040</td>
<td>Beta</td>
<td>85 (average)</td>
<td>5 mm</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>292 (endpoint)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{36}\text{Cl})</td>
<td>0.019</td>
<td>Beta</td>
<td>251.2 (average)</td>
<td>5 mm</td>
<td>2</td>
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<tr>
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<td></td>
<td></td>
<td>709 (endpoint)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{90}\text{Sr}/\  ^{90}\text{Y})</td>
<td>0.011/0.008</td>
<td>Beta</td>
<td>186 (average)</td>
<td>5 mm</td>
<td>2</td>
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<td></td>
<td></td>
<td></td>
<td>546 (endpoint)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>934 (average)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2283 (endpoint)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note 1: All activities decay corrected
Note 2: Source was encapsulated, shielding all radiations except photon

Experiments performed using \(^{60}\text{Co}\), and \(^{137}\text{Cs}\) employed encapsulated sources, shielding all beta radiation. Additionally, \(^{241}\text{Am}\) experiments intended to observe low energy photon radiation effects utilized a thin sheet of paper as shielding to block alpha particles while allowing photon irradiation to reach the spectrometer.
4 RESULTS AND ANALYSIS

4.1 Neutron irradiation scintillation in Gallium Nitride

Scintillation pulse height spectra with background subtracted, normalized, and calibrated where applicable for the neutron experiments discussed earlier are presented in Figure 22 and Figure 23.

![Figure 22. Energy calibrated pulse height spectra from 2.3 and 2.8 MeV neutron irradiations](image)

Figure 22. Energy calibrated pulse height spectra from 2.3 and 2.8 MeV neutron irradiations
As is evident in the spectra, between the 2.32 MeV and 2.82 MeV experiments the lower level discriminator was increased to reduce the deadtime of the detector. Additionally, as was mentioned before, spectra recording was performed using different ADCs and software. For that reason the 14.1 MeV experiment could not be accurately calibrated, leaving the horizontal axis in channel instead of energy. For a more detailed discussion regarding the energy calibration of Figure 22 and the applicability to Figure 23, see Appendix 4.

To understand the features present in each of these spectra we recall the ion recoil predictions seen in Figure 5, Figure 6, and Figure 7. The contribution from gallium in Figure
22 and Figure 23 can be seen below 100 keV, although the prominent peak seen in Figure 5 and Figure 6 is lost due to imperfect detector resolution and the previously observed partial differential cross section of low recoil energies for both ions creating a large low energy signal. A similar structure can be seen in Figure 23, with the nitrogen continuum ranging up to nearly 3 MeV, and the low energy portion increasing drastically with decreasing recoil energy, as predicted by Figure 7. Analyzing Figure 22 more closely we see endpoint channels, showing a numerical increase as is predicted with increasing maximum ion recoil energy. In the 14 MeV spectrum we see a large low energy component, as well as a continuum above background present up to channel 16000. In the lower energy experiments, there is a prominent peak around 200 keV in each spectrum. Although the recoil spectra predict a gallium peak, the peak that is present appears to be of too high energy. To account for this feature, we must consider non-elastic reactions undergone by nitrogen and gallium during neutron irradiation. The most likely non-elastic reaction is the $^{14}$N(n,α)$^{11}$B reaction, with the ratio of (n,α) to (n,el) cross sections provided below in Figure 24.
Figure 24. Ratio of $^{14}$N (n,α) to (n,el) total cross sections

As can be seen, although the (n,α) reaction does not become dominant, it becomes non-negligible in this energy range. To see the effect then we perform the same analysis as before with the $^7$Li(p,n)$^7$Be and D-T fusion reactions, looking at the boron energy as a function of the alpha emission angle, producing Figure 25.
Figure 25. $^{14}\text{N}(\text{n},\alpha)^{11}\text{B}$ alpha emission angle vs. boron energy

As we can see the boron energy can range from 180 keV and up, depending upon the emission angle and the initial neutron energy. Although differential cross section data is not available for this reaction in the energy range of interest, the five nearest normalized differential cross sections are presented below, with scatter angles converted to resulting boron energy in a similar manner to the earlier conversions to recoil energy, in Figure 26.
For the available energies we see that the low energy boron production, corresponding to low angle alpha emission, are more probable. Assuming this trend continues for neutrons of 2.3 and 2.8 MeV, we would expect to see a peak in the 200 keV range, exactly as was seen experimentally. Additionally, we can look at the relative intensity of the peak in the 2.3 MeV spectrum. To do this we begin by assuming that the underlying continuum spectrum is continuous, and we separate out the peak from the continuum, as shown in Figure 27 below.
As we can see the continuum spectrum closely resembles the elastic ion recoil spectra predicted in Figure 5. Analyzing further, if the peak is due to the \((n,\alpha)\) reaction we would expect the ratio of total peak counts over continuum counts to be approximately equal to the respective cross sections. Therefore, if we take the ratio of areas under the peak and continuum spectra we get 0.1, approximately the same as the ratio of the \(^{14}\text{N} (n,\alpha)\) to (n,el) cross sections at 2.3 MeV as seen in Figure 24. At first glance we may assume that the scintillation pulses from the boron and alpha would not be distinguishable due to the relatively low and similar stopping times being estimated in the tenths of picoseconds and integration times of the electronics vastly exceeding
these. Regardless, we can expect to see the scintillation pulse from the boron separated from the alpha because of the ionization, and resulting ionization density due to the ions in the spatial region around the recoil.

In order to understand this we first consider the recoiling boron ion and alpha particle separately. Each particle will carry energy away from the site of the recoil, as determined previously, and subsequently lose this energy to the surrounding GaN via processes discussed in chapter 2. This energy loss leads to ionization and electron hole creation in the immediate area of the particle. For an arbitrary particle \( c \), with track \( r_c \) a simplified illustration of this can be seen below in Figure 28.

![Figure 28. Charged particle induced ionization region](image)

Now considering both ions at the same time, the ionization region around the entire track of the boron ion will coincide with the beginning of the ionization region of the alpha ion, as seen in below in Figure 29 for an alpha emitted at 90° for illustration of the concept.
Figure 29. Illustration of overlapping ionization region of $^{14}$N ($n,\alpha$)$^{11}$B products

For this reason, the ionization density in the region immediately surrounding the boron track will be greater than the ionization density of the region surrounding the track of the alpha which is not coincident with the boron track. Performing a simulation of corresponding boron and alpha energies utilizing SRIM shows that the ionization from both particles is roughly equivalent, doubling the ionization density in the region around the boron track.

It has been shown\textsuperscript{73} that scintillation pulse rise time in CsI(Tl) can be drastically affected by ionization density, up to factors of 2 to 3. Unfortunately similar data is not available for GaN under ion irradiation. Previous studies\textsuperscript{74} have found carrier lifetimes in GaN as long as 2 ns. Therefore the resulting scintillation pulse could be expected to contain two separate peaks, as envisioned below in Figure 30.
Figure 30. Model pulse shape in processing electronics from the $^{14}$N (n,$\alpha$)$^{11}$B reaction

In this instance, the initial high energy peak from the energetic alpha particle exceeds the highest bin in the ADC and would be discarded, leaving the remaining boron pulse to be processed and binned. The resulting accumulation of boron pulses would then lead to the peak seen in Figure 27. Unfortunately the electronic equipment used for these experiments was not well documented. However, sufficiently fast electronics with proper pile-up processing capabilities were available at the NSWCCD PIAF. It is important to note that this model depends not only upon the size of the ionization region surrounding each track, but the actual effects of
this ionization density on the scintillation pulse characteristics. Investigation into both of these effects has not previously been carried out for GaN. For this reason, further analysis is required.

Due to the previously mentioned increase of the lower level discriminator removing a significant portion of the lower energy recoil counts we cannot perform a similar analysis of the 2.8 MeV data. Qualitatively though, looking back at Figure 22 we can now see that, both the peak energy and spread increase with increasing neutron energy, as should be expected.

Therefore, assuming ion energy dependent scintillation, we can conclude that by accounting for the most probable reactions of neutrons with GaN, not only can we predict the resulting pulse height spectrum, but we have multiple methods of retrieving neutron energy information from the resulting spectra including the spectrum endpoint and shifting non-elastic reaction peak locations.
4.2 Proton irradiation scintillation in Gallium Nitride

Scintillation pulse height spectra for the proton experiments utilizing detector version 2 were recorded and normalized to allow for peak comparison. The results for each proton experiment are shown below in Figure 31, with the cumulative results presented in Figure 32.
Figure 31.a. 1.2 MeV

Figure 31.b. 1.4 MeV

Figure 31.c. 1.55 MeV

Figure 31.d. 1.8 MeV
Figure 31. Individual proton scintillation pulse height spectra for detector version 2
Figure 32. Cumulative proton experiment results for detector version 2

In each spectrum we note a pronounced peak at increasing channel number, with non-gaussian tails both above and below. In addition, at higher proton energies distortions begin to appear below the peak, as well as a massive low energy component in the lowest few hundred channels. To explain these features, we must investigate the actual radiation environment the detector is in.

When assuming only scatter from the foil, and an infinitesimal foil thickness we would predict each of these spectra to be essentially mono-energetic at the energy presented in Table 5 as the respective maximum ion post-scatter energy. However, as these assumptions do not carry
over to the actual performance of the experiment we must take these factors into account to interpret the experimental results. First, as was mentioned earlier, of all ions incident upon the scattering foil only a small fraction is scattered into the detector while the remainder of the beam passes through, losing energy to coulomb interactions and emerging at angles dependent upon any scattering which took place within the foil. In these experiments no collimation was available within the experimental chamber, meaning that with regards to ions on the detector, in addition to the primary desired ion scatter from the foil additional secondary scatter could come from the experimental chamber wall. To approach this issue, we estimate the cross section for an ion to be scattered at an angle greater than θ as

$$\sigma = \pi \left( \frac{Z_1 Z_2 e^2}{E_0} \right) \left( \frac{1 + \cos \theta}{1 - \cos \theta} \right)$$  \hspace{1cm} (29)$$

For initial ion energy $E_0$, and $k$ Coulomb's constant. Evaluating this expression for the extremum experimental proton values for varying angle results in Figure 33.
Figure 33 shows that much of the beam is effectively not scattered during transit through the gold foil. We assume then that any ion not scattered toward the detector in the foil continues straight. Therefore, to understand the ion spectrum on the detector we must estimate both the primary ion spectrum scattered from the target and the secondary spectrum created by the chamber wall, constructed out of stainless steel. A diagram of this situation is shown below in Figure 34.
Figure 34. Ion experimental chamber diagram

Estimating the scatter spectrum from the foil and the experimental chamber both entail a similar calculation. This calculation accounts for the energy lost to the medium between incidence and scatter, energy lost to scatter, and energy lost to the medium between scatter and exiting, or

$$E_f = kE_b - \Delta E_{exit}$$

(30)

where $E_f$ is the final ion energy emerging from the medium, $k$ is the kinematic factor accounting for the energy lost to scatter, $\Delta E_{exit}$ is the energy lost to the medium between the
point of scatter and emerging from the foil, and $E_b$ is the energy of the ion at the point of scatter, as determined by

$$E_b = E_a - \Delta E_{enter}$$  \hspace{1cm} (31)

where $E_a$ is the initial ion energy and $\Delta E_{enter}$ is the energy lost between entering the medium and the scatter. $\Delta E_{enter}$ and $\Delta E_{exit}$ take the form of an integral of $\frac{dE}{dx}$ over the corresponding distance and energy. For ease of calculation these can be iteratively approximated by

$$\Delta E = \sum_{i=1}^{n} E_{i-1} - E_i$$  \hspace{1cm} (32)

where $E_i$ is given by

$$E_i = E_{i-1} - dx \left( \frac{dE}{dx} \right)_{E_{i-1}}$$  \hspace{1cm} (33)

where $dx$ is an appropriately chosen step distance such that $ndx$ is the total distance the ion travels through the medium and $E_0$ of $\Delta E_{enter}$ and $\Delta E_{exit}$ are $E_a$ and $E_b$ respectively. Adding this all together, equation (30) becomes

$$E_f = k \left( E_a - \sum_{i=1}^{n} dx \left( \frac{dE}{dx} \right)_{E_{i-1}} \right) - \sum_{j=1}^{i} dx \left( \frac{dE}{dx} \right)_{E_{j-1}}.$$  \hspace{1cm} (34)

By iteratively performing this calculation and recording the Rutherford cross section paired with the $E_f$ at each step of the first summation index, we can produce an expected ion spectrum on the detector for each initial ion energy where the cross section predicts the intensity of the matched final ion energy. To accomplish this, I have written an original program, provided
in Appendix 5 which allows this calculation to be carried out for user specified geometry, ion, and scatterer, utilizing externally provided stopping power data in the form of output from the Stopping and Range of Ions in Matter.

Using the program with stopping powers for gold and stainless steel, and due to the typical atomic abundances of isotopes in stainless steel, assuming the scatter in the experimental chamber wall is off of iron, we calculate the expected spectra from each of the proton energies investigated producing Figure 35 below.
Figure 35.a. 1.2 MeV

Figure 35.b. 1.4 MeV

Figure 35.c. 1.55 MeV

Figure 35.d. 1.8 MeV
As can be seen, the primary scatter provides a nearly monoenergetic beam at every energy as intended. Unfortunately the secondary scatter contributes a continuum ranging from 0 to just below the primary scatter beam, as would be expected with the kinematics of proton
scattering on gold and iron. This does not entirely explain the spectral features noted earlier which requires accounting for the detector resolution. To do this, we begin by taking the spectrum from **Figure 35** showing the least deformation, which is the spectrum from the 1.2 MeV experiments, and convert the channel number to energy assuming the peak location is the proton peak location and a linear conversion with respect to proton energy. Doing so produces **Figure 36** below

![Figure 36. 1.2 MeV proton energy converted spectrum](image)

Where indicators have been added to show the full width half maximum (FWHM) locations. As can be seen, the FWHM is about 1000 keV, giving a detector resolution of 83% at 1.2 MeV. To update the spectra presented in **Figure 35** a thru h, we assume a constant resolution
over the proton energy range and perform averages at each point over the adjacent channels equivalent to the determined resolution. Doing so for every spectrum creates Figure 37 below.
Figure 37.a. 1.2 MeV

Figure 37.b. 1.4 MeV

Figure 37.c. 1.55 MeV

Figure 37.d. 1.8 MeV
As can be seen, by accounting for the detector resolution we see the non-gaussian features both above and below the primary peak emerging in the same manner as seen experimentally. Due to the unreliability introduced through the detector resolution on exact
scintillation energy dependence on initial ion energy, the endpoint of each spectrum is the best figure of merit regarding scintillation. The reason for this is that in each ion spectrum the gold scatter is separated entirely from the secondary scatter, and therefore we can assume that the endpoint of each spectrum corresponds with the maximum scintillation efficiency for a known ion energy. Conversely, the convolution of secondary scatter continuum with the primary scatter peak shifts effectively downshifts the peak location from the true primary scatter peak. Therefore, plotting the maximum proton energy on detector from gold scatter versus the endpoint channel produces Figure 38 below.

![Figure 38. Proton energy vs. endpoint channel](image)
In order to determine the endpoint, the peak normalized spectra presented in Figure 31 were analyzed, with the endpoint defined to be the point where the spectrum reaches 1% of the peak height. As we can see, the scintillation intensity increases nearly linearly with the proton energy, affirming previous predictions\textsuperscript{76} regarding GaN scintillation from proton irradiation.
4.3 Nitrogen irradiation scintillation in Gallium Nitride

Next, the scintillation pulse height spectra for the nitrogen experiments described earlier are provided below in Figure 39.

![Figure 39.a. 0.6 MeV](image1)

![Figure 39.b. 0.8 MeV](image2)

![Figure 39.c. 1.2 MeV](image3)

![Figure 39.d. 1.5 MeV](image4)
Due to the mass and charge of the particles involved in scattering, we can no longer assume that the secondary scatter is well described using the Rutherford cross section, identical to the difficulty encountered in analyzing the nickel-nitrogen recoil. Therefore, we begin estimating the primary spectra analogous to our primary scatter approach as before, creating Figure 40.
Figure 40. Estimated primary nitrogen scatter spectra on detector

As is expected due to the increased stopping power of nitrogen, the primary scatter spectra are far more dispersed than the almost mono-energetic proton spectra. Next, although we cannot determine the secondary nitrogen spectrum in each experiment with any degree of certainty, we can use the results of Figure 20 to determine the maximum scattered nitrogen energy of the secondary scatter component for each energy. To do this, we first use stopping powers for nitrogen in gold to determine the approximate maximum nitrogen energy emerging from the foil and hitting the experimental chamber wall. Then, using equation (12) we can determine the maximum energy nitrogen recoil off iron, assuming no energy is lost before scatter. Doing this,
and including the minimum nitrogen energy from primary scatter from Figure 40, produces

Table 7 below

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.06</td>
<td>0.50</td>
<td>0.21</td>
</tr>
<tr>
<td>0.8</td>
<td>0.25</td>
<td>0.65</td>
<td>0.27</td>
</tr>
<tr>
<td>1.2</td>
<td>0.6</td>
<td>0.95</td>
<td>0.40</td>
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<tr>
<td>1.5</td>
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<tr>
<td>3</td>
<td>2.06</td>
<td>2.59</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Plotting the initial energy vs. the minimum primary scatter energy and maximum secondary scatter energy produces Figure 41 below.
Although we cannot reproduce the spectra observed experimentally through analysis, we can see that the nitrogen spectra observed experimentally make sense in that the higher energy spectra show a peak, assumed to be from the primary gold scatter, separated from the low energy recoil, assumed to be from the secondary nitrogen scatter, while in the low energy experiments the secondary scatter overlaps the primary scatter, creating the spectral features observed in Figure 39 a thru f. We see the peak emerging at an energy above the intersection in Figure 41 due to the resolution, as discussed earlier. Once again though, due to the kinematics observed through our analysis we see that the maximum ion on detector energy and the spectrum endpoint

**Figure 41. Nitrogen scatter characteristics**

![Graph showing scattered energy vs initial energy with two lines, one solid for minimum primary scatter and one dashed for maximum secondary scatter.](image)
are the best figures of merit regarding the scintillation intensity. Plotting the maximum nitrogen energy on detector versus the spectrum endpoint for each experiment produces **Figure 42** below.

![Figure 42: Nitrogen ion energy on detector vs. endpoint channel](image)

As with the proton data, we see that the endpoint channel increases linearly with the maximum nitrogen energy on the detector. In the case of the nitrogen spectra, the endpoint was determined based upon features present in the spectrum. For those spectra that exhibited peaks, the endpoint was determined in the same way that the proton spectrum endpoints were determined. In the case of spectra with no discernable peak, the endpoint was assumed to be the channel where 99.9% of the counts were found below.
Proceeding, in order to make this data relevant to the previously described elastic recoil neutron spectroscopy we would like to generalize the scintillation response of GaN to ions. To do this we begin by assuming that the scintillation efficiency, or luminescence per unit energy deposited, is described in the manner suggested by Birks\textsuperscript{77}, commonly employed for inorganic scintillators\textsuperscript{78,79}, or

\[
\frac{dL}{dE} = \frac{a}{1 + b \left( \frac{dE}{dx} \right)}
\]

(35)

Where \( \frac{dL}{dE} \) is the light output per unit of energy deposited, a and b fitting parameters, and \( \left( \frac{dE}{dx} \right) \) the stopping power. Looking at equation (35) qualitatively, we see that it relates the scintillation output of GaN to the stopping power of the ion under consideration, providing the connection desired for application to ion elastic recoil scintillation production. In our situation we can use the endpoint channel as a proxy indicator for the light output with energy deposited assumed to be the initial ion energy, drawing an equivalence between \( \frac{dL}{dE} \) and the endpoint channel number. In order to allow for simple comparison with previously determined experimental data for other scintillators, we first convert the channel to an approximate photon output, a detailed discussion of which can be found in Appendix 6, and normalize the result to that of the 662 keV gamma from \(^{137}\text{Cs}\). This result is obtained from data presented later, in section 4.4.3. Next, with these \( \frac{dL}{dE} \) values we solve equation (35) for b, resulting in
\[
b = \frac{\frac{a}{(\frac{dL}{dE})} - 1}{\frac{(dE)}{dx}}.
\]  
(36)

Now we numerically optimize the a and b parameters, using the previously calculated \(\frac{dL}{dE}\) and stopping powers by iteratively calculating the b values which would result from a particular a value using equation (36), average the resulting b values, and calculate the total square displacement of the experimental data from the subsequent model using the specified a, and averaged b values. The parameters minimizing this metric are provided below in Table 8.

Table 8. Calculated Birks parameters for Gallium Nitride and other common scintillator materials

<table>
<thead>
<tr>
<th>Material</th>
<th>a</th>
<th>(b \left[ \frac{g}{MeV cm^2} \right] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN</td>
<td>1.883</td>
<td>1.83x10^{-4}</td>
</tr>
<tr>
<td>NaI(Tl)^a</td>
<td>0.905</td>
<td>9.10x10^{-4}</td>
</tr>
<tr>
<td>CsI(Tl)^a</td>
<td>1.08</td>
<td>1.29x10^{-3}</td>
</tr>
<tr>
<td>GSO(Ce)^a</td>
<td>1.03</td>
<td>3.22x10^{-3}</td>
</tr>
</tbody>
</table>

Note a: Parameters obtained from reference 74

Looking at the comparison between GaN and other common scintillator materials, we see both a larger a value and smaller b value. The larger a value indicates that as the scintillation outputs were normalized to the \(^{137}\)Cs, GaN provides a larger ion signal compared to gamma induced signal which is useful for a device based upon ion induced scintillation. This may be misleading as we will see later in section 4.4.3 due to the potential for incomplete energy deposition of the \(^{137}\)Cs gamma used for normalization leading to a low estimate of the photon response of GaN to the gamma. Additionally, a lower b value indicates a lower quenching effect, meaning that for
ions heavier ions with intrinsically larger stopping power, GaN presents an advantage in the form of lower quenching, especially useful in terms of this device as it is based on heavy ion recoils. Finally, these comparisons may be further clouded by our use of the endpoint for spectrum analysis.

Moving back to our device, using the values presented for GaN in Table 8, we plot the result of equation (24) with the experimental data, producing Figure 43 below.

![Figure 43: Predicted scintillation efficiency and experimental results](image-url)
Finally, looking at the experimental data obtained using version 3 of the detector, we get Figure 44 below.

**Figure 44. Detector version 3 proton spectra**

We can already observe stark differences between these spectra and the previously observed spectra obtained with detector version 2. To begin with, the full energy peak from foil scatter is no longer present, instead there is a single continuum, with endpoint at a much lower channel for each experiment. Performing a similar endpoint channel analysis and including the data from detector version 2 for comparison produces Figure 45 below.
As we can clearly see, although increasing the detector thickness theoretically would increase the amount of neutron data observed due to the increased probability of neutron interaction, the scintillation efficiency decreases drastically, by roughly 75%. Unfortunately, due to availability of materials we could not isolate the thickness and doping variables, meaning that to verify the contribution to scintillation loss from each the decreased doping leading to less overall scintillation, and the increased thickness leading to increased self-absorption of emitted photons further experiments need to be performed.
With the scintillation response of GaN observed, we can look back at the neutron data analyzed earlier, affirming our conclusions. As we have seen scintillation intensity in GaN due to ions increases with ion energy and decreases in a predictable manner with increasing ion stopping power. Therefore, we see that the previous determination of the scintillation response from neutrons fits the recorded data perfectly. As seen earlier, the gallium recoil peaks from neutron recoil was concealed, merging with the low energy nitrogen recoil due to the predicted decreased scintillation efficiency for gallium from increased stopping power. In addition, the peak earlier identified as the boron recoil from the \((n, \alpha)\) reaction should indeed be seen at the relative position it was seen due to the similar scintillation characteristics predicted for boron and nitrogen ions. Therefore, once again we have seen that the GaN detector provides multiple methods of determining neutron energies, including elastic ion recoil and non-elastic reactions. In addition, with some improvement in detector resolution the scintillation based GaN detector could also theoretically be used to perform charged particle spectroscopy, as shown by the charged particle experimental results discussed above.
4.4 Other Radiations

4.4.1 Alpha

The normalized alpha scintillation pulse height spectra of Am241 recorded using both detector versions are presented below in Figure 46 below.

![Figure 46. Alpha scintillation pulse height spectra](image)

Like the spectra of protons earlier, we see that the location of the alpha peak of detector version 3 indicates that the less doped, thicker wafer results in approximately 75% less
scintillation. In addition, we can calibrate the x axis for each spectrum in a similar manner as in Figure 36, resulting in Figure 47 below.

**Figure 47. Calibrated Am-241 alpha spectra**

As can be seen, the detector resolution does not provide separation of the multiple alpha energies emitted by $^{241}$Am, and the various photon radiations give rise to a low energy signal, fully separated from the alpha peak seen. Due to the various forms of energy deposition the energy calibration performed will not accurately determine both the photon and alpha energies. Once again, calculating the resolution of each detector version we see resolutions of 53.6% and
62.1% for version 2 and 3 respectively for a 5.5 MeV alpha, further demonstrating the degrading effect on detector performance of increasing the width and decreasing the doping. In addition, we perform the same analysis with the alpha spectrum produced by detector version 2 as was performed with the ion data, with endpoint determination as described for the nitrogen spectra, and update Figure 43 accordingly, resulting in Figure 48 below.

![Gallium Nitride ion scintillation efficiency](image)

**Figure 48. Gallium Nitride ion scintillation efficiency**

This update shows us that the recorded alpha data corresponds with the scintillation model developed earlier and giving further evidence of the interpretations of both ion and neutron data.
4.4.2 Beta irradiation scintillation in Gallium Nitride

Scintillation pulse height spectra recorded during the beta experiments listed in Error! Reference source not found. are presented below in Figure 49.

![Beta experiment results](image)

**Figure 49. Beta experiment results**

Although the spectra exhibit an increasing endpoint with increasing beta energy, the overall shape of the spectra do not reflect the actual beta distribution, with the low energy portion of the spectra over-represented. This can be attributed to incomplete energy deposition. To observe the effect of incomplete energy deposition, we estimate the channel of the endpoint
of each spectrum. In the case of full energy deposition and conversion to scintillation, this channel would correspond to the endpoint beta energy and would be expected to increase linearly. The endpoint channel determined by analyzing activity normalized spectra, and corresponding beta energies are given below in Table 9.

Table 9. Beta endpoint channels

<table>
<thead>
<tr>
<th>Source</th>
<th>Endpoint channel</th>
<th>Endpoint energy [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-14</td>
<td>140</td>
<td>156</td>
</tr>
<tr>
<td>Tc-99</td>
<td>265</td>
<td>292</td>
</tr>
<tr>
<td>Cl-36</td>
<td>500</td>
<td>709</td>
</tr>
<tr>
<td>Sr/Y-90</td>
<td>1350</td>
<td>2283</td>
</tr>
</tbody>
</table>

In the case of the beta experiments, endpoints were determined in the same manner as the nitrogen spectra which did not exhibit a peak. By plotting the endpoint energy vs. channel, we get Figure 50 below.
As mentioned above, the beta energies present should provide a linear endpoint increase in scintillation output if all beta energy is deposited in the crystal, which we see is in fact the case. However, although the endpoint corresponds to the maximum energy deposited in the crystal, it does not reflect the most likely energy deposition from the radiation as is easily verifiable via the spectra in Figure 49. There are three major factors which would contribute to this phenomenon, beta range exceeding the wafer thickness, backscatter, and bremsstrahlung. To start with, we look at the range of electrons, as provided by the NIST ESTAR database, shown below for GaN in Figure 51.
As can clearly be seen, the range of electrons in GaN exceeds the wafer thickness well below the highest energy beta observed experimentally. We therefore define $E_{\beta \text{max}}$ as the maximum energy electron which will be completely stopped within the wafer assuming a straight path. For wafers of 250 µm $E_{\beta \text{max}}$ is approximately 350 keV. Therefore, we would expect electrons incident on the wafer with energy greater than $E_{\beta \text{max}}$ to completely penetrate the wafer, only losing a fraction of their energy, which would result in an over-representation of the low energy portion of the spectrum, as observed experimentally. The underlying assumption here is that the electron travels a straight path through the wafer. As the coulomb interactions can...
deflect the electron, and the electron mass is low, significant deviations from a straight path can occur. For this reason, we do see full energy deposition demonstrated in Figure 50, albeit at a lower relative intensity than is present in the actual beta spectra as observed in Figure 49. Next, by evaluating equation

$$\frac{dE_p}{dx} \left/ \frac{dE_e}{dx} \right. \approx \frac{EZ}{700}$$

(4)

for GaN we get Figure 52 below.
As we can see, for the energies being discussed the loss of energy to bremsstrahlung is non-zero, on the order of 1-3% for the highest energy betas observed from Sr/Y-90, increasing with the beta energy. With what amounts to a conversion of beta energy to photon which can easily escape the crystal without depositing energy, we see another source of overrepresentation of the low energy portion of the experimental spectra.

Finally, the well-known phenomenon of backscatter\textsuperscript{80} with regards to beta radiation entails beta particles being reflected at the surface of the material without depositing significant measurable energy into the crystal. This effect increases with increasing atomic mass of the
material and decreasing beta energy. Although studies of the backscatter from GaN are not available, using previously observed data\textsuperscript{81} for other materials we can estimate the amount of backscatter would be on average 20%. This means that of all beta particles incident upon the wafer, on average 20% of them would be reflected without depositing a significant amount of energy, although this amount is affected by the initial electron energy. Although relatively little energy would be deposited in the wafer, due to the range of the coulomb interaction some energy will still result in scintillation. This minor energy deposition hen leads to more low energy counts, as observed experimentally. With all three of these effects in mind, the overrepresentation of the low portion of the beta spectra can be explained.
4.4.3 Photon irradiation scintillation in Gallium Nitride

The gamma emitting isotope experiments result in the spectra presented in Figure 53 below.

![Gamma emitting isotope spectra](image)

**Figure 53. Gamma emitting isotope spectra**

Performing an endpoint analysis like those completed previously produces Figure 54 below where the endpoint is determined in the same way that the endpoints of beta spectra and nitrogen spectra not exhibiting peaks were.
As we can see the endpoint increases in a linear fashion as would be expected in the case of complete energy deposition but most of the counts observed due to photons are below the endpoint. As the photon radiation is not emitted in a continuum, unlike the beta radiation, this leads to the conclusion that photon radiation rarely undergoes complete energy deposition within the wafer. To understand this, we begin by considering the possible gamma interactions with GaN under the assumption of a beam of photon radiation.

To do so the National Institute of Standards and Technology (NIST) x-ray attenuation FFAST databases\textsuperscript{82} were used to obtain the attenuation coefficients for photons in GaN, which
can be viewed as representing the likelihood of the corresponding reactions occurring when a photon is travelling through the wafer. By taking the total attenuation coefficients as determined by the FFAST database, we evaluate equations

\[ A(E_\gamma) = 1 - e^{-\mu_t(E_\gamma)\ell} \]  \hspace{1cm} (9)

and

\[ \ell(E_\gamma) \approx \frac{1}{\mu_t(E_\gamma)} . \]  \hspace{1cm} (11)

for multiple gamma energies assuming a thickness of 250 µm, resulting in Figure 55 below.
As can be seen, full photon attenuation is only achieved below a certain energy we will call $E_y$. Above this energy partial photon attenuation would lead to complex energy deposition in the crystal. For a wafer thickness of 250, $E_y$ of 20 keV would be expected. To predict the partial attenuation results for photon energies above $E_y$ we must consider the possible interactions and the implications thereof separately. To do this we separate out the total attenuation coefficient into the component parts for Compton scattering, photoelectric effect, and pair production provided by FFAST, and plot the percentage of the total attenuation coefficient of each for multiple photon energies. This results in Figure 56 below.
As can be seen, for low photon energies the photoelectric effect dominates and increasing energy causes Compton scattering to increase in importance and dominate above approximately 500 keV. Continuing up the energy scale, above the threshold of 1.02 MeV, the importance of pair production begins to increase as well. Proceeding we would like to determine the result of each of the reactions separately.

In the case of the photoelectric effect, the binding energies of electrons in N and Ga range up to approximately 10 keV\(^{83}\), so we would expect the result of any such interaction to be an electron with energy ranging from approximately the initial photon energy, to 10 keV below.
With the results of the beta experiments where we calculated an $E_{\beta_{\text{max}}}$ of approximately 350 keV for wafers of 250 µm, we can see that depending upon the initial photon energy, a significant portion of the photon energy that is transferred to the photoelectron can escape the wafer, depending on the path, due to the range of the electrons in GaN.

In the case of Compton scattering we begin by evaluating equation

$$\frac{d\sigma}{d\Omega} = Z \frac{\delta^2}{r^2} \frac{\delta}{Z} \left( 1 + \frac{(\alpha\delta)^2}{\delta(1+\alpha\delta)} \right)$$

(5)

, utilizing the Auto-Zeff$^8$ software package to determine the effective atomic number of GaN for the relevant photon energies, and normalizing the result, creating Figure 57 where the angular coordinate represents the scatter angle and the $r$ axis represents the normalized probability.
As can be seen, the probability of forward scattering increases rapidly with increasing photon energy. Proceeding, to calculate the energy transferred to the electron during scattering at each angle we can use equation

\[
E_e = E_{\gamma 0} \frac{\alpha (1 - \cos \theta)}{1 + \alpha (1 - \cos \theta)}
\]

\[(7)\]

, and plot against the normalized results calculated for Figure 57 above. Doing so we get
Figure 58 below, showing the electron energy probability distribution for various incident photon energies.

Figure 58. Electron energy distribution due to Compton scatter in Gallium Nitride

Once again, as with the photoelectric effect the energy of resulting electrons implies that a significant portion of the energy information will escape from the detector. With these results in mind we can understand the gamma spectra observed experimentally since for photon energies above 20 keV there is diminishing probability of interaction, and for those photons that do undergo reactions the resultant electrons which would create scintillation are either of low energy or have high enough energy to escape the wafer. The combination of these effects leads
to the spectra seen experimentally with the low end emphasized and no clear peaks as would be
observed with, for instance, a germanium detector.

These results also go towards explaining the low energy feature of the neutron spectra
observed earlier. Although the low energy recoil cross section can account for the feature, there
is potential for direct gamma production from neutron interactions, as well as the possibility of
inelastic collisions with gallium resulting in x-ray radiation. Because of this, during neutron
irradiation additional counts will be provided to the low energy portion of the spectrum due to
the interactions observed above resulting from produced photon radiation.
5 DISCUSSION

In the previous chapter we saw that not only does GaN exhibit a scintillation response to various forms of ionizing radiation, but that we can predict the expected scintillation response for radiations exhibiting full energy deposition within the active volume of the detector. For the initial intention of neutron spectroscopy, although complete energy deposition does not necessarily always occur, the proposed scintillation detector provides multiple inherent methods of neutron energy determination. In addition to the elastic recoil scintillation produced by the crystal components initially proposed as the energy conversion mechanism, the nuclear reactions, in particular the boron from the $^{14}\text{N}(n, \alpha)^{11}\text{B}$ were observed experimentally to provide initial neutron energy information.

To verify the response from neutron radiation was from the proposed heavy ions, the various experiments performed demonstrated a predictable scintillation response to charged particles. In each beta, proton, and nitrogen experiments a linear increase in spectrum endpoint energy was observed. In the case of the beta radiation the spectrum observed was distorted due to incomplete energy deposition, but otherwise demonstrated the usefulness of GaN as a scintillation spectrometer. In the case of the nitrogen and proton experiments the largest detractor from the final performance of the spectrometer was the resolution. The cause of this poor resolution had many contributing factors, not necessarily detracting from the suitability of GaN for these purposes.

Finally, to evaluate the potential performance of the spectrometer in situations in which multiple radiations are present the scintillation response to ionizing photon radiation was tested.
During these experiments it was noticed that spectra endpoints increased in a linear fashion with photon energy, but due to the penetrating power of photon radiations actual spectroscopy was not practical. This observation is beneficial for two separate reasons. First, for the purposes of neutron spectroscopy we desire the detector to be “gamma blind” to reduce neutron signal contamination with gamma signal. In the thin wafer setup, as the probability of photon interaction is relatively low, we do in fact observe a relatively “gamma blind” spectrometer. In a final spectrometer setup, the overall gamma response can be accounted for with a concurrent gamma measuring system allowing for signal subtraction to provide only neutron information. Second, if desired, a similar setup could in theory be created for gamma spectroscopy. The largest wafers of GaN currently available are 1 mm thick, whereas to perform gamma spectroscopy the thickness would need to be on the order of 10 mm thick to ensure complete energy deposition. This obviously makes creation of a GaN gamma detector currently impossible, due to the advantageous qualities of GaN discussed earlier though the use of GaN as a gamma spectrometer could become attractive, with the major detractor being the relative low mass of the atomic constituents.

In order to intercompare the scintillation performance of GaN between all forms of radiation observed we perform the channel to photon production analysis mentioned earlier, discussed in Appendix 6. Doing so produces Figure 59 below
Figure 59. Endpoint scintillation per unit of energy deposited

As we can see, ion scintillation compares well with gamma and beta scintillation over the range of energy of consideration for neutron spectroscopy. This could be due to the assumption of endpoint correlation for the higher gamma and beta energy breaking down due to incomplete energy deposition as could be expected from the analysis of both beta and gamma radiations presented in chapter 4. However, the result is the same, for the ranges of energy under concern GaN presents a relatively gamma, and to an extent “beta blind” neutron spectrometer with sufficient scintillation in the heavy ion range to perform as desired and predicted, even in real world scenarios of mixed radiation fields.
As was mentioned above, the resolution of the detector observed for heavy ion experiments was a limiting factor, and as noted in the previous chapter, during transfer of the initial highly doped crystal from the preliminary detector setup to the second setup, significant structural damage was caused. Informally we know that this damage can result in a loss of resolution and degraded performance\textsuperscript{85} in a general scintillation spectroscopic system, but with the data from neutron and heavy ion experiments we can numerically confirm and define this effect in this spectrometer. As we saw, the resolution of version 2 of the detector was 53\% for alpha particles of 5.4 MeV and approximately 83\% for protons of 1.2 MeV. Performing a similar analysis on the boron peak identified during neutron experiments, seen in Figure 27, results in a resolution for boron of approximately 180 keV of 25.7\%. Due to the smaller signal created by low energy heavy ions, the typical resolution for higher energy ions is lower than for low energy ions\textsuperscript{86}, as seen experimentally with the alpha and proton resolutions. This implies that the effect on the resolution of the damage was significant, but it also underscores the ability of GaN to perform charged particle spectroscopy as even with significant damage the spectrometer was able to observe energy information of multiple ion species.

Other than the structure of the wafer, multiple other factors were considered and identified to effect resolution. We saw that by increasing the width of the wafer and decreasing the doping, the resolution decreased by almost 10\%, from 53.6\% to 62.1\%. The cause of this resolution decrease could be from a multitude of effects. It has been assumed, and shown, that both a decrease in doping and an increase in thickness results in less scintillation reaching the PMT for identical radiations but the exact cause of the reduction in scintillation was not
explored. This reduction could be simply from a reduction in doping leading to reduced scintillation in the bulk of the material or reduced doping could lead to a change in the dominant scintillation wavelength which could lead to increased self-absorption and the scintillation reduction seen. Additionally, an increase in wafer thickness regardless of doping would be expected to lead to increased self-absorption due simply to the longer path through the medium. To further develop the GaN spectrometer for charged particles, and consequently neutron spectroscopy, further experiments need to be performed to both quantify the effect and optimize the crystal dimensions and doping concentrations.

In addition to optimizing the wafer itself to maximize scintillation creation, additional work can be done to optimize the optical setup to maximize scintillation collection. In the experiments described above, a relatively straightforward setup was employed. This allowed for simple signal processing, portability, and affordability. In all the experiments the maximum possible collection solid angle was $2\pi$, because the PMT only covered one surface of the wafer. As the scintillation emission is isotropic, this means the tested setup omits approximately half of the possible scintillation signal. To improve on this, more sophisticated optical setups can be envisioned which would ostensibly improve the resolution and performance.

Furthermore, future experiments should focus on additional mono-energetic as well as multi-energetic neutron fields. In addition to elastic recoil study, these experiments should also focus on investigation of non-elastic reactions, including the $^{14}\text{N}(n,\alpha)^{11}\text{B}$ observed in this work, as well as the $^{4}\text{N}(n,p)^{14}\text{C}$ reaction, the next most probable in the energy range investigated here. Although experiments presented here proved the ability to use GaN as a transducer in a
scintillation based fast neutron spectrometer, the experiments themselves proved limited due to availability of equipment, in particular, mono-energetic neutron generating machines.

Supplementary studies into the fundamental properties of GaN during irradiation to various forms of ionizing radiation would also be useful for further development and characterization of the spectrometer. As we saw during analysis of the neutron spectrum, the pulse time characteristics including rise and fall time should be further investigated. In addition, exploration into the photoluminescent characteristics of the generated pulses from varying radiations would be invaluable, allowing for determination of exact scintillation processes undergone during each irradiation and how these vary from radiation to radiation. Possible photoluminescent spectrum differences between ions and energies would allow for simple discrimination of pulses, allowing for more detailed analysis of the pulse height spectra.

Finally, a component wise investigation of partial system response to neutron and other radiations should be performed. Along these lines, although PMTs have been utilized for spectroscopic applications and suitability has been studied\textsuperscript{87,88} and shown to be favorable\textsuperscript{89}, the light detection elements, PMT in this case, should be tested in the absence of scintillator crystals in order to assess the background in pulse height spectra induced by the light detection element itself. Not only will this allow for further verification of the system effectiveness, but it will also allow for system induced background subtraction in future applications possibly leading to increased resolution.
6 Conclusion

In the preceding chapters we have introduced and proven the novel concept of a GaN based neutron spectrometer via elastic recoil induced scintillation. The theoretical framework was developed and presented along with computational and experimental support demonstrating function in agreement with the theorized operational principals. Predicted nitrogen and gallium elastic recoil energy distributions were calculated, showing that the charged particle spectrum resulting from a neutron irradiation can be related back to the initial neutron energy. Ion irradiation experiments were performed, demonstrating energy dependence of scintillation resulting from charged particle induced ionization. Neutron irradiations were performed, resulting in pulse height spectra in agreement with the previously determined elastic recoil energy distributions with features explained with non-elastic recoil mechanisms. Finally, gamma and beta irradiations were performed, showing an insensitivity to these radiations resulting in a “gamma-blind detector”. Not only was the concept of a GaN based scintillation ionizing radiation spectrometer proven to be effective, but multiple future experiments and optimizations were discussed, including quantifying the effects of doping and wafer thickness on initial scintillation output and self-absorption, and improvements in the optical design of the device.
APPENDIX 2 – HAMAMATSU R329-02 SPECIFICATION SHEET

PHOTOMULTIPLIER TUBE
R329-02

FEATURES
- Fast time response

APPLICATIONS
- For scintillation counting
- High energy physics

SPECIFICATIONS

GENERAL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description / Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral response</td>
<td>300 to 650</td>
<td>nm</td>
</tr>
<tr>
<td>Wavelength of maximum response</td>
<td>450</td>
<td>nm</td>
</tr>
<tr>
<td>Photocathode Material</td>
<td>Ba/Se</td>
<td></td>
</tr>
<tr>
<td>Minimum effective area</td>
<td>4.4</td>
<td>mm</td>
</tr>
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<td>Window material</td>
<td>Borosilicate glass</td>
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<tr>
<td>Dynode Structure</td>
<td>Linear focused</td>
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<td>Operating ambient temperature</td>
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<td>Base</td>
<td>21-pin glass base</td>
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</tr>
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<td>Suitable socket</td>
<td>E678-21C (supplied)</td>
<td></td>
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</table>

MAXIMUM RATINGS (Absolute maximum values)

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<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage</td>
<td>Between anode and cathode</td>
</tr>
<tr>
<td>Average anode current</td>
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</tr>
</tbody>
</table>

CHARACTERISTICS (at 25 °C)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
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<td>Cathode sensitivity</td>
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<td>90</td>
<td></td>
<td>μA/m</td>
</tr>
<tr>
<td>Blue sensitivity index (CS 5-58)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiant at 450 nm</td>
<td>85</td>
<td></td>
<td></td>
<td>mW</td>
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<tr>
<td>Anode sensitivity</td>
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<td>100</td>
<td></td>
<td>A/m</td>
</tr>
<tr>
<td>Radiant at 420 nm</td>
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<td></td>
<td>A/W</td>
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<tr>
<td>Gain</td>
<td>1.1 x 10^6</td>
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<tr>
<td>Anode dark current (after 30 min storage in darkness)</td>
<td>6.0</td>
<td>40</td>
<td>nA</td>
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</tr>
<tr>
<td>Anode pulse rise time</td>
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<td></td>
<td></td>
<td>ns</td>
</tr>
<tr>
<td>Electron transit time</td>
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<td></td>
<td></td>
<td>ns</td>
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<td>Transit time spread (TTS)</td>
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<td></td>
<td></td>
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<td>Pulses linearity at 2% deviation</td>
<td>15 (100)</td>
<td></td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>at 5% deviation</td>
<td>30 (200)</td>
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<td></td>
<td>mA</td>
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</tbody>
</table>

NOTE: Anode characteristics are measured with the voltage distribution ratio shown below. Measured with the special voltage distribution ratio (Tapered Divider) shown below.

VOLTAGE DISTRIBUTION RATIO AND SUPPLY VOLTAGE

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<th>Electrodes</th>
<th>K</th>
<th>G</th>
<th>Dy1</th>
<th>Dy2</th>
<th>Dy3</th>
<th>Dy4</th>
<th>Dy5</th>
<th>Dy6</th>
<th>Dy7</th>
<th>Dy8</th>
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<th>Dy10</th>
<th>Dy11</th>
<th>Dy12</th>
<th>P</th>
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</thead>
<tbody>
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<td>1.6</td>
<td>1</td>
<td>1</td>
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<td>1.2</td>
<td>1.5</td>
<td>2</td>
<td>2.4</td>
<td>3.9</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Supply voltage</td>
<td>1500 V, K, Cathode, Dy, Dynode, P, Anode, Grid</td>
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<td></td>
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</tbody>
</table>

* The shield pin should be connected to Dy5.

VOLTAGE DISTRIBUTION RATIO AND SUPPLY VOLTAGE (Tapered Divider)

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<thead>
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<th>Electrodes</th>
<th>K</th>
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<th>Dy3</th>
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* Subject to local technical regulations and regulations, availability of products included in the promotional material may vary. Please consult with our sales office.

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Figure 1: Typical spectral response

Figure 2: Typical gain characteristics

Figure 3: Dimensional outline and baying diagram (Unit: mm)

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HAMAMATSU PHOTONICS K.K., Electron Tube Division
314-5, Shihonkaza, Iwata City, Shizuoka Pref., 438-0193, Japan, Telephone: (81) 53462-3248, Fax: (81) 53462-2206

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APPENDIX 3 – NATIONAL ELECTROSTATICS CORPORATION ACCELERATOR OVERVIEW

NEC Accelerator System Overview

A complete NEC electrostatic accelerator system consists of:

- Injection beamline(s) – Includes ion sources and other optical and diagnostic components leading up to the accelerator entrance.
- Beamline – Includes the pressure vessel, accelerator beamline, charging system, and more.
- High energy beamline(s) – Includes optical and diagnostic components from the exit of the Beamline up to and including the extraction(s) or drift.
- Control System – Includes hardware and software for computer control of the full accelerator system, specifically customized for each system configuration.

Each system’s component configuration and layout are customized to meet the user’s specific needs.

Source and Injection Beamline

Injectors begin with one or more ion sources that produce positive or negative ion beams. The source is typically followed by beam magnets or electrostatic analyzers that focus the ion beam into the accelerator. Diagnostic equipment and other focusing elements are an integral part of the injector. Various configurations can be used depending on the user’s requirements. Detailed information regarding our various available sources can be found in the sources section.

![Image of NEC accelerator system overview](image-url)
**Pelletron**

Electrostatic accelerators work on the basic principle that negative ion beams are attracted to a positive terminal and that positive beams are accelerated away from a positive terminal. Decades ago, charging belts were used to create a high-voltage terminal. These belt systems were known as Van de Graaff generators. As the scientific community realized the importance of creating high-voltage terminals, experiments were conducted to increase the terminal voltage by using different charging materials and insulating gaps. Continuous research through the decades resulted in the creation of the most stable and reliable electrostatic accelerator system in use today: the Pelletron.

Pelletrons consist of the following:

- Pressure vessel
- Charging system
- Acceleration tube
- Column or support structure
- Gas or foil stripper

Pelletrons can either be tandem or single ended. Tandem Pelletrons start with negative ions that go through a stripping process to break up molecules and strip electrons, thus creating the necessary positive beam. Single-ended Pelletrons, on the other hand, start with a positive ion produced directly from the source inside the terminal.

---

**High Energy Beamline**

After the positive beam has been accelerated, it exits the pressure vessel and enters the focusing beamline, which is the name it continues to flow the beam. At this point, there can either be a single extended beamline leading to an analysis chamber, implantation detector, or an existing magnet with up to 7 ports for multiple extended beamlines. Additional beam focusing, steering, or diagnostic components are all typically part of the extended beamlines. More information regarding these components can be found in the products section, like the injector beamlines, the high energy beamlines can be configured to meet user-specific needs.

---

**Control System**

The accelerator system is run by a centralized control system. All accelerator parameters needed for normal operation are input with the control console.

Most of the controls and readouts interface with the control console via an In House Data Acquisition System known as the NEC. Prior to 2009, interfacing was via CAMAC.
The control console consists of a dedicated computer system, assignable meters and knobs, and oscilloscope for displaying signals.

The computer system is configured with NEC accelerator control software, AccuNET. AccuNET manages the display and control functions through a database management system operating in a multi-tasking environment. Linux, AccuNET is configured for each system by tailoring its data to the accelerator configuration.

Parameters are displayed in two formats: text formatted pages of parameter lists, and graphic displays of the system layout. Controls can be adjusted by menu-driven instruction, direct input of displayed values, or numeric increment buttons. Keypad input of the desired parameter value, or assigning the parameter to a knob for analog mode adjustments. Values of readouts are displayed on the monitor and can be assigned to either an analog display or the on-screen strip chart recorder.

Vacuum and other interlocks are incorporated into the control system to protect personnel, equipment and samples.

Operators may save and restore preferred system configurations and setup preferences. This allows for an easy beam startup, little to no fine tuning needed.
In order to perform a first order energy calibration of the spectra recorded during neutron irradiation experiments a few assumptions need to be made. First, we must assume that the features exhibited in the spectra are from known sources. Second, we assume that transduction to scintillation, and therefore scintillation intensity is linearly proportional to initial ion energy.

Regarding the first assumption, the analysis presented in the body of this thesis shows that we can determine the continuum, underlying spectrum to be from the ion recoil of constituent nitrogen and gallium ions. Additionally, the prominent peak seen in each spectrum is likewise shown to be from the energetic boron from the $^{14}\text{N}(\text{n}, \alpha)^{11}\text{B}$ reaction. The kinematic analysis presented support that this peak should begin where we see, and extend further into the high energy, interfering with the nitrogen recoil spectrum.

Regarding the second assumption, through the analysis presented in the section dealing with the ion experiments performed we see that although this assumption is not entirely accurate, the underlying idea of an increase in scintillation from increasing ion energy is valid for all ions discussed, and all energies investigated. The linear assumption although not entirely accurate as shown through the analysis presented in this thesis, does allow for a first order energy calibration.

With this being said, in order to calibrate the neutron spectra presented we assume that the high endpoint on the high energy side is the end of the nitrogen recoil spectrum, with energy determined via the kinematic analysis which was incorporated into the differential cross-section determination. Next, the lowest boron energy, as shown in the body of the thesis, determined by
the kinematic analysis discussed, is assumed to be the location of the prominent peak in each of
the spectra. The reasoning behind this follows that discussed in the body of the work, that
although the specific data for the partial differential cross section is not available for this specific
energy, those available show a trend that the lowest energy is the most probable, with decreasing
cross section with increasing energy.

With these points we have two distinct elements for each spectrum given by:

(nitrogen peak channel, maximum nitrogen recoil energy)

(boron peak channel, minimum boron recoil energy)

Which allow us to determine a channel to energy relationship with the linear assumption.

After performing the ion experiments discussed following the neutron section of this thesis a
further calibration could be performed, using the scintillation efficiency as determined in order to
account for the change with regards to stopping power etc. Unfortunately, the number of ion
experiments performed as well as the inaccuracies involved due to crystal structure change as
discussed, different electronic setup, etc. mean that this additional calibration would not increase
accuracy, or be very useful. In order for this additional calibration to be performed accurately
additional experiments must be performed both with mono-energetic neutrons, and ions, utilizing
the same detector setup throughout, including crystal, optical equipment, and signal processing
equipment to allow for intra-experimental analysis. This is also the main reason that a calibration
of the high energy neutron experiment cannot be performed. As the endpoint of the spectrum is
beyond the last channel, and there are not multiple additional significant features which would
allow for identification of calibration points, an energy calibration cannot be completed.

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In addition to the energy calibrations performed for the neutron experiments, it may be noticeable that energy calibrations were not performed for the following ion experiments, nor the radioactive source experiments. The reasoning behind this in terms of the ion experiments was due to the usefulness of channel number for the scintillation efficiency analysis performed, which in itself verifies the applicability of the neutron energy calibration. In terms of the source experiments, with the exception of the Am-241 experiment (for which an energy calibration was completed and presented), there are not features which can be matched with known energies, so although the structures can be validated and important conclusions can be drawn from the analysis shown, completing an energy calibration would be inaccurate at best.
APPENDIX 5 – PROGRAM TO DETERMINE ESTIMATED SCATTER SPECTRUM

The program provided below, written in Fortran, allows for determination of a complete scatter spectrum from one source as described in the text for multiple ion energies, as specified via an input file. Creation of the scatter spectrum from multiple sources can then be performed by applying the program to multiple setups and adding the results. To account for inherent energy spread of the initial ion beam the program takes the ion energy (or energies) and approximates a gaussian distribution of a user defined width.

Comments are provided in standard Fortran notation throughout the program to explain the program operation. In general the program reads in a file containing the physical specification of the setup under consideration. This file contains the target thickness and width, the beam and target nuclear and atomic numbers, the number of steps to take through the target, the angles $\theta$ and $\varphi$, and the gaussian width of the ion energy distribution. After reading in these parameters the program reads in stopping powers from a formatted file (in the case of this work the outputs of SRIM for all materials under consideration, both Au and stainless steel, were placed into a single .txt file) and saves them as an array. Next, in the main operation portion of the program, the constants for calculations are determined and the ion interaction is iteratively performed for each significant energy present in the gaussian distribution. At each step the stopping power is determined using a defined function, discussed in the body of the program, and the energy loss corresponding to the stopping power and step size is calculated and subtracted from the initial ion energy. Next the Rutherford cross section for the current energy,
$E_0$, is determined and recorded, then the ion energy is adjusted by the kinematic factor corresponding to a reflection of the user defined angle and ion/target mass, then walked back to the surface the appropriate number of steps as calculated using the geometry of the situation and the step size as determined by the inputs, losing energy according to the stopping power of the material for the current energy at each step, and the final ion energy at the surface is used to bin the cumulative Rutherford cross section for the calculated surface energy, $E_1$. As these are the ion energies emerging from the surface of the target in the direction of the detector, we assume that the Rutherford cross section represents the probability of an ion of that energy impinging upon the detector with no further energy loss. Returning to $E_0$, the next step is calculated, etc. After performing this calculation for the number of steps designated via the input the cumulative resultant spectrum, as described by the cumulative Rutherford cross sections is written to an output file both for each individual initial ion energy specified, and in a single file containing all ion energies run.

To clarify the main calculation steps, below the first three steps of the calculation, after user input and constant determination, are described.

First step – Rutherford cross section is calculated for the initial ion energy and binned.

Second step – The ion energy is adjusted with

$$\Delta E = \frac{dE}{dx} \times dx \quad (37)$$
And the Rutherford cross section of the adjusted energy from the is calculated and saved. The energy this ion would be at the surface is calculated by determining the number of steps to the surface accounting for the reflection angle and walking the ion iteratively back, subtracting the energy difference in the same manner as before, and this energy is used to bin the Rutherford cross section.

Third step – The initial adjusted energy from the previous step is taken and adjusted again to account for further travel. The Rutherford cross section for the new energy is calculated and saved. The energy at the surface is then calculated by taking the appropriate number of steps back iteratively using the appropriate stopping power at each step. The energy calculated as the surface energy is then used to bin the Rutherford cross section.

Further steps – This process is performed for the number of iterations required for the user defined step size. The final cumulative binned cross sections should then be representative of the spectrum scattered by the target.

Notes on implementation:

Step Size: in this work multiple step sizes were investigated. Reducing the step size too low would drastically increase the number of calculations performed, and hence the time to perform them. In the end the lattice constant of the material of consideration was used. This not only
provided an appropriate result in a timely manner, but also could be understood as scattering can only occur in the presence of a scatterer. Therefore, the cross section should only be calculated every lattice constant, where a potential scatterer could be.

Gaussian energy distribution: The gaussian distribution mentioned above not only makes for a more realistic representation as the ions on target will not realistically be monoenergetic, but also smooths the final distribution, accounting for potential binning artifacts. The bin size used in the work presented above was 1 keV. As the calculation process is identical irrespective of ion species, this allows for a broad range of simulations, if the underlying assumption of Rutherford scattering remains valid.

Alternative software packages: Although multiple software packages have been developed to simulate ion interactions with matter, all reviewed for use in this work had limitations, necessitating development of a novel program. In some instances, the energy range covered by the software was insufficient for this application, in others the allowable ion species was too restrictive for the system under consideration, or although the software could handle the simulation, it also accounted for many factors which did not influence the outcome of the calculation causing unnecessarily long computation times. In all software reviewed for suitability, the calculation was performed via Monte Carlo calculations. Although these methods are certainly accurate, due to the difficulties previously mentioned, they proved unsuitable for implementation here. For these reasons, the new code was developed which only considered
Rutherford scattering, and performed the calculation in a way to result in a direct scatter spectrum at user specified angles, accommodating the desired ions, energies, and targets, rather than vicariously determining that spectrum through many unnecessary calculations. This is not to say that the method of spectrum determination employed here is more accurate, but it is enough for the present purposes without imposing restrictive calculation times.
program scatterspec
  implicit none
  double precision, dimension(:,,), allocatable :: spmatrix, sbc
  ! Allocatable arrays representing the stopping powers for all materials and the overall spectrum
  ! for each initial ion energy calculated

  double precision, dimension(:,), allocatable :: beame
  ! Array which contains the desired beam energies to be scattered

  double precision :: beamz, targz, beama, targa, angle1, angle2, dx, targwidth, e1, e2, pi
  ! Variables representing the beam and target atomic number, beam and target atomic weight, the
  ! angle from normal the beam is incident on the target, the angle from incidence the ion is
  ! reflected into, the distance of each step during the main calculation, the width of the target, the
  ! energy of the ion at the beginning of the current step during the main calculation, and energy of
  ! the ion being walked back to the surface and eventually the binning energy, pi as used in
  ! calculations

  double precision :: rcs, cst, cst2, sp, steps, gval, pval1, pval3, pval4
  ! Variables used to represent the Rutherford cross section calculated at each step, two constants
  ! for use in the main calculation which do not change with ion energy, the stopping power as
determined in a contained program utilizing the stopping power inputs, the number of steps to
take through the target, the gaussian distribution calculated at the beginning of each step, three
variables which are used to reduce the final printed spectrum datapoints to only those relevant

  integer :: i, ii, iii, iv, nlines, binnum, nsteps1, nsteps2
  ! Four variables used for do statements, a variable used to track the number of lines in files to be
  ! read in, the number of bins the final spectrum should be put into, the number of steps taken in
  ! and out

  integer :: beams, gwidth, indexval, pval2, pval5, pval6
  ! The number of initial beam energies to be investigated, the width of the energy gaussian, an
  ! index for use in creating the output file names, three variables for use in removing unnecessary
  ! datapoints from the output files

  character(150) :: oldfile1, oldfile2, newfile1, newfile2, a, titleenergy
  ! Titles of old files read in, new files created, and place holders

  character(5) :: ie, beam, targ, units
  ! Place holders for reading and writing

! Standard Fortran calculation of pi employed for accuracy
pi=4.D0*DATAN(1.D0)
!Opens the user defined files and reads in the user defined variables
oldfile1="beamcreation.txt"
open(unit=90,file=oldfile1)
read(90, *)
read(90, *) beams, beam, targ, targwidth, beamz, targz, beama, targa, steps, angle1, angle2, gwidth

!Allocates the array which will contain the binned spectrum for each initial ion energy and the array which will contain the desired initial ion energies
allocate(sbc(4000,beams),beame(beams))
doi=1, beams
   read(90,*) beame(i)
end do
close(90)

!Determines the number of lines contained in the stopping power file
oldfile2="stoppingpowers.txt"
nlines=1
open(unit=91, file=oldfile2)
do
   read(91,'(a)',end=10)
nlines=nlines+1
end do
10 close(91)

!Allocates the stopping power arrays assuming there are two material stopping powers contained in the previously read file, then reads in the provided stopping powers and ensures all energy units are the same for reference
nlines=(nlines-2)/2
allocate(spmatrix(nlines,6))
open(unit=91, file=oldfile2)
doi=1, 2
doi=1, nlines
   read(91,*) spmatrix(ii,1+(i-1)*3), units, spmatrix(ii,2+(i-1)*3), spmatrix(ii,3+(i-1)*3)
!print*, spmatrix(ii,1+(i-1)*3), units, spmatrix(ii,2+(i-1)*3), spmatrix(ii,3+(i-1)*3)
if (index(units,"MeV") .gt. 0) then
   spmatrix(ii,1+(i-1)*3)=spmatrix(ii,1+(i-1)*3)*1000.0
else if (index(units,'kev') .gt. 0) then
   else
   spmatrix(ii,1+(i-1)*3)=spmatrix(ii,1+(i-1)*3)/1000.0

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end if
end do
end do
end do
close(91)

!Converts angles to radians, calculates constants used throughout the main steps which do not depend on energy
angle1=angle1*pi/180
angle2=angle2*pi/180
cst=((beamz*targz)**2)*((197.3/137)**2)*(1/(sin(angle2)**4))
cst2=(1-((2*beama*targa)/((beama+targa)**2))*(1-cos(angle2)))
dx=steps
nsteps1=ceiling((targwidth/(cos(angle1)))/dx)
nsteps2=ceiling((targwidth/(sin(angle2)))/dx)

!Sets all spectra to zero
sbc=0.0

!The initial do loop iterates the process for each desired initial ion energy
do iii=1, beams

!The next do loop calculates the gaussian distribution value at intervals of 1 keV up to 4 MeV centered at the initial ion energy, if the distribution value exceeds a defined magnitude, here .0001 where the maximum of the distribution is normalized at 1, then it proceeds, otherwise the next magnitude is calculated etc.
do i=1, 4000
gval=(exp(-((i-beame(iii)**2.0)/(2.0*gwidth**2.0))/(gwidth*10.0))
if(gval .gt. .0001) then

!If the distribution value is large enough the Rutherford cross section of the gaussian energy is calculated and binned, weighted by the calculated gaussian distribution magnitude
e1=i
e2=e1*cst2
rcs=(1/((e1/1000.0)**2))*cst*0.01
binnum=ceiling(e2)
sbc(binnum,i)=sbc(binnum,i)+rcs*gval

!The do loop to perform the steps through the material is now initiated, it will run for the number of steps calculated earlier unless it is determined at any step the ion can no longer emerge from the surface due to insufficient energy
mloop:      do ii=1, nsteps1
The stopping power for the current ion energy is determined by a function included, and described at the end:

\[ sp = sp\_lookup(e1, spmatrix) \]

The ion energy is updated as taking a step in, losing energy as described by the determined stopping power:

\[ e1 = e1 - sp \times \frac{dx}{1000} \]

If the ion energy becomes negative it will clearly not have the energy required to emerge from the surface and therefore this ion is “terminated”, and the next gaussian step is initiated, otherwise the calculation proceeds:

\[ \text{if } (e1 \lt 0.0) \text{ then} \]
\[ \quad \text{exit mloop} \]
\[ \text{end if} \]

The Rutherford cross section for the updated energy is calculated and the energy reduction of the ion due to kinematic loss is accounted for:

\[ rcs = \frac{1}{((e1/1000) \times 2)} \times cst \times 0.01 \]
\[ e2 = e1 \times \text{cst2} \]

The number of steps needed to reach the surface is calculated for the specified reflection angle:

\[ nsteps2 = \text{ceiling}(ii / \sin(\text{angle2})) \]

The do loop to walk back to the surface is initiated:

\[ \text{do } iv = 1, \text{nsteps2} \]

The stopping power for the current ion energy is calculated and the energy is updated. If the energy drops below zero this ion, and all iterations that begin further into the target will not reach the surface and this gaussian step is terminated, otherwise the calculation continues:

\[ sp = sp\_lookup(e2, spmatrix) \]
\[ e2 = e2 - sp \times \frac{dx}{1000} \]
\[ \text{if } (e2 \lt 0.0) \text{ then} \]
\[ \quad \text{exit mloop} \]
\[ \text{end if} \]
\[ \text{end do} \]

Upon reaching the surface the Rutherford cross section is binned, weighted by the gaussian distribution value:

\[ \text{binnum} = \text{ceiling}(e2) \]
\[ \text{sbc(binnum, iiii) = sbc(binnum, iiii) + rcs \times gval} \]

End do mloop

End if
!After accounting for each significant value from the gaussian distribution the program writes the spectrum produced. The spectrum is written in a do loop where a series of logic steps determines if the current cross section is significantly different from the previous, or spaced far enough apart, if so the energy and cross section are printed to the file, otherwise the value is skipped. This is done to ensure that the resultant spectra are clear for later plotting purposes. It can be eliminated if further calculations are to be performed with the resultant spectra although the full spectrum will be printed later. After the scatter spectrum for the current initial ion energy is printed the main do loop is ended, if there are more initial ion energies to run it returns to the start of the gaussian calculation process, otherwise the main do loop terminates.

write(titleenergy,*) beame(iii)
indexval=index(titleenergy,'.)
titleenergy=titleenergy(indexval-4:indexval-1)
newfile1=trim(titleenergy)/"keV"//trim(beam)//" on "//TRIM(targ)//" scatter spectrum.txt'
newfile2=trim(titleenergy)/"keV"//trim(beam)//" on "//TRIM(targ)//" ionization in GaN spectrum.txt'
newfile1=trim(newfile1)
newfile2=trim(newfile2)
open(unit=92, file=newfile1)
pval1=0.0
pval2=0
pval4=0.0
pval6=0
do i=0, 4000
   if(sbc(i,iii) .gt. pval1) then
      pval1=sbc(i,iii)
pval5=i
   end if
end do
print*, pval1
do i=2, 3999
   if (pval6==0 .and. sbc(i,iii) .gt. 0.0) then
      write(92,*) i, sbc(i,iii)
pval3=sbc(i,iii)
pval2=i
pval4=0.0
pval6=1
   elseif (sbc(i,iii) == pval1) then
      write(92,*) i, sbc(i,iii)
pval3=(sbc(i,iii)+sbc(i+1,iii)+sbc(i-1,iii))/3.0
pval2=i
pval4=0.0
elseif (sbc(i,iii) .gt. 0.0 .and. pval6==1 .and. abs((pval3-pval4/(i-pval2))/pval1) .gt. 0.05 .and. i-pval2 .gt. 5) then
  write(92,*) i, pval4/(i-pval2)
pval3=pval4/(i-pval2)
pval4=0.0
pval2=i
elseif (sbc(i,iii) .gt. 0.0 .and. i-pval2 .gt. 50) then
  write(92,*) i, pval4/(i-pval2)
pval3=pval4/(i-pval2)
pval4=0.0
pval2=i
elseif (pval6==1 .and. sbc(i+1,iii)==0.0) then
  write(92,*) i, pval4/(i-pval2)
pval6=2
endif
pval4=pval4+sbc(i,iii)
end do
close(92)
enddo

!A file is now printed which contains all the determined scatter spectra. Unlike before no data
points are omitted.
newfile1='all scatter spectrum.txt'
newfile1=trim(newfile1)
open(unit=92, file=newfile1)
do i=1, 4000
  write(92,*) i, sbc(i,:)
endo
close(92)

!The main program has terminated below the function devised to calculate the stopping power of
an ion of given energy is provided and described.

CONTAINS
FUNCTION sp_lookup (energy,sps) RESULT(spout)
!This function reads in a given ion energy and uses the stopping power matrix to determine the
stopping power, providing it as the only output. The function assumes that the stopping power
array is sorted in terms of increasing energy, split into component parts of electric and nuclear
stopping power. The function splits the stopping power list into four parts and first checks which
part of the overall list the ion energy is in, then evaluates each entry in the list to find which two
entries the stopping power is between. As the stopping power is only give for discrete values the program assumes it behaves in a linear fashion between given points, and calculates the respective stopping power for the particular ion energy for both electric and nuclear. The program then combines each of these components and returns the overall stopping power.

```fortran
implicit none
double precision :: energy
!The ion energy being considered
double precision :: spout, spout1, spout2
!The total stopping power which will be returned, the electric stopping power component, the nuclear stopping power component
double precision, DIMENSION(:,::) :: sps
!The stopping power array passed into the function
integer :: n, low, high, ecount, t1, t2, t3
!Integer for do loops, and integers for determination of location of stopping power in array of stopping powers.

!Calculates the size of the stopping power array and determines where the section demarcations should be.
ecount=size(sps,1)
t1=floor(ecount/4.0)
t2=floor(ecount/2.0)
t3=floor(ecount*3.0/4.0)

!Checks to see if the ion energy is in the first half of the stopping power array, if so it determines which quartile it is in, records the indices of that quartile and proceeds to calculation.
if (energy >= sps(1,1) .and. energy <= sps(t2,1)) then
  if(energy .lt. sps(t1,1)) then
    low=1
    high=t1
  else
    low=t1
    high=t2
  end if

!Checks to see if the ion energy is in the second half of the stopping power array, if so it determines which quartile it is in, records the indices and proceeds to calculation
elseif (energy >= sps(t2,1) .and. energy <= sps(ecount,1)) then
  if(energy .lt. sps(t3,1)) then
    low=t2
```

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high=t3
else
    low=t3
    high=ecount
end if

!Checks to see if the ion energy is either above or below the bounds of the stopping power matrix
and sets the indeces accordingly.
elseif(energy < sps(1,1)) then
    low=1; high=1
elseif(energy > sps(ecount,1)) then
    low=ecount; high=ecount
end if

!If the ion energy was either above or below the bounds of the stopping power matrix, the closest
stopping power is used. The maximum stopping power provided to the program was for 10MeV
ions, therefore the maximum was never used. The minimum stopping power corresponded to 1
ev, therefore if an ion energy of less than 1 ev was encountered this would effectively terminate
the ion in the next step.
if (low==1 .and. high==1) then
    spout=sps(1,2)+sps(1,3)
elseif (low==ecount .and. high==ecount) then
    spout=sps(ecount,2)+sps(ecount,3)
else
    a: do n=low, high-1
        if (energy > sps(n,1) .and. energy < sps(n+1,1)) then
            spout1=sps(n,2)+(sps(n+1,2)-sps(n,2))*(energy-sps(n,1))/(sps(n+1,1)-sps(n,1))
            spout2=sps(n,3)+(sps(n+1,3)-sps(n,3))*(energy-sps(n,1))/(sps(n+1,1)-sps(n,1))
            spout=spout1+spout2
            exit a
        elseif (energy==sps(n,1)) then
            spout=sps(n,2)+sps(n,3)
            exit a
        elseif(energy==sps(n+1,1)) then
            spout=sps(n+1,2)+sps(n+1,3)
    end if
end do a

!Using the indices recorded earlier the function initiates a do loop to search each interval
between the indices, inclusive, and determines the nearest values for the ion energy under
consideration. Then, assuming a linear relationship, determines the stopping power using the
nearest values as line endpoints for both the electric and nuclear stopping power, combining
these into the total stopping power. If the ion energy corresponds to a particular stopping power
array entry, this value is given instead.
else
    a: do n=low, high-1
        if (energy > sps(n,1) .and. energy < sps(n+1,1)) then
            spout1=sps(n,2)+(sps(n+1,2)-sps(n,2))*(energy-sps(n,1))/(sps(n+1,1)-sps(n,1))
            spout2=sps(n,3)+(sps(n+1,3)-sps(n,3))*(energy-sps(n,1))/(sps(n+1,1)-sps(n,1))
            spout=spout1+spout2
            exit a
        elseif (energy==sps(n,1)) then
            spout=sps(n,2)+sps(n,3)
            exit a
        elseif(energy==sps(n+1,1)) then
            spout=sps(n+1,2)+sps(n+1,3)
    end if
end do a
exit a
end if
end do a
end if
endfunction splookup

dend program scatterspec
APPENDIX 6 – CONVERSION FROM CHANNEL NUMBER TO PHOTONS PRODUCED

A qualitative analysis of light output of a scintillator from irradiation can be performed by comparing results from the exact same experimental setup for varying radiations. However, in order to allow intercomparing between experiments utilizing different setups, either out of necessity to accommodate specific scintillator characteristics (i.e. different band-gap requiring a different PMT, with an inherently different quantum efficiency) it is necessary to determine the actual photon production of a scintillator. In most of the work presented here only comparison between data from the same experimental setup was required, therefore channel number sufficed for the majority of the analysis. However, occasions arose in which conversion to actual photon production was useful. In order to account for this we must understand every step of the process from photon production to creation of the spectrum. We therefore envision the process as shown below in Figure 60

![Figure 60. Scintillation to spectrum process](image)

Ideally we want to solve for an equation of the form

\[ c = a_1 a_2 a_3 a_4 p \]  

(38)
where $p$ is the number of photons produced by a quanta of ionizing radiation, $c$ is the channel the resultant pulse is sorted into, and $a_c$ are to be determined conversion factors accounting for each step of the process shown in Figure 60.

To begin with, the first step of the process, photon migration from the crystal into the PMT, was discussed in section 3.1. Therefore, we see that $a_1$ should be approximated by the constant determined for this experimental setup, or 0.13. In order to account for possible photon self-absorption, potentially introduced by either intrinsic effects or the crystal damage mentioned in section 3.1, we reduce this to 0.1.

Next, in order to account for the conversion of photons in the PMT to electrons, we must account for both the quantum efficiency of the PMT for the wavelength of concern, $q_{eff}$, and the gain from the applied bias on the PMT, $G_{PMT}$, or

$$a_2 = \frac{G_{PMT}}{q_{eff}}.$$(39)

By assuming a band gap dominant photon emission, we can obtain these values from Appendix 2 – Hamamatsu R329-02 Specification Sheet, as 0.2 and 6000 for the quantum efficiency and gain respectively.

Next, the current supplied to the NIM electronics discussed in section 3.1 is converted to a voltage by the pre-amplifier according to

$$V_o = \frac{Q_{PMT}}{C_{preamp}}$$ (40)

where $Q_{PMT}$ and $C_{preamp}$ are the current output from the PMT in amps and the capacitance of the pre-amplifier in farads respectively, and $V_o$ is the voltage created by the pre-amplifier, giving

$$a_3 = \frac{1}{C_{preamp}}.$$ (41)
For the electronics listed in section 3.1 the capacitance was 45 pF.

Next, the signal is fed through an amplifier, providing a multiplicative factor to the voltage supplied by the pre-amplifier of $G_{\text{amp}}$, which in these experiments was 500, which we represented as $a_3$.

Finally, the voltage is binned into channels according to the analog to digital converter of the software used. For the software used this binning was approximately $1000 \frac{\text{channels}}{v}$, which we can use as $a_4$.

With all of this in mind, we look back at equation 38, and can solve for $p$, giving

$$p = c \frac{C_{\text{preamp}}}{a_1 G_{\text{PMT}} q_{\text{eff}} G_{\text{amp}} a_4}$$

which results in

$$p \approx 4.68c.$$  \hspace{1cm} (43)

For this reason, any point in the text which discusses the scintillation output of GaN in terms of photons utilizes this conversion method.


