

Study of ^{134}In Beta-Delayed Neutron Emission and Development of a New Generation Neutron Detector

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Degree

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*For my wife, Julie, my dog, Maple, and God, these three making the greatest support
system I could ask for.*

Acknowledgments

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Abstract

Beta-delayed neutron emission in very neutron-rich nuclei plays an essential role in nuclear structure and the understanding of the astrophysical r-process. A complete description of this process requires knowledge of both steps, beta decay and neutron emission. A leading theory poses the intermediate daughter nucleus to behave as a compound nucleus. The conditions for beta-delayed neutron emission of ^{134}In are not well described by the assumptions in the neutron pandemonium hypothesis, therein providing a unique case to this process due to the proximity to ^{132}Sn . Single-particle states in ^{133}Sn observed after neutron emission have dissimilar shell occupancy compared to neutron-hole states in daughter nucleus states populated in Gamow-Teller transitions. A short experiment observing ^{134}In decay was conducted with the ISOLDE Decay Station. Multiple neutron-emitting states in ^{134}Sn were identified and the results will be compared with statistical model predictions to establish if the assumption of the "compound nucleus" behavior can be valid for ^{134}In beta-delayed neutron emission.

The continued development of radioactive ion beam facilities which can create very neutron rich nuclei necessitates detectors with improved neutron energy resolution and neutron selection. Exotic nuclei near the neutron drip line are far from beta decay stability and become more likely to undergo beta delayed neutron emission processes. The Neutron dEtector with Tracking (NEXT) is a high resolution neutron detector designed as a neutron-gamma discriminating-plastic scintillator detector with position sensitive readout. Recent advancements in PSD plastic scintillators as well as position sensitive detectors are the foundation of the compact design of the NEXT detector. A segmented detector prototype has been made from optically separated bars of EJ-276 (Eljen Technology) coupled to a

position sensitive PMT and has been shown to have correlated position and timing with monoenergetic neutrons from proof of principle tests.

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Chapter 1

Introduction

Measurements of neutron rich nuclei away from the line of stability are important for nuclear structure and modelling of nuclear astrophysical processes. Many of the overwhelming number of isotopes in this region serve as a first test for the predictive power of nuclear models. As radioactive ion beam facilities continue to push the boundaries of observable nuclei, the limits of modern nuclear physics models are tested. Towards the neutron drip line, nuclei partake in the astrophysical rapid neutron capture process (r-process), whereby nuclei much heavier than ^{56}Fe are created. A common form of studying these nuclei is through beta decay. For especially neutron rich nuclei, beta decay with subsequent neutron emission from an excited state becomes a dominant decay mode.

Proposed here is the study of the neutron emission mechanism and the development of a high-resolution neutron detector. The observed population of pure single particle states in ^{133}Sn can provide insight into the neutron emission process and its possible dependence on the parent wave function. The in-depth understanding of this mechanism has important implications for nuclear structure and r-process nuclei. A new neutron detector has been developed and will now be tested for its performance. The neutron detector will measure the position of the interaction within the scintillator volume to sub-centimeter resolution and be able to reject gamma background.

1.1 Beta Decay

Beta decay is the most common nuclear decay mode and is also an important tool for probing the structure of a nucleus. $\beta^\pm$ decay is mediated by the $W^\pm$ boson, changing quark flavors and emitting an electron (positron) and an accompanying electron anti-neutrino (neutrino). Due to the large mass of the W boson, the interaction length can be thought of as being point-like, meaning the process occurs within the mass radius of the nucleus. For neutron rich nuclei, β^- decay is the only energetically favorable form of beta decay whose energy is given as the mass difference between the mother and daughter nucleus:

$$Q_{\beta^-} = [M(Z, N) - M(Z + 1, N - 1)]c^2. \quad (1.1)$$

Beta decay half-lives given in equation 1.2 are dependent on the beta decay strength function, $S_\beta(E_i)$, and the 3 body decay phase space represented by the Fermi integral $f(Z, Q_\beta - E_i)$ [7]. In β^- decay, the emitted electron is attracted to the nucleus, slowing the beta particles as they leave the nucleus. The Fermi integral contains a correction to the electron (positron) plane wave due to Coulomb interactions.

$$T_{1/2}^{-1} = \int_0^{Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i) dE_i \quad (1.2)$$

1.1.1 Allowed Decays

Allowed beta decay can occur under two types of transitions based on the spin alignment of the emitted electron and anti-neutrino. When the spins are anti-parallel, the decay undergoes a Fermi Transition, in which the spin of the nucleus stays the same and no spin is carried away by the emitted particles. If the spins are parallel, then the nuclei undergo a Gamow-Teller transition, and the emitted particles carry away $S_\beta = \vec{1}$. The beta decay strength depends on what type of transition occurs due to the different coupling strengths of Fermi and Gamow-Teller decay. Fermi decays are described by the isospin ladder operator, converting

a neutron into a proton (or vice-versa):

$$\sum_{i=1}^A \tau^-(i) = T^-. \quad (1.3)$$

Gamow-Teller decay couples the neutron and proton spin with the isospin ladder operators, allowing the decay to occur between different isospin multiplets:

$$\sum_{i=1}^A \vec{\sigma}(i) \tau^-(i) = Y^- \quad (1.4)$$

The energy differences between isobaric analogue states increases with increasing Z (β^- decay) due to the Coulomb potential, meaning GT transitions are the most abundant form of β^- decay [8]. GT transitions access different isobaric states by removing a unit of spin from the nucleus, accessing lower energy states.

1.1.2 Forbidden Decays

Forbidden decays should also be discussed due to the unique capability of these type of β decays to access different parity states. Forbidden decays involve a change in orbital angular momentum of the final state, making them less likely to occur. The reduction is due to the l th order in the multipole expansion of the lepton wave function, $(qR)^l$. The expansion parameter, Rq , is dependent on the radius of the nuclei, R , and the momentum transfer in the decay, q [8]. Forbidden transitions play very little role except in decays of large nuclei and large Q_β values.

1.2 Nuclear Shell Model

Many theoretical models have been proposed for the arrangement of individual nucleons within a nucleus. Generally, macroscopic behavior is determined from microscopic interactions between nucleons. While many models have been able to accurately predict phenomena in low mass nuclei, medium to heavy nuclei are very difficult to describe with modern theoretical approaches. The shell model was proposed as a central potential where

the mean field is self-generated from all the nucleons in the nucleus and any residual corrections are accounted for as two body interactions [9–11]. Commonly chosen, the Woods-Saxon potential with spin orbit interactions (M. Goeppert-Mayer 1963 Nobel Prize [12]) matches experimentally measured shell closures the best [13]. In modern shell model calculations, residual interactions are also included for nuclei that have more than two nucleons outside a doubly closed core. This accounts for the additional effects due to nucleon-nucleon interactions that are not accounted for in the average potential.

1.2.1 ^{132}Sn Region

Using the Shell Model with a realistic Woods-Saxon potential and spin-orbit interactions, magic numbers 2, 8, 20, 28, 50, 82, 126, and more can be extracted from large gaps in energy between a filled outer shell and the next available shell for a nucleon to occupy. Effects from these large gaps have been measured in experiments but most importantly, a doubly magic or doubly closed core provides an essential benchmark for testing modifications to the shell model. In particular, properties of nuclei with few nucleons outside a doubly closed core are generally very well described by the shell model. ^{132}Sn is a doubly closed core nucleus with $Z=50$ and $N=82$ and is considered one of the most ideal doubly magic nuclei [14]. Figure 1.1 shows the single particle orbital arrangement around the closed cores (shaded area) in ^{132}Sn .

1.3 Beta-Delayed Neutron Emission

For an isotopic chain, as N/Z becomes large, the beta decay endpoint energy, Q_{β^-} increases. Not only does this better the likelihood of a nucleus undergoing beta decay, but also the ability to populate highly excited states in the daughter nucleus becomes available. Because neutron separation energies decrease with increasing neutron number, states in the daughter nucleus that are higher than one, two, and even higher order neutron separation energies become accessible. When a state above the neutron separation energy is populated, the nucleus can de-excite via neutron emission instead of emitting a gamma ray as shown in Figure 1.2. This entire process is known as beta-delayed neutron emission and it plays a

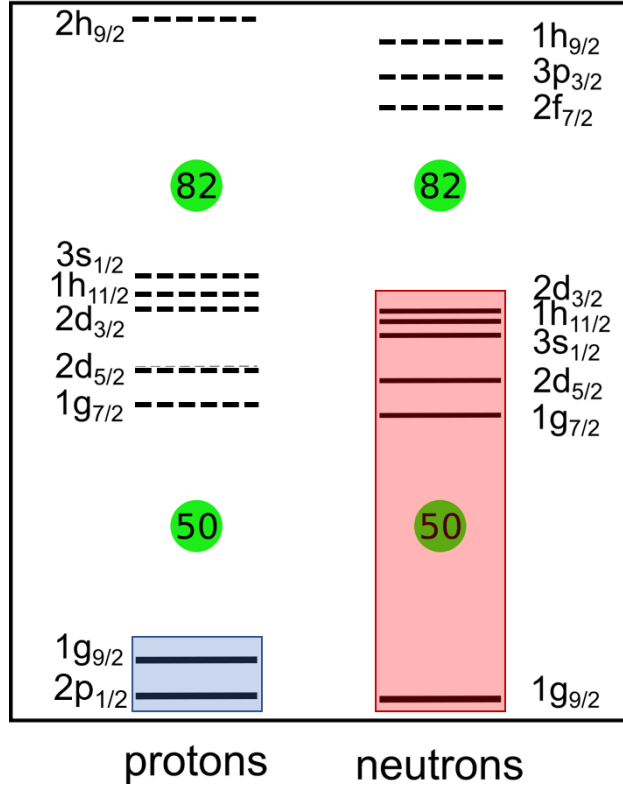


Figure 1.1: Single particle proton and neutron orbitals in the vicinity of ^{132}Sn relevant for studying beta decays of nuclei discussed in this dissertation.

very important role in the study of nuclei with large N/Z . Figure 1.3 displays $Q_{\beta^-} - S_n$ values of all known isotopes, reflecting the increasing probability of neutron emission with respect to larger N . In the past, the percentage of decays that have undergone subsequent neutron emission have been modeled with a so called Cutoff approach [15], but recent results show that a Hauser-Feshbach statistical model may better predict the neutron emission [16–18].

1.3.1 Cutoff Model for Delayed Neutron Emission

Older models of beta-delayed neutron emission had a very simple approach for calculating the expected probability of neutron emission. It was often assumed that if a state above the one neutron separation energy was populated, it was guaranteed to emit a neutron, and states above the two neutron separation energy would emit two neutrons. Neutron emission probabilities are calculated by integrating the beta decay feeding intensity in the respective energy windows between subsequent neutron separation energies [15]. The mathematical formulation for the total neutron emission rate from Ref. [15] is given as

$$\lambda_n = \sum_{\Omega} \int_{-Q+S_n}^0 \frac{\Gamma_n}{\Gamma_n + \Gamma_{\gamma}} \lambda_{\Omega}(E) dE$$

where Ω signifies the various beta decay transition types. Because experimental data was limited at the time of the articles publication, few studies had been done on the importance of the angular momentum carried away in the neutron emission, so the competition factor was assumed to be unitary, $\frac{\Gamma_n}{\Gamma_n + \Gamma_{\gamma}} = 1$. This approximation works well for nuclei that have intense feeding in the energy range well above the neutron separation energy but below the two neutron separation energy. For other nuclei, the failure of this approach is due to no consideration for neutron-gamma competition and single neutron emission above the two neutron separation energy. While the neutron-gamma competition can be combined easily with the Cutoff model, a more sophisticated neutron emission model must be used to account for the latter situation in the previous statement.

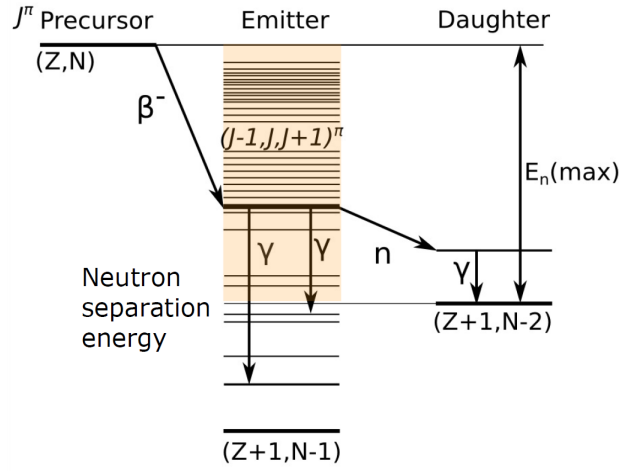


Figure 1.2: Schematic showing the beta delayed neutron emission process. The precursor nucleus beta decays to an excited state above the neutron separation energy in the emitter nucleus, thereby opening another channel for the nucleus to de-excite through neutron emission.

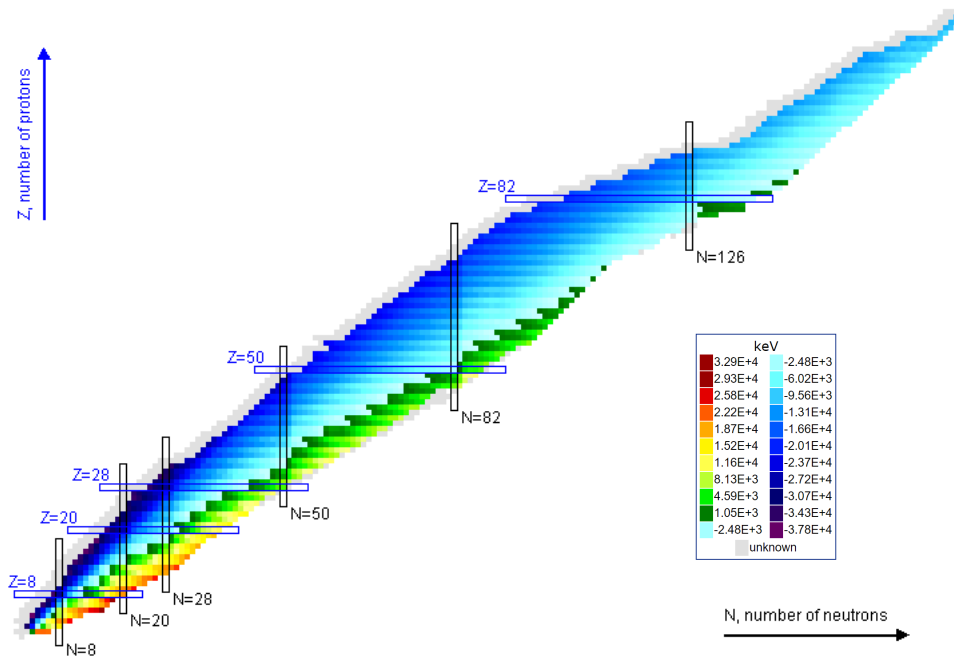


Figure 1.3: Chart showing $Q_{\beta^-} - S_n$ values for known isotopes.
(Image Credit: <http://www.nndc.bnl.gov>)

1.3.2 Statistical Model

Unlike the Cutoff model, a statistical approach treats the neutron (or gamma ray) emission with a more complete microscopic framework. The daughter nucleus is assumed to be a compound nucleus meaning its subsequent behavior is independent of its formation. This point is a crucial test for this work and its significance will be substantiated later in Section 2.1.1. For now, a brief overview of the approach using the Hauser-Feshbach statistical model will be explained.

W. Hauser and H. Feshbach first showed that in the inelastic scattering of neutrons, a purely statistical approach may be taken to the neutron emission when the target nucleus can be treated as a compound nucleus [19]. A compound nucleus is formed when an incident particle fuses with the nucleus long enough that the entire nucleus equilibrates, and the incident particle is indistinguishable from the rest of the nucleus [20]. The compound nucleus “forgets” how it was formed and the decay products are entirely independent of the formation process except that angular momentum and parity must be conserved. In this case, the nucleus is assumed to be excited to states in a region with high enough level density where the widths of neighboring states overlap with one another creating a superposition of eigenstates at a given excitation energy. It is also assumed that the incident beam energy resolution is broad enough that many levels of the compound nucleus are populated [19]. The phase relations between the matrix elements for the formation and decay of the compound nucleus are then random. When averaged, all interference terms will vanish due to the random phases and the compound nucleus can be treated with a statistical or continuum theory [21]. Hauser and Feshbach calculated the neutron inelastic scattering cross section in this model and found the energy and angular distribution of emitted neutrons only to be dependent on the difference in quantum numbers E , J , and l between the initial and final state [19]. The transition is no longer dependent on any detailed properties of the inherent nuclear structure of the initial and final state and the neutron energy distribution is heavily dependent on the density of states in the compound nucleus.

Statistical models have been used to calculate nucleon emission from excited states for many years [22, 23]. T. Kawano, P. Möller and W.B. Wilson proposed using a Hauser-Feshbach statistical method to predict beta delayed multi-neutron emission and recent experimental results show strong agreement with this new model [16, 18]. Beta decay transitions to excited states in the emitter nucleus are done in a typical quasiparticle random phase approximation (QRPA) method. The excited states of the emitter nucleus populated in beta decay are treated as a compound nucleus [16]. Neutrons emission transition probabilities from these states are calculated using the same formalism as the Hauser-Feshbach statistical model where the only factors affecting the shape of the neutron energy spectrum are the energy level densities and the orbital angular momentum and spin of the emitted neutron.

Chapter 2

Motivation for ^{134}In

2.1 Neutron Emission mechanism

The process by which a neutron is emitted after beta decay has not been studied experimentally in great detail. As mentioned in Section 1.3.2, it is believed the highly excited states populated in beta delayed neutron emission can be treated as compound nuclei. However, some known beta delayed neutron emitters have shown behavior indicative of direct neutron emission from broad resonances [1, 24]. Whether the neutron emission is direct or indirect has large implications on how analysis of measured neutron spectra with limited energy resolution can be used to assess the level densities and nuclear structure of pertinent nuclei. This nucleus also resides in an extremely important region of the chart of nuclides near the doubly magic ^{132}Sn nucleus.

2.1.1 Beta Delayed Neutron Emission of ^{134}In and single-particle states in ^{133}Sn

The ^{133}Sn nucleus was of interest originally for its position in the chart of nuclides. Doubly closed shell (DCS) nuclei have always been staples of testing new and existing nuclear models. Surrounding nuclei typically are the first to highlight any abnormality in the treatment of nuclei with non-ideal shell structure. The single-particle nature of ^{133}Sn was first studied via direct beta decay from ^{133}In [25]. Due to the large beta decay endpoint energy in ^{133}In

($Q_\beta = 13.41$ MeV) and beta-decay selectivity, no single particle states were populated. The highly excited states around ~ 3.5 MeV decay predominately via neutron emission ($P_n \simeq 85\%$) which further reduced the capability of studying any low-lying states through gamma-ray cascades.

In the beta-delayed neutron emission of ^{134}In ($Q_\beta = 14.8$ MeV), the daughter is left in a highly excited state for similar reasons as stated for ^{133}In beta decay. ^{134}Sn , the daughter nucleus, predominately emits neutrons from these excited states to multiple states in ^{133}Sn . The low-lying ^{133}Sn single particle states, otherwise inaccessible through normal ^{133}In β^- decay, are fed from the ^{134}Sn neutron emitting states. Hoff et al. were the first to observe this process of feeding to ^{133}Sn low-lying particle states from ^{134}In beta-delayed neutron emission [25]. Using an upgraded ISOLDE target system (ISOLDE-PSB), decays of ^{134}In were measured using two closely spaced liquid scintillation cells and two 70% Ge detectors. Neutron emitting events were tagged using pulse shape discrimination in the scintillator while coincident gamma rays were recorded in the Ge detectors. Hoff et al. concluded that the observed lines at 854, 1561, and 2005 keV were most likely transitions to the ^{133}Sn ground state based on their small contribution to the gamma-gamma coincidence data. A semi-empirical argument provided by Hoff et al. asserts the spin assignments of the 854, 1561, and 2005 keV single particle levels as $3p_{3/2}$, $1h_{9/2}$, and $2f_{5/2}$ respectively, supported by a reference to shell model calculations of single particle levels in the ^{132}Sn region [25]. A schematic overview of the beta-delayed neutron emission process of ^{134}In and the population of single particle states in ^{133}Sn can be seen in Figure 2.1.

The single particle nature of the states discovered by Hoff et al. [25] were studied with an inverse kinematics $^{132}\text{Sn}(d,p)$ experiment performed by Jones et al. [14]. Spectroscopic factors, $S = (\frac{d\sigma}{d\Omega})_{exp}/(\frac{d\sigma}{d\Omega})_{theory}$, were extracted for observed 854, 1363, and 2005 keV states. The 1561 keV state was not significantly populated due to the large angular momentum transfer necessary to populate the $h_{9/2}$ state. For each observed state, S values showed little fragmentation with the single neutron strength, confirming the single particle nature of the low-lying excited states in ^{133}Sn .

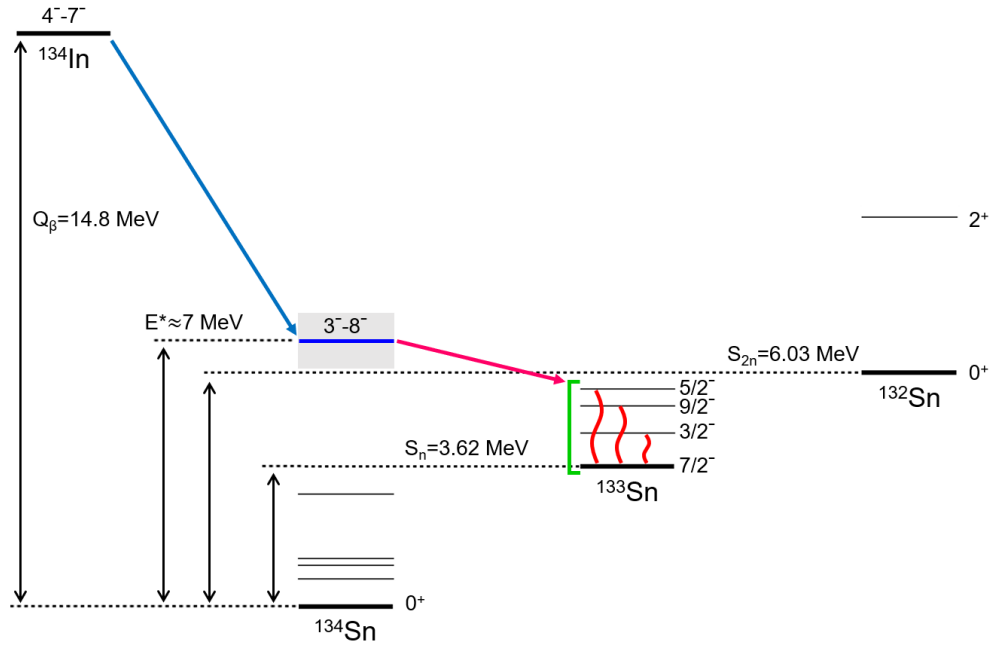


Figure 2.1: Schematic diagram of the ^{134}In beta delayed neutron emission process. The blue arrow represents a Gamow-Teller beta decay transition to an excited state in ^{134}Sn . The magenta arrow represents the neutron emission from a ^{134}Sn excited state to single particle states in ^{133}Sn . The red curves show the decay of the excited ^{133}Sn states to the ground state.

2.2 R-process Nucleosynthesis

Nuclei in the $N \gg Z$ region are extremely important for informing r-process nucleosynthesis modeling. The r-process is thought to be responsible for over half the production of natural elements heavier than iron. During r-process nucleosynthesis, there is competition between neutron captures (n, γ) and photodissociation (γ, n) or beta decay in very neutron rich nuclei along isotopic chains [2]. At certain waiting points where an equilibrium is reached, beta decay half-lives become comparable to neutron capture and photodissociation rates. Beta decay begins feeding between isotopic chains at these points, where the relative abundances between the chains are set by the relative decay rates of the most abundant isotope [2].

The lifetimes of the equilibrium points are dependent on what astrophysical environment is mediating the r-process. Eventually, equilibrium fails, and the neutron rich nuclei decay back to stability which is governed by four simultaneous processes: neutron capture, photodissociation, beta delayed neutron emission, and normal beta decay. This final decay back to stability sets the final abundance pattern for the given astrophysical process.

2.3 Goals of this analysis

An experiment carried out by Madurga et al. observed the beta decay of ^{133}In ($\nu g_{7/2}$ to $\pi g_{9/2}$) to highly excited states in the daughter [26] like that shown by the solid red arrow in Figure 2.2a. The ground state particle occupation of ^{134}In can be seen in Figure 2.3a, which is similar to ^{133}In . The dominant Gamow-Teller transitions in ^{134}In will occur between the same shell levels, leading to a particle-hole state around 7 MeV in excitation [27], as shown in Figure 2.3b.

2.3.1 Nature of the intermediate nucleus

As mentioned in Section 1.3.2, a highly excited nucleus possibly behaves as a compound nucleus if the level density is high enough for the majority of states to overlap. The strongest consequence of this approximation is that the transitions to and from the compound state are separate processes, therefore how the compound nucleus was formed has no implication

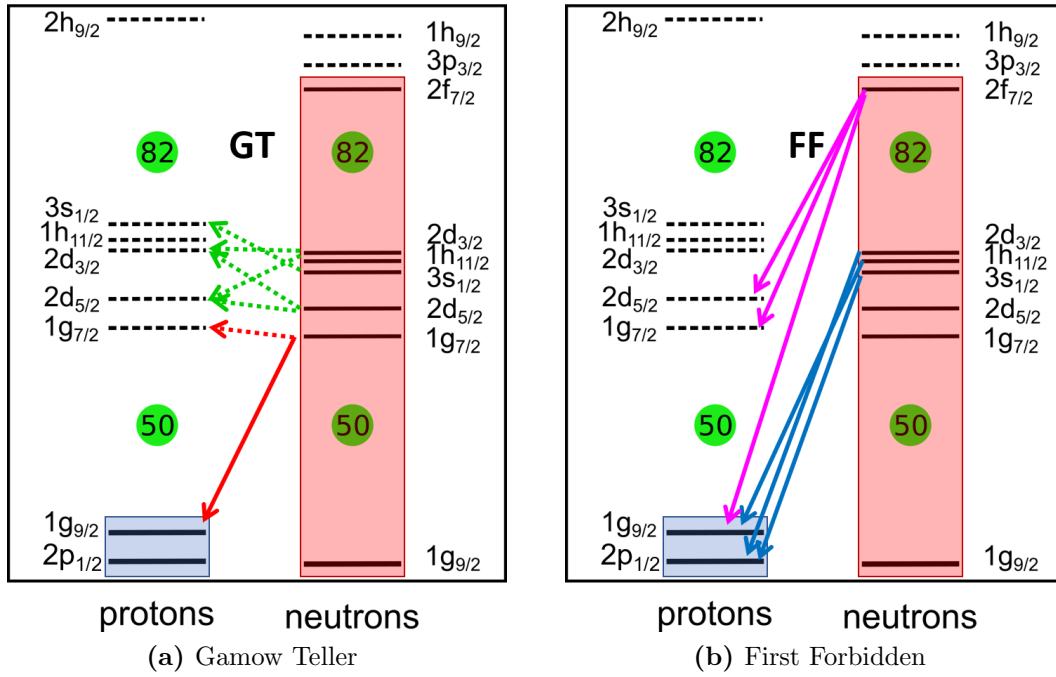


Figure 2.2: Shell Level Structure of ^{134}In . The left plot shows the origin of the highly excited states in the daughter of ^{134}In due to the only allowable Gamow-Teller type transition from deep within the filled neutron shells. The right plot shows the first forbidden decays ($\Delta l = 1$).

on the decay of the compound nuclear state. Figure 2.3a shows the occupied shell levels for ^{134}In and the varying beta-decay transitions which can occur are shown in Figure 2.2. The resultant particle level occupation from Gamow-Teller or First Forbidden transitions can be seen in Figure 2.3b and Figure 2.3c respectively. The structure of first forbidden transitions represented by the blue arrows in Figure 2.2 were not considered because they are further suppressed by kinematics as compared to the first forbidden transitions denoted with purple arrows. When the ^{134}Sn compound nucleus emits a neutron, it populates the single particle states in ^{133}Sn observed by Hoff et al. and Jones et al, as represented by Figure 2.3d. These ^{133}Sn single particle states ($2f_{7/2}, 3p_{3/2}, 1h_{9/2}, 2f_{5/2}$) have little overlap in structure with the emitter ^{134}Sn states populated in ^{134}In Gamow Teller beta decays. The applicability of a Hauser-Feshbach statistical model to neutron branching ratio calculations will be tested by calculating ^{134}Sn excited states and level branching ratios to single particle states in ^{133}Sn from measured neutron and gamma ray energies. If these states are shown to be populated through Gamow-Teller beta decays in a region of high level density, this would then prove that the excited emitter nucleus could behave as a compound nucleus, thereby supporting the claims made by T. Kawano et al. in Ref. [16]. Neutron energy measurements are needed to fully reconstruct the feeding intensities for comparison with shell model calculations and determine if the neutron emitting state was populated via a Gamow-Teller transition. Only then can the neutron emission process be fully understood as occurring from a compound nucleus, certifying the statistical treatment of this process.

2.3.2 Importance of ^{134}In βn Emission Probabilities

An important input for r-process modeling is the probability of neutron emission from r-process nuclei. During the decay back to stability, not only does the competition between beta-delayed neutron emission and beta-delayed gamma emission play a large role in the setting of the final abundance pattern but also the possibility of emitting more than one neutron affects the path to stability. Figure 2.4 shows that different model treatments of the neutron emission process could lead to variations in the final abundance pattern. This treatment become incredibly important towards the neutron drip line where the beta-decay

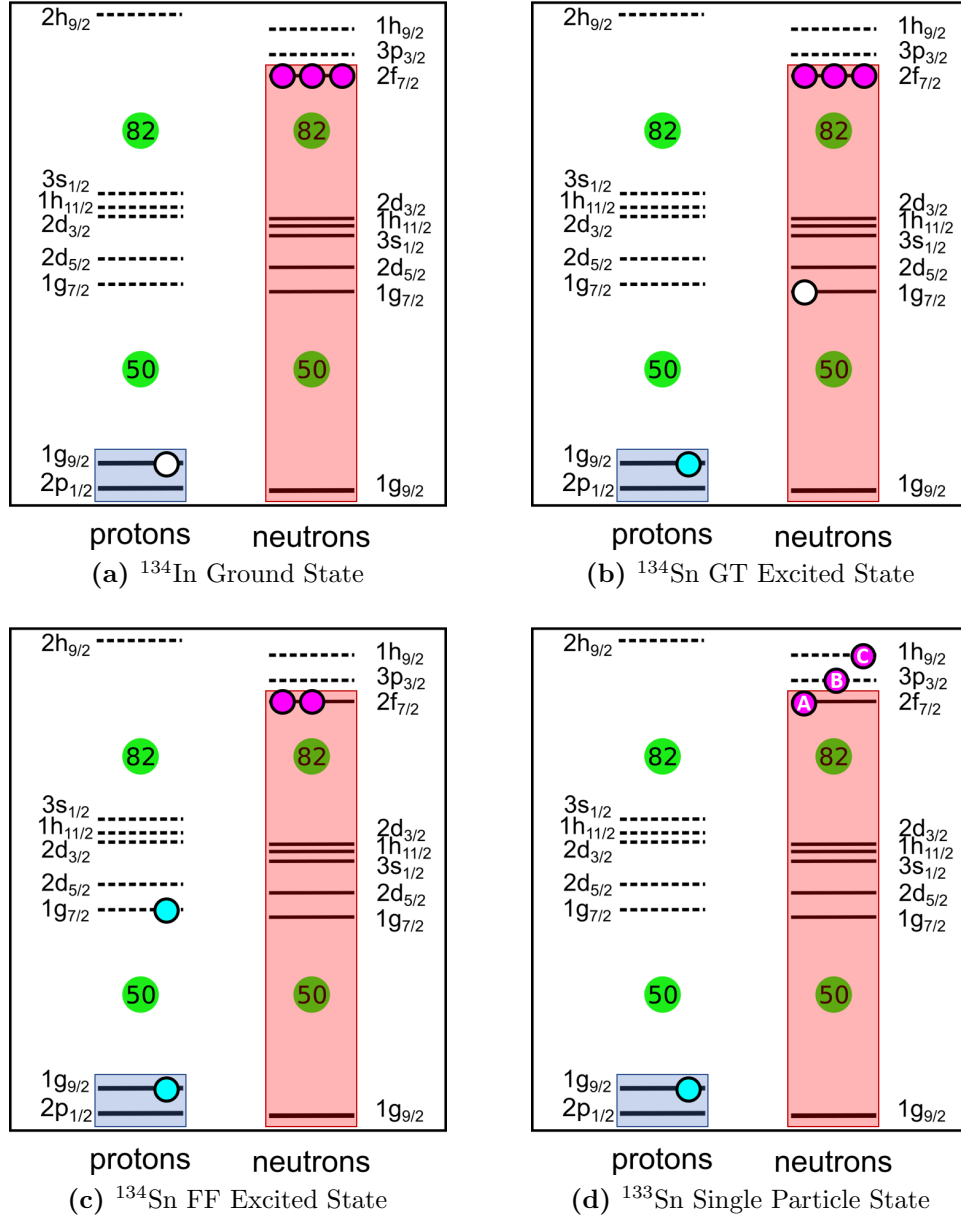


Figure 2.3: Three images showing the shell model level occupation of the precursor, emitter, and daughter nucleus from left to right respectively.

endpoint energy is so large that it become possible to populate states which can subsequently emit up to 5 neutrons.

A sensitivity study performed by M. Mumpower et al. showed that beta-delayed neutron emission probabilities in the south-east corner around the ^{132}Sn region play an important role in the final abundance patterns for cold wind supernova and neutron star merger environments [2]. The specific importance of each nuclei was determined by setting individual P_n values to zero and comparing the results to a baseline simulation. The results, shown in Figure 2.5, concluded that the ^{134}In P_n value is among the strongest influencers in beta-delayed neutron emission setting the final abundance pattern [2].

For most r-process modeling, unknown emission probabilities are calculated using either of the two approaches mentioned before in Section 1.3. This analysis is not only important for determining the most applicable treatment of neutron emission, but is also important in corrections to measured P_n values from neutron counting detectors. ^3He -based neutron counting detectors are designed to be highly efficient at counting neutrons emitted after nuclei undergo beta delayed neutron emission but are incapable of determining the energy spectrum of the emitted neutrons. Low energy neutrons can be easily tagged with high density ^3He tubes but detector efficiency suffers decreases steadily for medium to higher energy neutrons. This causes complications as the target nuclei are extended towards the neutron drip line; the energy window for emitted neutrons greatly increases with greater disparity between N and Z . For most neutron counting detectors, the ^3He tubes are placed in plastic moderator which greatly increase the efficiency to ~ 1 MeV [28]. Above this energy, the rate of decrease in efficiency depends on the amount of moderator and ^3He . Typically, a calculated neutron energy spectrum is used to make corrections in the analysis of neutron counting data, but an experimental neutron energy spectrum is the most accurate tool for efficiency corrections. A deconvolved energy spectrum from this analysis will be important to BRIKEN P_n measurements of ^{134}In made in November 2017.

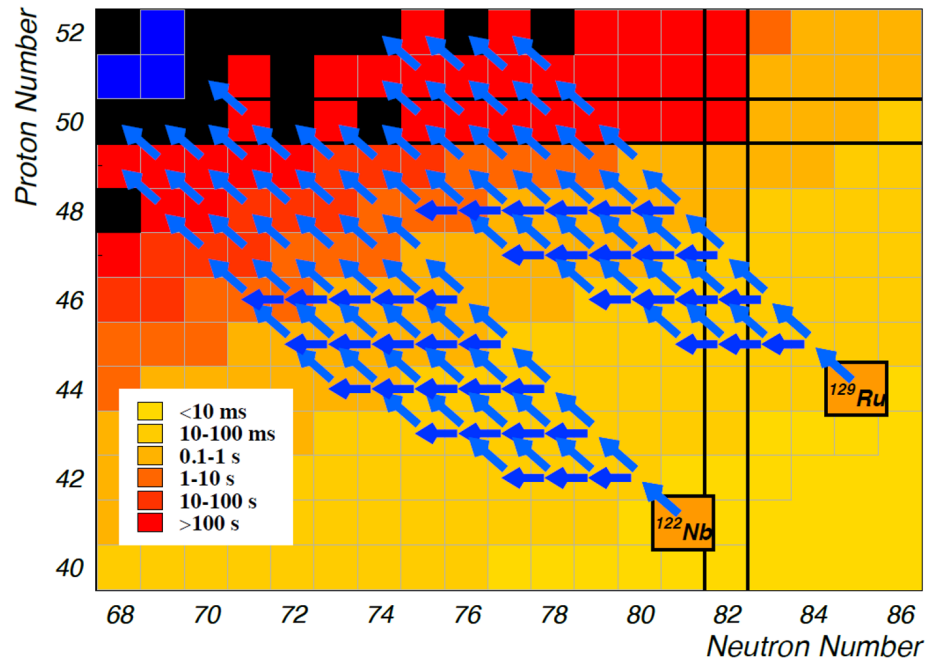


Figure 2.4: Possible pathways back to stability via beta-delayed neutron emission of nuclei formed in the r-process. Light blue arrows are beta decay and dark blue arrows signify neutron emission.

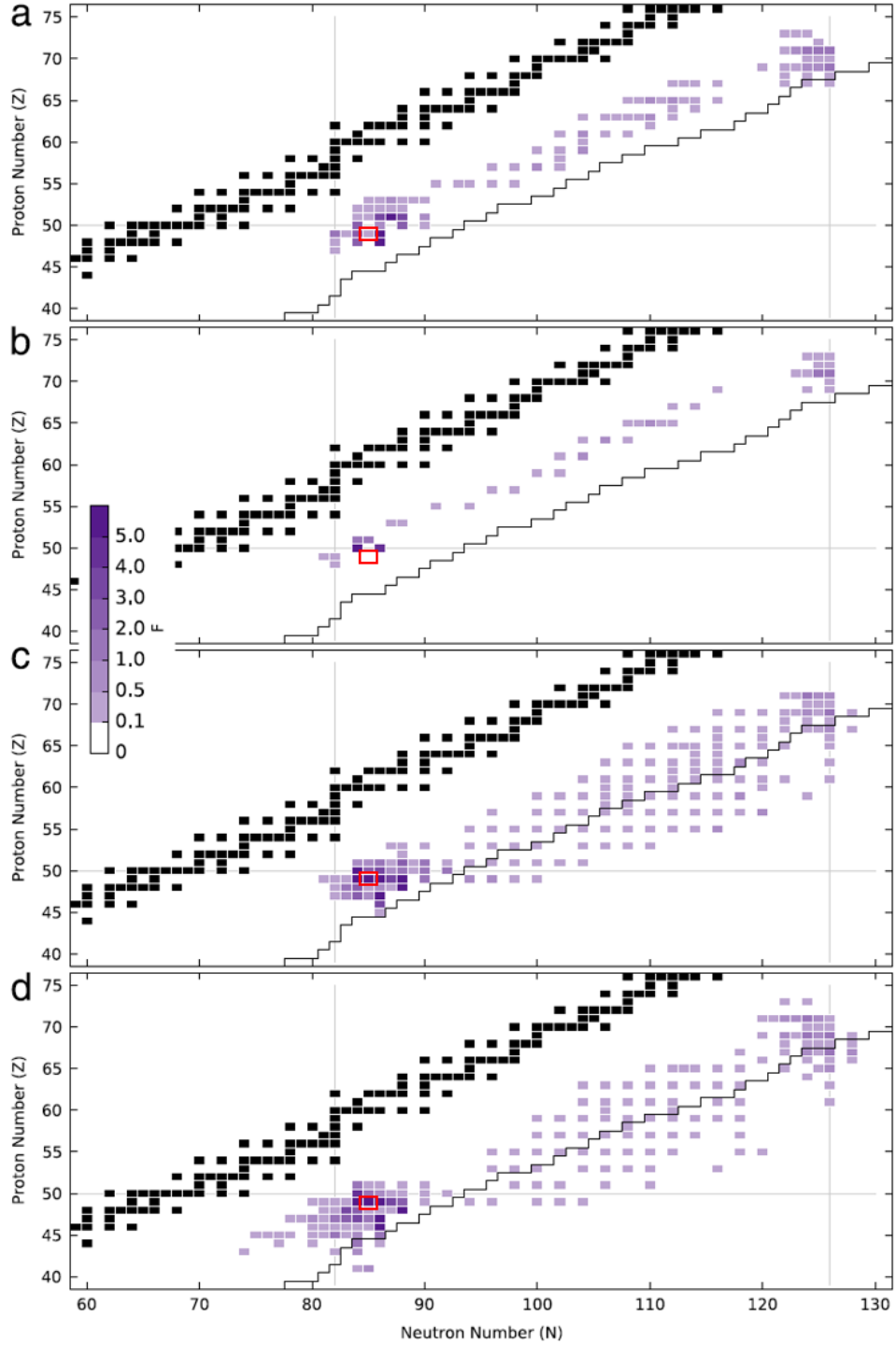


Figure 2.5: Plots showing the sensitivity of the final isobaric mass abundance to the setting of P_n values to zero for r-process nuclei in four different astrophysical environments: (a) low entropy hot wind, (b) high entropy hot wind, (c) cold wind, and (d) neutron star merger. The red box in each plot indicates ^{134}In . Adapted from M. R. Mumpower et al. [2]

Chapter 3

Experimental Setup

The experiment for observing beta delayed neutron emission from ^{134}In was carried out at the Isotope Mass Separator On-Line Facility (ISOLDE) at CERN in Geneva, Switzerland. The dataset of observed ^{134}In beta decays was supplementary to the main dataset of ^{133}In beta decays. The main isotope was observed with enough statistics such that the remaining 8 hours of beam time were used to collect data for the ^{134}In beta-delayed neutron emission.

3.1 ISOLDE

ISOLDE is an isotope separation on-line (ISOL) facility utilizing a pulsed 1.4 GeV proton beam to produce radioactive ion beams from spallation, fragmentation, and fission reactions in thick targets. The facility layout is shown in Figure 3.1. At ISOLDE, the products from the proton bombardment are thermalized in the target chamber and captured in the ion source chamber. The ion source chamber is coupled to an ionizing laser (RILIS) such that the products from the target are ionized before they leave the hot cavity [29]. RILIS at ISOLDE can be tuned to specific wavelengths that excite and knockout electrons in a two step process. The first laser beam excites an electron to a highly excited state and a second laser beam follows and excites the electron into the continuum, thereby ionizing the nuclei of interest. This method is extremely selective, offering high beam purity when tuned properly. The ions are then accelerated and passed through the High Resolution Separator, purifying

the beam even more with a resolution of $M/DM=5,000$ [30]. The beam is then delivered to the ISOLDE Decay Station seen in Figure 3.2

3.2 IDS

Once the beam is electromagnetically separated, the ions are transported to the ISOLDE Decay Station (IDS). The ions are implanted on a movable tape in the center of IDS through a circular opening in the center of the beta detector. The ISOLDE Decay Station (IDS) (red star in Figure 3.1) configuration for this experiment utilizes a tape system where the beam is implanted on a thin movable tape directly surrounded by a beta particle detector which triggers on beta decay events. For this experiment, the beam is operated in a "take-away" mode optimized for short decay lifetimes. The ISOLDE proton beam is pulsed at 1.2 s, which designates the overall tape cycle time. The beam implant time was set to 450 ms ($\sim 3.2t_{1/2}$) with an additional 100 ms buffer before the tape move cycle. The tape was then moved for 650 ms to clear the decay chamber of all long-lived activity.

Shown in Figure 3.3, the beta decay detector consists of two separate layers of high efficiency scintillator surrounding the implant point. The beam passes through the hole in the front scintillator while the tape is run through the slit between the front and back layer. The entire scintillator is wrapped in reflective material and coupled to PMT's on opposite ends of the detector. Beam spread caused the thinner back layer of the beta detector to become contaminated necessitating its removal for the ^{134}In data taking. Calibration data was also taken with this configuration which will help account for any inconsistencies with standard ISOLDE analysis.

When radioactive decay does not directly transfer to the ground state in the daughter nucleus, it's important to measure any subsequent de-excitation to properly reconstruct level schemes. To measure gamma rays emitted after beta decay, four HPGe clover detectors were arranged for maximum efficiency around the implant point (Figure 3.2b). Supported by an aluminum shell, the front face of each HPGe clover was roughly 80 mm from the center of the beam spot. The efficiency curve for full addback between all HPGe detectors is shown in Figure 3.4.

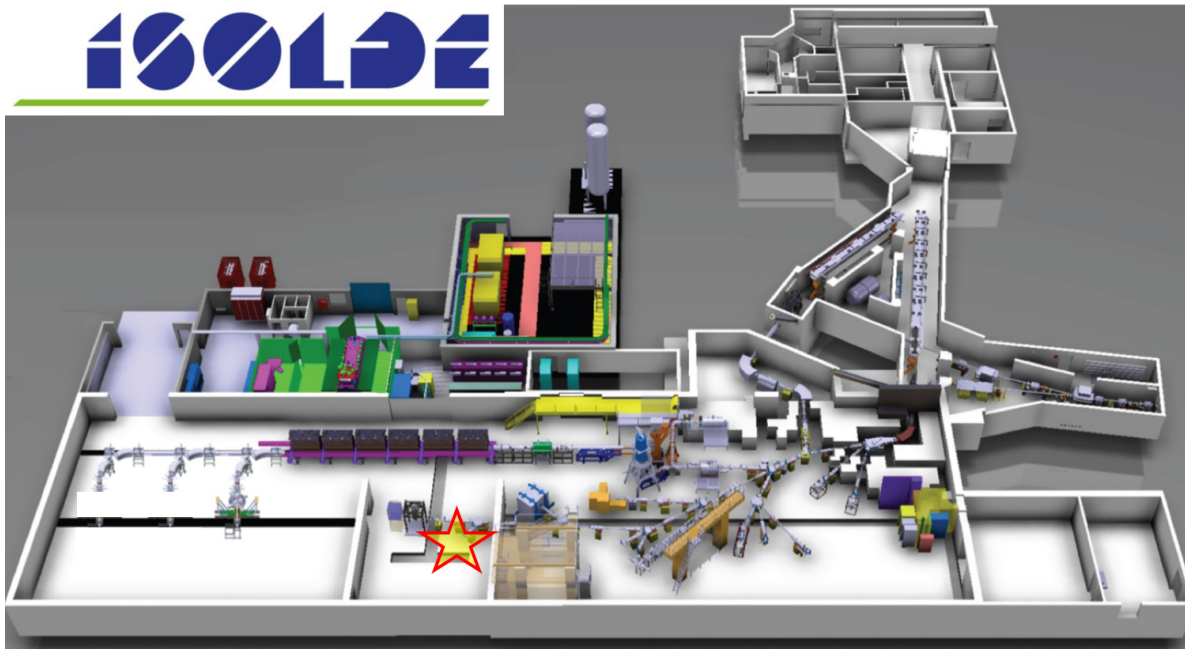
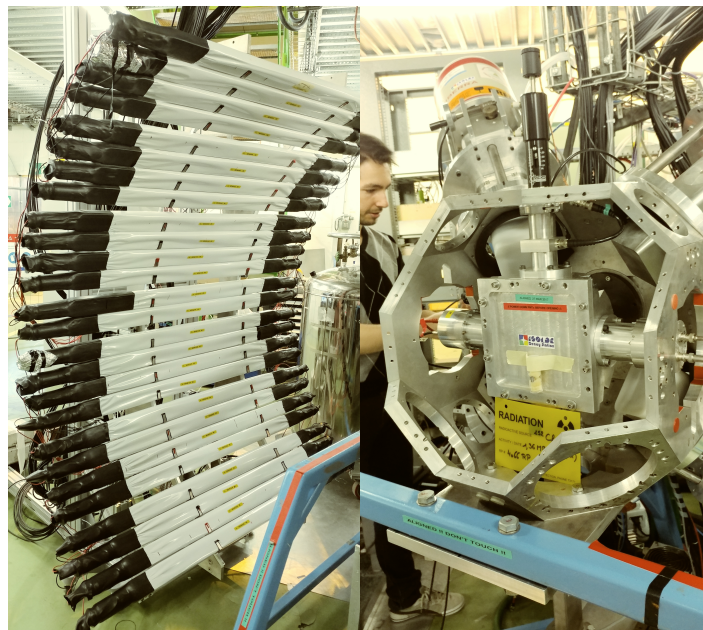


Figure 3.1: Layout of ISOLDE Facility at CERN in Geneva, Switzerland.



(a) INDiE

(b) HPGe

Figure 3.2: Experiment setup with the INDiE setup on the left. The neutron detector is mirrored across the implantation point by the beta detector and the 4 high purity Germanium detectors shown in the right image.

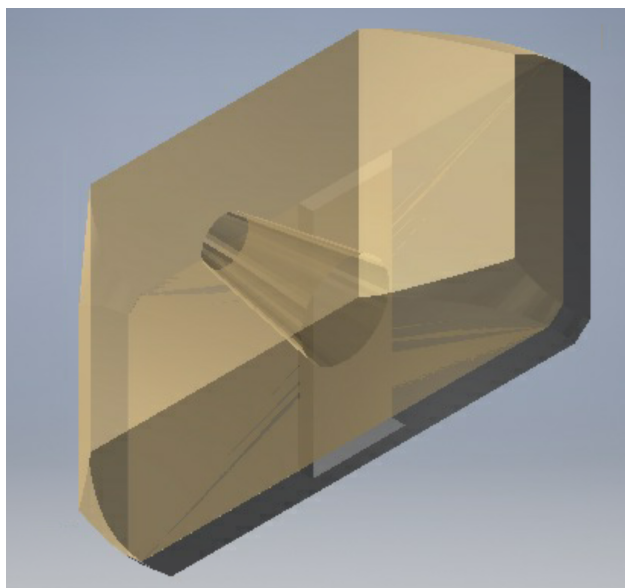


Figure 3.3: 3D model of the front and back sections of the beta detector. The beam enters through the hole in the center of the large detector to where the tap is run in the slot between the front and back portion.

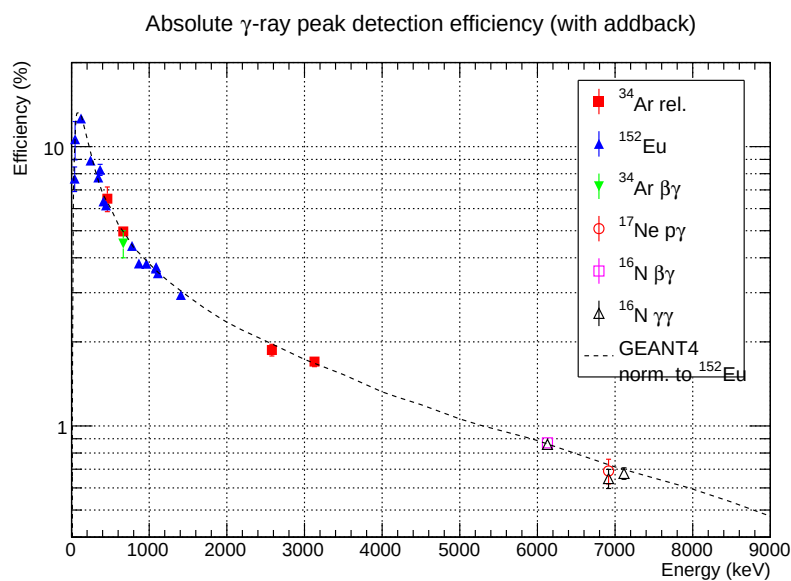


Figure 3.4: Efficiency data and curve for the four HPGe detectors at IDS. The shape of the curve was derived from Geant4 simulations of the setup and normalized to calibration data taken with the full setup.

3.3 IDS Neutron Detector

Because the dominant decay mode of ^{133}In and ^{134}In is beta delayed neutron emission, the primary detector used in this experiment was the ISOLDE Decay Station Neutron Detector (INDiE) consists of 26 individual detector modules, each made of a single $2\times 6\times 120\text{ cm}^3$ bar of Eljen 200 plastic scintillator coupled to Hamamatsu PMTs on each end [26]. The array can be seen in Figure 3.2a. The design of INDiE is based on the Versatile Array of Neutron Detectors at Low Energy (VANDLE) which was conceived at the University of Tennessee Knoxville [31]. An overview of neutron detection with scintillating detectors is presented in Appendix B which explains how neutron energies are measured at the INDiE. Information on how the scintillation process works can be found in Section 6.1.2. Each scintillator bar is wrapped with aluminized mylar for light-tightness and improved light capture in the detector. The position of the scintillation along the bar can be determined from two PMTs which improves time of flight calculations. The bars are mounted to a customized frame that orients them in a cylindrical pattern around implantation with a 105 cm flight path between the implantation point and the front face of the neutron detectors. The entire neutron detector covers a solid angle 14.9% of 4π and was calibrated to have a 40% detection efficiency for 1 MeV neutrons from a ^{252}Cf source [26]. The overall efficiency of the decay station setup with an in-vacuum beta detector at 90% efficiency for full observation of a beta-delayed neutron emission event is between 3-7%, depending on neutron energy [26].

3.3.1 Data Acquisition

In order to record the light detected by the photomultiplier signals, the signal outputs are connected to fast digitizers which record the analog PMT signals at fixed intervals. This method of using a digital data acquisition is extremely advantageous for online triggering as well as preserving original raw data that can be reprocessed as necessary.

The neutron detectors were connected to XIA Pixie16 12-bit digitizers that sampled at a 250 MHz rate. This fast sample rate is key for offline analysis on the recorded light pulse as the light pulse rise times are usually on the order of 8 to 10 ns. These digitizers usually capture two to three points along the rising edge of the pulse which helps further constrain

neutron time of flight when methods outlined in Section 4.1.2 are utilized. Each channel has its own local fast trapezoidal filter (fast trigger) which is optimized to minimize trigger thresholds. Another benefit of using this type of digital DAQ system is that the onboard logic circuit can propagate individual channel triggers between modules to generate coincidence and global triggers [3]. In an analog system, a complex combination of logic instrument modules and cabling is required to reject any event that is considered background. There are two main trigger modes to which an individual Pixie16 channel can respond: pairwise and global. Pairwise triggers are generated between neighboring digitizer channels which both individually register an event via the fast trigger within a specified time window. When a signal from the beta-decay detector triggers in coincidence with a pairwise trigger, a global trigger is then generated (see Figure 3.5). The global trigger is then propagated back to all Pixie16 channels and information is recorded only if the original fast trigger for that channel still coincides with the global triggers. The global triggering scheme enables the detection threshold to be set well below electrical noise levels when the trigger timing parameters are set correctly. There are numerous parameters in the entire triggering scheme which when properly setup, helps eliminate systematic and random room background from scattered neutrons and gamma rays in the experimental hall. For this experiment, the pairwise coincidence window for a VANDLE bar was set to 104 ns, approximately 10 times longer than it takes light to propagate from one end of a bar to another. The global coincidence window was set to 1.5 μ s. These time windows account for the uncertainties related to the signal dependence of the on-board trapezoidal trigger filter and provide enough time to capture the full background in the time of flight spectrum as well as capture low energy neutrons with TOF $\sim$ 200 ns. A software package, Pixie Acquisition and Analysis Software Suite (PAASS), was developed to handle the high data throughput from these digitizers and record the list mode data format [32]. This software also controls the acquisition parameters that determine the different triggering schemes and trigger thresholds.

3.3.2 INDiE Efficiency

The amount of scintillation light has a linear relationship with the amount of energy deposited by a neutron in the plastic scintillator. Light production and detection is one of the

main factors in determining detector efficiency. For lower and lower neutron energies, the maximum amount of light that can be created by a neutron scatter decreases and reaches a point that the full detector system (scintillator, photomultiplier, data acquisition, ...) will no longer be able to ever trigger a neutron with that given energy. This point is called the detection threshold. At neutron energies higher than the detection threshold, there isn't always a guarantee of triggering on a neutron event, whether it be a neutron passes through the scintillator without interacting or the signal is so small that the DAQ does not trigger an event. This all determines the detector efficiency which is important for corrections made when calculating branching ratios.

To experimentally determine detector efficiency as a function of neutron energy, a VANDLE bar of the same design was taken to Ohio University's Edwards Accelerator Laboratory for testing. The facility specializes in efficiency measurements and uses a well know $^{27}\text{Al}(\text{d},\text{n})$ reaction to characterize detector efficiencies. The VANDLE bar was set 11 m from the interaction location and data was recorded until approximately 1×10^6 neutron times-of-flight were recorded, all while the beam current was being integrated for spectrum normalization. Using a pre-binned spectrum provided by the facility and renormalizing by the detector solid angle and integrated beam current, the detector efficiency dependence on energy was calculated by finding the ratios between the measured and renormalized spectrum. The neutron energy efficiency curve of a single VANDLE bar which was used for the analysis of this dataset is shown in Figure 3.6. For comparison, an efficiency curve up to 4 MeV from a ^{252}Cf source measurement is shown alongside the $^{27}\text{Al}(\text{d},\text{n})$ reaction curve. For both curves, errors in the efficiency are calculated from the uncertainty of counts in a given energy bin $(\sqrt{N})$.

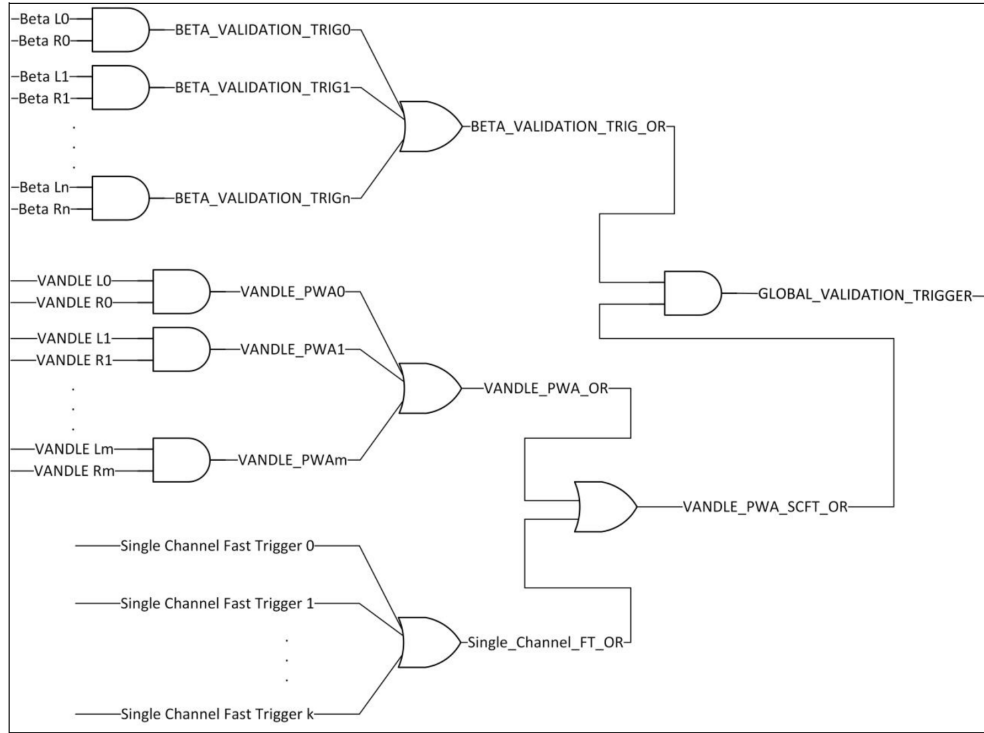


Figure 3.5: Schematic showing the generation of a global trigger in the XIA Pixie16 data acquisition from coincident beta and vandle triggers [3].

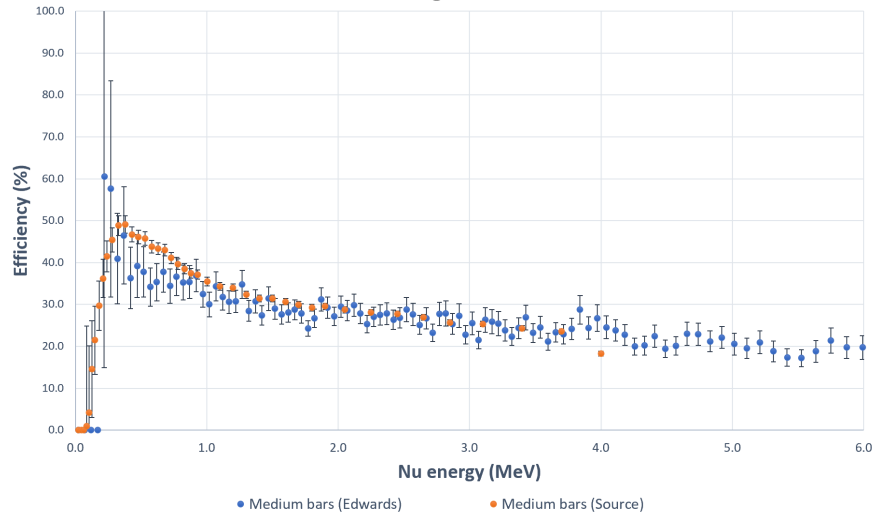


Figure 3.6: Single VANDLE Bar Efficiency for neutron energies between 0.1 MeV and 6 MeV. Data taken with a ^{252}Cf (orange) [4] and from an $^{27}\text{Al}(\text{d},\text{n})$ reaction (blue).

Chapter 4

Analysis

4.1 Methods

4.1.1 Neutron Energy Measurements

Energies of neutrons from ^{134}In beta delayed neutron emission were determined by measuring the neutron time of flight over a fixed distance. The method is fully described in [Appendix B](#) but a quick overview is given here. Signals from photosensors on either end of the scintillating bars were digitized and processed using the experimental setup described in [Section 3.3.1](#). Using double ended detectors not only improves time of flight resolution but also allows the flight path distance to be corrected by position of scintillation along the length of the bar. Neutron energies are determined via precise timing measurements. Due to the large neutron mass, beta delayed neutrons emitted from nuclei can be treated classically. Neutron kinetic energies are commonly calculated from time-of-flight (TOF) measurement for fixed flight path distance, L , given below:

$$E_{TOF} = \frac{1}{2}mv^2 = \frac{1}{2} (939.6 \text{ MeV}/c^2) \left(\frac{L}{TOF} \right)^2 \quad (4.1)$$

The resolution of neutron energy measurements is dependent on the uncertainties in L and TOF . Precision neutron time of flight measurements are explained in the next section.

4.1.2 High Resolution Timing

The primary use of these signals in the time of flight setup is to extract the time difference between a start and stop signal. However, if the raw timestamp of the digitized signal is used, then the timing resolution would only be 4 ns. In order to determine a more precise timing, a digital polynomial constant fraction discriminator (PolyCFD) was developed to calculate a higher precision time measurement [4]. A longer explanation of the PolyCFD can be found in Appendix B.1, but the fundamentals will be explained here. The digitized signal trace peak is fit with a third order polynomial around the maximum in order to approximate the actual maximum of the original analog signal and derive the amplitude. The trace phase is then determined by calculating where the trace crosses an amplitude fraction threshold set by the user. The high resolution timestamp, HRT, is set as the Pixie16 timestamp minus the trace delay plus the phase.

$$t_{HRT} = t_{timestamp} - t_{delay} + \phi_{CFD} \quad (4.2)$$

Figure 4.1 shows graphically how the trace is analyzed with the green line representing a third order fit to find the maximum, the magenta line representing a first order fit around the threshold, and the red and blue lines representing the phase and threshold crossings.

4.1.3 Event Building, Correlations, and Corrections

Decay events are built by processing the raw binary file recorded with PAASS, the dedicated software package mentioned before. This C++ suite unpacks the binary file by scanning the digitizer channel information for the first channel event, creating a 5 us event window from that initial timestamp. All subsequent events with timestamps in the event time window are grouped into the raw event data. The next event window is set from the first channel event found outside the previous event window. The channel information is stored and categorized by channel number and other tags specifying detector type (vandle, gamma, beta, logic, ...). Detector types with higher level analysis are processed to extract information from the traces such as high-resolution-timing and QDC. Pairwise channels from opposing ends of a single VANDLE bar are used to calculate the neutron TOF by subtracting the average

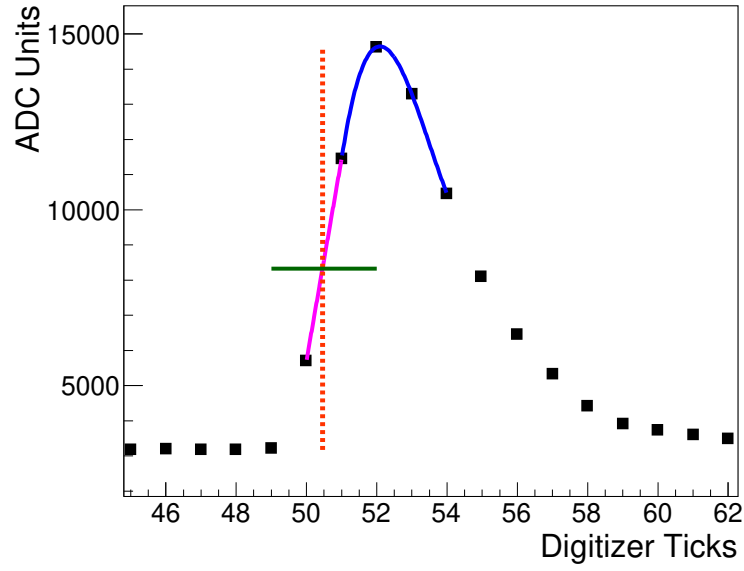


Figure 4.1: Graphical representation of the PolyCFD method to extract the phase of the trace for a higher precision time measurement.

HRT of a VANDLE detector from the average HRT of the beta-decay detector. In the first pass-through of the analysis software, enough data is processed such that a characteristic gamma peak is present in the TOF spectrum for each VANDLE bar. Two different timing features are corrected for in each bar due to slight time differences between all channels in the XIA data acquisition.

Any axial timing difference in a single VANDLE detector is corrected for by calculating the FWHM of the time difference spectrum and centering it around 0 ns. Figure 4.2 shows the uncalibrated axial time difference plotted against bar number and Figure 4.3 is a plot of the time difference for all bars after the offset correction has been made. The other timing offset which must be corrected for is the time-of-flight offset between the start and stop signals. The gamma peak in the TOF spectrum is fit with a gaussian to extract the mean. The TOF offset for an INDiE bar is then calculated as the difference between the mean and the calculated gamma-ray time of flight for the distance of center of the bar from the implant point. The distance to each bar was calculated using known neutron energies from ^{17}N beta-delayed neutron emission given. The neutron unbound states in ^{17}O and the associated neutron energies from H. Ohm et al. are shown in Table 4.1 [1]. The flight path length was varied for a χ^2 analysis of the neutron energies calculated from the TOF spectrum. The flight path lengths determined from the χ^2 analysis were used to calculate the TOF offset correction. For each bar, the two offsets are passed as parameters in the scan configuration file. This process ensures any systematic corrections made for position along the bar and TOF distance are the same for each bar. Neutrons in this study of beta-delayed neutron emission were emitted isotropically such that the bars are uniformly illuminated. The scattering position along the bar must be accounted for in the neutron flight path otherwise the neutron energy could be underestimated. It's also important to scale all TOF measurements to the same flight path length to eventually deconvolve the neutron TOF spectrum correctly.

Using the speed of light in EJ200 and the time difference between the signals from either end, the distance from the center of the bar is calculated by multiplying the time difference by the speed of light and dividing it by two. The TOF measurement is then scaled by the ratio of the calculated flight path length to the distance to the center of the bar, $t = \frac{L}{L'}t'$, where

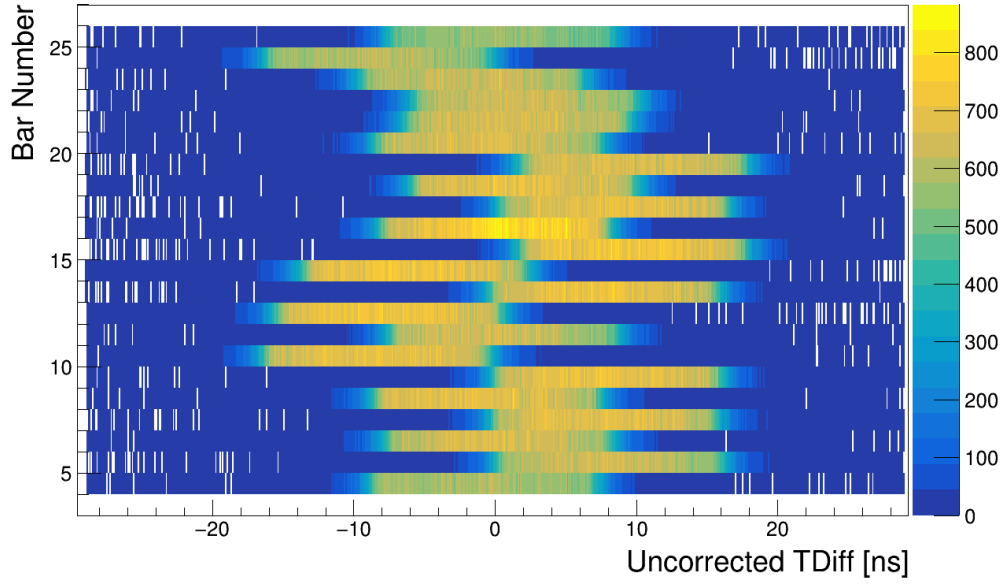


Figure 4.2: Two dimensional histogram showing the time difference distribution between detector at the end of a scintillator bar against the setup bar number. The offsets between events triggered in the digitizers due to signal transmission effects and inherent delays between digitizer channels.

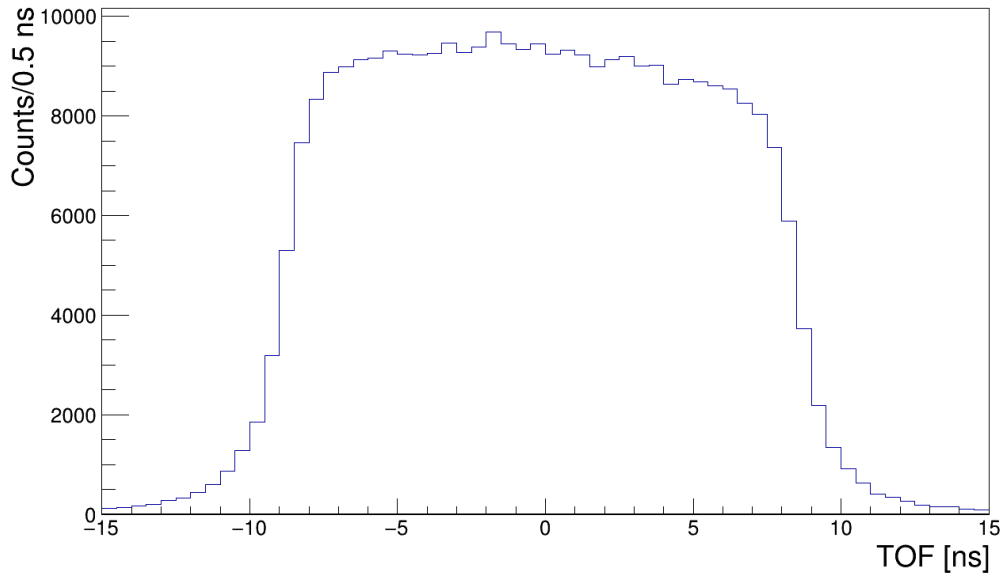


Figure 4.3: An aggregated plot for the entire neutron detector of the time difference between PMT's at the opposite end of a scintillator bar after the time difference for each bar has been centered on 0 ns.

$L = 100$ cm. The above corrections ensure that all the TOF measurements for each bar are as precise as possible and any systematic error is minimized. Because this analysis is done using the compiled spectra from all available VANDLE bars, the overall spectrum can be improved by making two position corrections to the TOF measurement. The scatter position along the bar is calculated using the time difference between opposing signals multiplied by the speed of light in a VANDLE bar. This position information is used to calculate the neutron flight path distance and scale the TOF measurement to the distance from the implant point to the center of the bar. To correct for any differences in distance between neutron flight path to the center of the bar, the TOF measurement is scaled again to a 1.0 m flight path. Figure 4.4 shows how applying these two corrections improves the TOF resolution for the overall spectra. The time-of-flight scaling of each bar to the same flight path for all detectors is required to properly analyze the data as one set, and not perform a deconvolution on a bar by bar basis.

4.2 Simulations and Analytical neutron response

4.2.1 IDS Simulation

Typical neutron time-of-flight detectors have a characteristic response based on how neutrons scatter off material in the experimental hall. When analyzing neutron time-of-flight spectra, one has to account for and characterize the tails of response functions using simulated and experimental data. To develop energy dependent response functions, the full experimental setup was constructed in Geant4 and mono-energetic neutrons were produced at the implantation point with isotropic trajectories. Figure 4.5 shows the full setup as Geant4 physical objects. PMT signals were generated from light produced in the scintillator bars by neutron scatters. For each event, the PMT signal was digitized and the same high resolution timing analysis used for experimental data was used. More details on the simulation framework can be found in Section 6.2.

Table 4.1: Known neutron unbound states in ^{17}O from Ref. [1].

Energy [keV]	Γ [keV]	E_{neutron} [keV]
4549.3(13)	54.8(4)	405.3
5387.1(12)	28(7)	1244.3
5949.9(19)	23(10)	1805

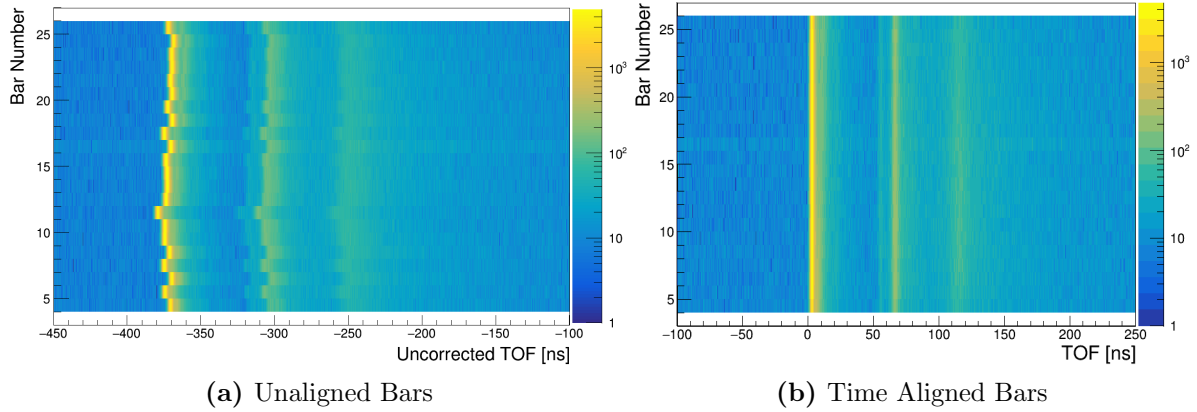


Figure 4.4: Two dimensional histograms showing TOF by bar before (left) and after (right) timing alignment and corrections have been applied. This process allows the data analysis to be carried out for the entire array at one, not on a bar by bar basis.

4.2.2 Neutron Response Function

200, 300, 500, 700, 1000, 2000, 3000, 5000, and 7000 keV neutrons were simulated originating from the implant point in the IDS Geant4 environment. For each energy, a time-of-flight histogram with 250 ps binning was made. The functional form of the neutron response and a full description of the following process can be found in Appendix A. The TOF histogram for each neutron energy was fit independently with the analytical neutron response function as shown in Figure 4.6.

The response parameters were extracted for each neutron energy and plotted against the corresponding TOF maxima. Varying polynomials were fit to the relationship between parameter values and time of flight. In doing so, an energy-dependent neutron response function was made to be used to deconvolve semi-continuous neutron TOF spectra.

4.2.3 Tuning the Response Function

The response function developed using simulated neutron time-of-flight data needed to be tuned using actual experimental data. When first compared to a realistic spectrum from ^{49}K beta delayed neutron emission, the responses were not wide enough to accurately capture the full details of the spectrum. Using data given for neutron emitting levels given in Ref. [33], the widths of the Lorentzian portion of the neutron response function was tweaked systematically until the entire spectrum was well represented analytically by the neutron responses for the given levels. The analytical response can be seen in Figure 4.7.

4.3 Background characterization and correction

In a beta-decay experiment, there are numerous sources of gamma rays which are energetic enough to be observed in plastic scintillator. The scintillator used to make the INDiE has no way of discriminating between an event where a neutron or gamma ray interacted with the material. The background can't be removed from the neutron TOF spectrum so it must be fit and added to the analytical description of the spectrum.

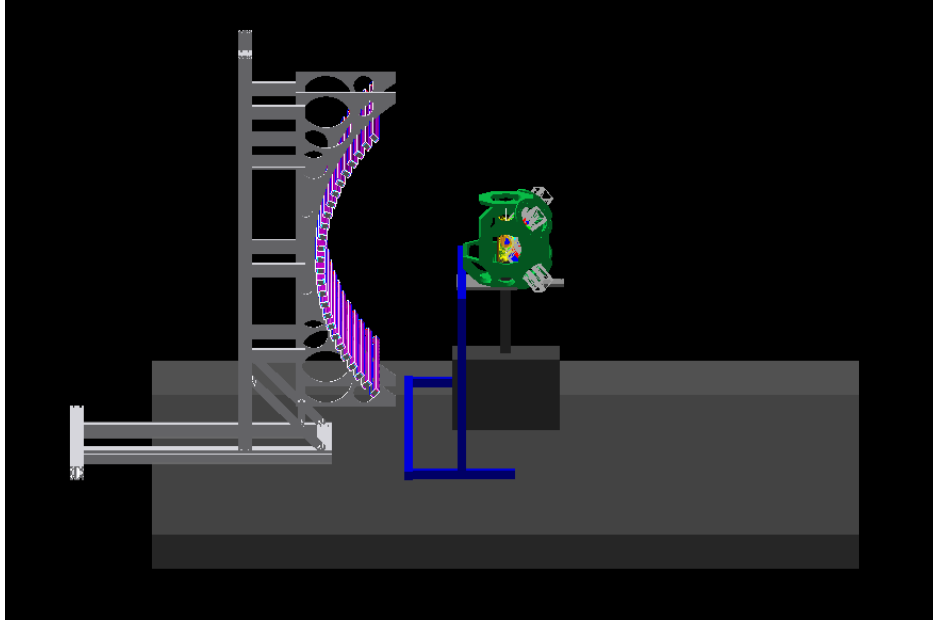


Figure 4.5: Geant4 rendering of the full ISOLDE Decay Station and with INDiE bars shown in magenta.

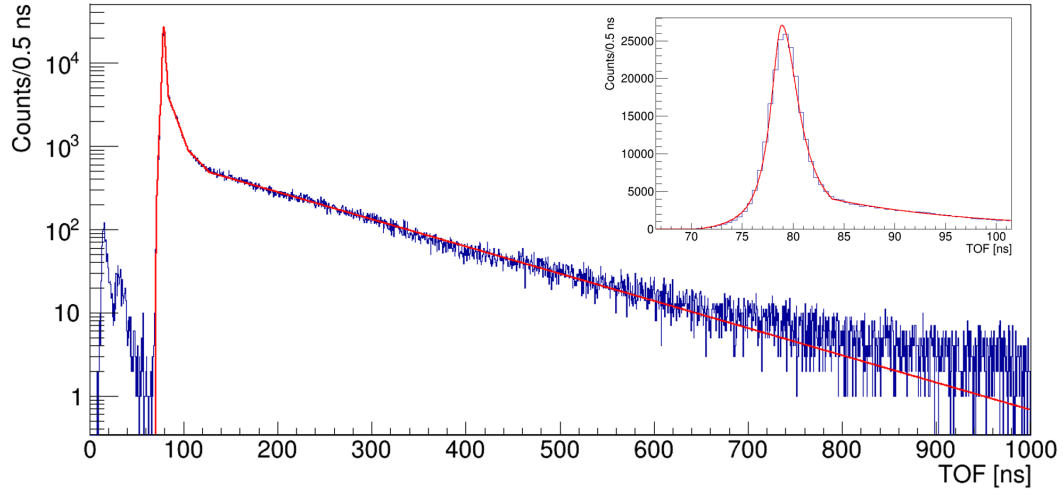


Figure 4.6: Histogram of 1 MeV neutron time of flight measurements (blue) using the IDS Geant4 setup. The red line is a fit of Equation 1 in Appendix A where all parameters are allowed to vary. The inset shows the fit to the main peak of the neutron response.

4.3.1 Contamination

It was known when this analysis began that there was a large source of gamma-ray background from contamination of the beta detector. During the run, the HRS drifted slightly and allowed a large portion of 8^{-134}Cs isomers to be implanted. The isomer has a ~ 3 h half life and decays almost entirely via emission of a 127.5 keV gamma ray. The contamination background in the VANDLE time-of-flight spectrum can be seen in Figure 4.8 as the brighter low QDC band.

This source of background not only can be seen in the INDiE but also the beta detector. A non-uniform effect of the contamination exists in the raw TOF spectrum from the experimental setup shown in Figure 4.9. By cutting above the noise in the beta detector, the non-uniform background is removed from the TOF spectrum. The resultant spectrum is fit with a double exponential plus an offset from the gamma peak to 600 ns, excluding the TOF region of interest between 25 ns and 400 ns. The background function over the TOF spectrum is shown in Figure 4.10.

4.3.2 Walk Correction

Due to slight amplitude dependent timing effects in the digital trace analysis, the gamma-ray peak in neutron time-of-flight measurement typically has a characteristic bend. The QDC dependent effect can be seen in Figure 4.11. A simple correction can be made by fitting a QDC dependent function to the gamma ray peak curve. For each QDC bin in the histogram shown in Figure 4.11, a projection onto the TOF axis was made to find the location of the TOF peak for that QDC value. A graph of TOF peak location vs QDC was fit with the function

$$f(x) = C + \begin{cases} p_1 \exp(x - p_2) & x \leq p_0 \\ p_3 x^2 + p_4 x & x > p_0 \end{cases}, \quad (4.3)$$

where p_0 is the location of the minimum in the curve. This function is then applied to straighten the gamma peak and align it to 3.33 ns, the time it takes a gamma ray to travel 100 cm to the front face of the detector. The results of the correction can be seen in Figure 4.12.

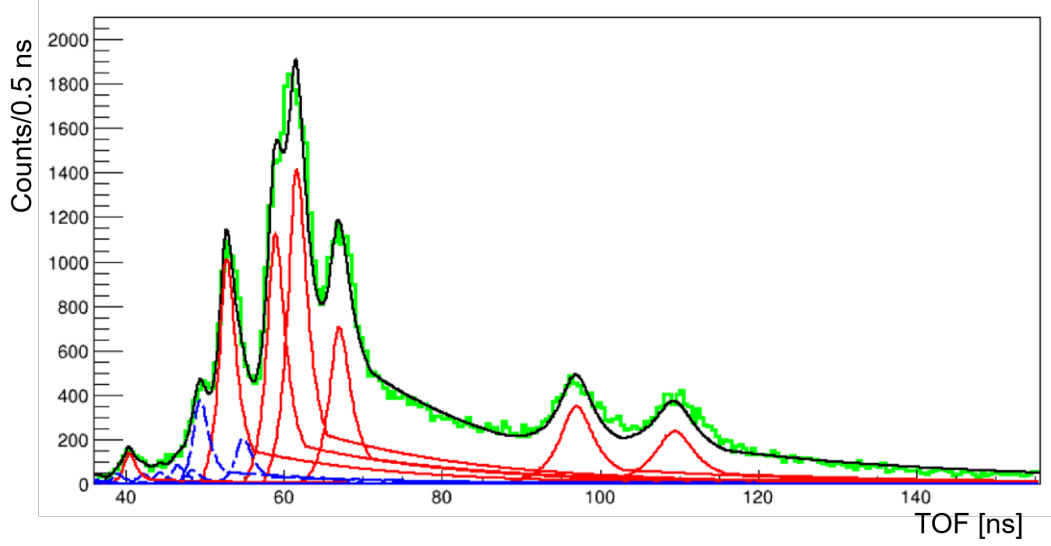


Figure 4.7: ^{49}K neutron time of flight spectrum (green) fit with the optimized neutron response peaks. The total fit represented by the black line with individual peaks shown in red (peak location unfixed) and blue (peak location fixed).

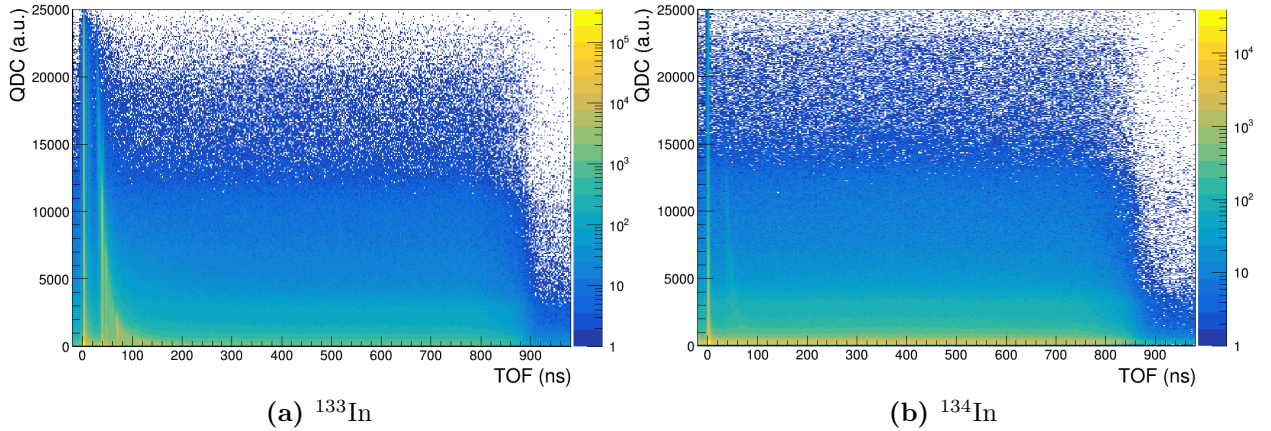


Figure 4.8: Event QDC versus time of flight for $^{133,134}\text{In}$ data taken during the experiment. The signal background is much higher in the ^{134}In data due to the contaminated beam.

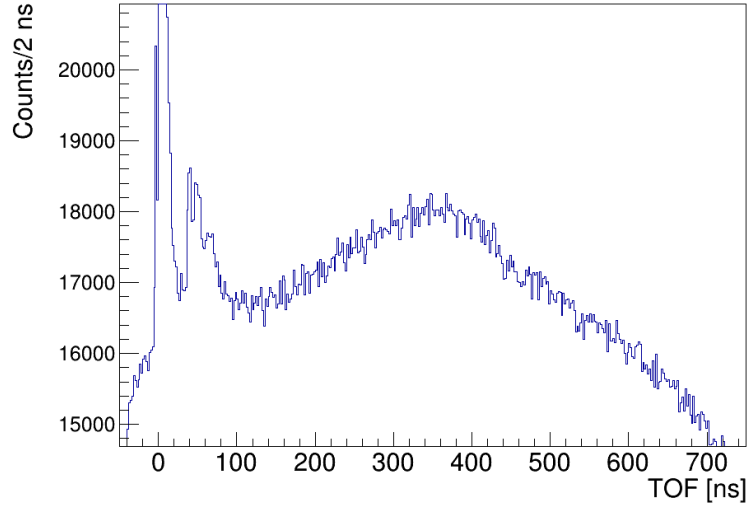


Figure 4.9: Histogram with 2 ns bins showing the non-uniform background in the neutron time of flight not easily described by an extension of the gamma-ray peak. This background is entirely removed by cutting events below the ^{134}Cs background in the beta detector.

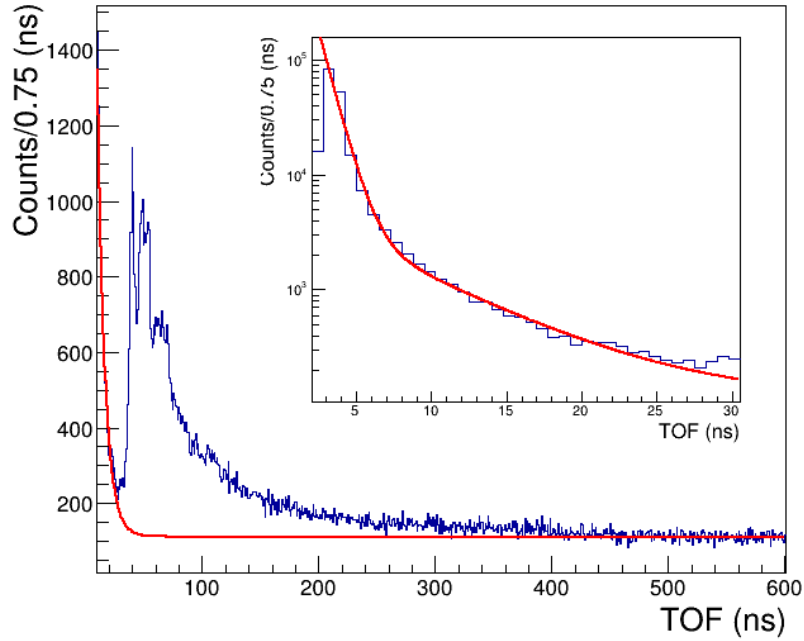


Figure 4.10: Neutron TOF spectrum from ^{134}In beta decay. The red line shows the fit of the analytical gamma response function to the overall spectrum, excluding the region of interest from 25 ns to 450 ns.

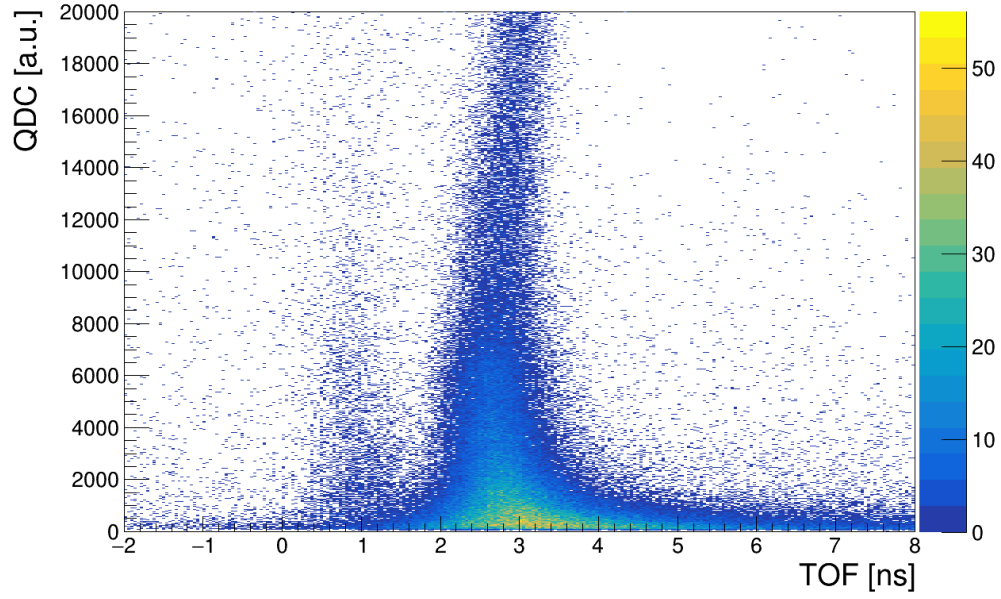


Figure 4.11: Event QDC versus time of flight zoomed in around the gamma peak. The bend is due to trigger latching effects which shift one signal in phase with respect to the other.

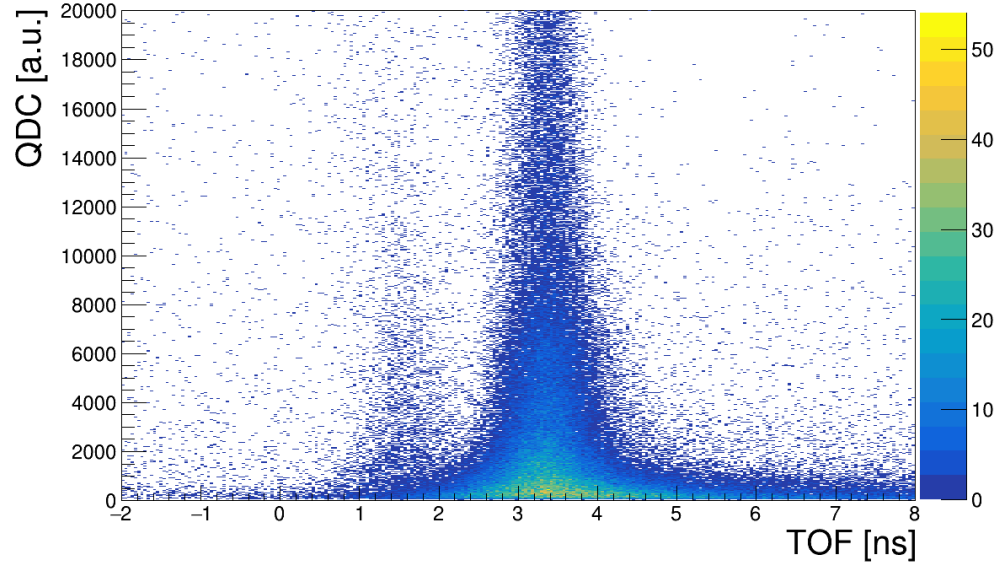


Figure 4.12: The time of flight distribution after applying a walk correction using Equation 4.3.

4.3.3 QDC Constraint

Most background in neutron TOF data is associated with low signal amplitudes. However, there is still a significant background at QDC values much larger than typically associated with noise. This background is due to neutrons scattering of large nuclei and gamma ray background from various types of activation and decay. Because we have neutron time-of-flight information, we know the associated neutron energy of an event independent of the amount of energy deposited in the scintillator. Events with larger QDC (energy deposition) than the energy calculated from the TOF measurement can then be disregarded in TOF spectrum. To properly remove said events, a reduced form of Birk's formula first proposed by Madey et al. is used to calculate the maximum equivalent electron energy for neutrons at a specific energy [34]:

$$T_e = a_1 T_p - a_2 \left[1.0 - e^{-a_3 T_p^{a_4}} \right] \quad (4.4)$$

where $T_p = \frac{4m_p m_n}{(m_p + m_n)^2} T_n$ for a back to back collision in which the neutron deposits a maximum amount of energy. Because $m_p \simeq m_n$, T_n can be directly substituted for T_p in Equation 4.4.

The parameters a_1 , a_2 , a_3 and a_4 can be taken from reference [35] using the values from NE-102 scintillator data discussed in the paper. Eljen 200 and NE-102 are similar plastic scintillators, so it can be expected the proton light yield quenching will be the same. The published values for a_1 , a_2 , a_3 and a_4 are 0.95, 8.0, 0.1, 0.90 respectively. The ^{49}K data used to optimize the neutron responses was used to generate a relationship between neutron energy and the electron equivalent energy of the maximum neutron single scatter energy deposition. The unit of electron equivalent energy is generally considered as kilo-electron volt electron equivalent (keVee). Using reported neutron energy data from L.C. Carraz et al. [33], the strong transitions that can be seen in the QDC vs TOF plot shown in Figure 4.13 were isolated.

For each neutron energy, the high edge of the QDC distribution was fit with a gaussian distribution. Here, the maximum neutron QDC was designated as the mean plus 3σ towards higher QDC. The QDC to keVee calibration from a first order polynomial fit to sealed source data proved to be inadequate for characterizing the maximum QDC at a given neutron energy. Instead, a first order polynomial used to describe the conversion of keVee to QDC

was folded with Equation 4.4, substituting the classical kinetic energy formula for T_n .

$$QDC_{max} = p_0 + p_1 T_e = p_0 + p_1 \times \left[a_1 \left[\frac{m_n L^2}{2 \times TOF^2} \right] - a_2 \left[1.0 - e^{-a_3 \left[\frac{m_n L^2}{2 \times TOF^2} \right]^{a_4}} \right] \right] \quad (4.5)$$

This equation was fit to the max QDC vs neutron TOF relationship based on the fixed parameters of Equation 4.4. The line of best fit is shown in red in Figure 4.14. Three different exclusion functions were made by scaling the original by 1.1, 1.5, and 2.0 to compare the effect of the QDC limit cut on the neutron TOF spectra. The limit scaled by 1.1 was used as an additional cut on neutron-gamma coincidence data to provide the cleanest information for calculating excited levels in ^{134}Sn . The limit scaled by 1.5 was used as a cut on creating the overall neutron TOF histogram for deconvolution.

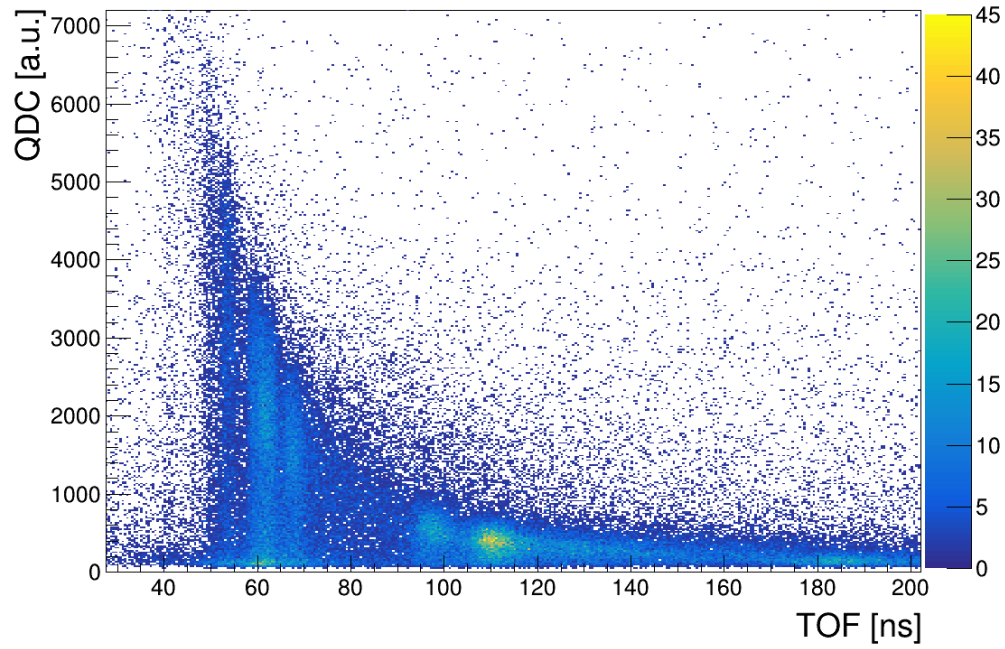


Figure 4.13: Event QDC versus time of flight for ^{49}K . The upper QDC edge for each peak in the TOF spectrum was used to adjust the parameters for Equation 4.5.

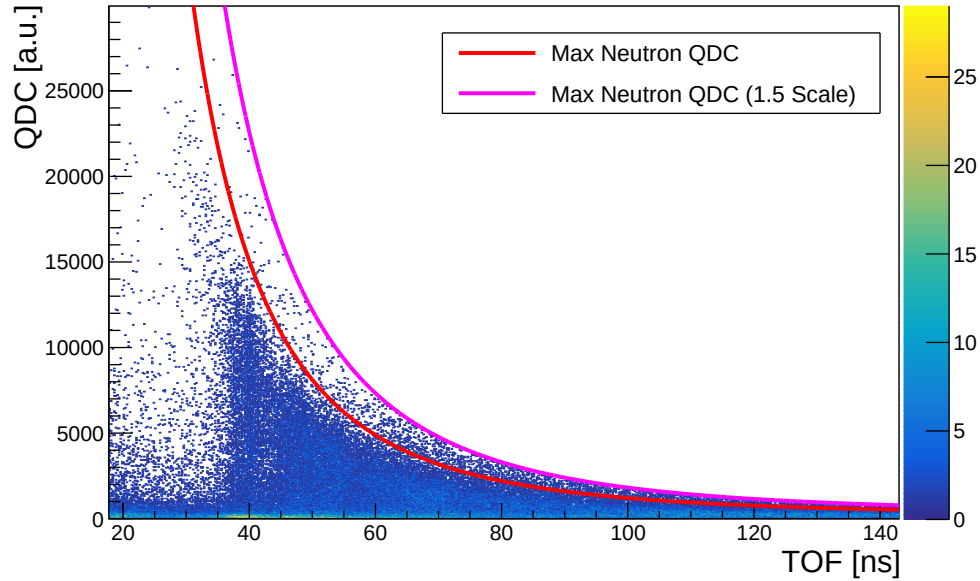


Figure 4.14: The red and pink line represent the QDC cut which was fit to ^{49}K data. The pink line is the maximum QDC from Equation 4.5 but has been scaled by 1.5 for a softer QDC cut.

Chapter 5

Results

5.1 ^{133}Sn Gamma Ray Emission

Previous studies of ^{134}Sn beta-delayed neutron emission have shown three dominant gamma ray transitions observed in coincidence with an emitted neutron [25]. The relative feeding to these levels will help determine the proper model treatment for the neutron emission. The associated neutron energies for each transition will also be the first step in determining the level structure for ^{134}Sn states populated in ^{134}In beta decay.

5.1.1 Neutron- γ gated energy levels

To first constrain ^{134}Sn daughter states populated from beta-decay, neutron TOF was gated on known gamma-ray transitions in the beta delayed neutron emission of ^{134}In [25]. Figure 5.1 shows gamma-ray energies in 1 keV bins from 800 keV to 2.1 MeV for events within 700 ms of the last proton cycle time. The prominent random background is due to the high trigger rate caused by ^{134}Cs contamination. Additional background peaks are present due to (n, n') scattering off the various materials in the experiment setup [36]. The three gamma ray energies associated with single particle excited states in ^{133}Sn , 854 keV ($p_{3/2}$), 1561 keV ($h_{9/2}$), and 2004 keV ($f_{5/2}$), are shown in Figure 5.2. In order to set proper gates on the gamma ray energy, gamma ray background was reduced by setting thresholds on the beta detector QDC and requiring a coincident neutron time-of-flight between 25 ns and 250 ns.

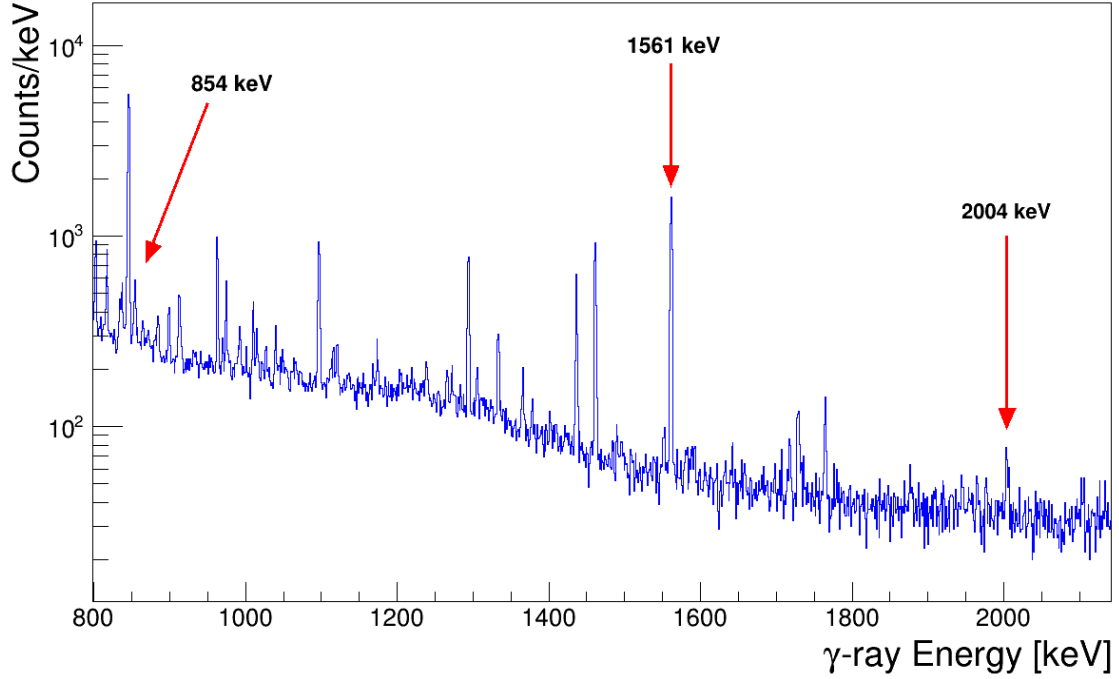


Figure 5.1: Histogram of gamma rays observed from ^{134}In beta decay for events within 700 ms of the last proton cycle time. The large random background is due to the high beta trigger rate due to ^{134}Cs contamination. There is also abundant background from (n, n') reactions in the surrounding support material.

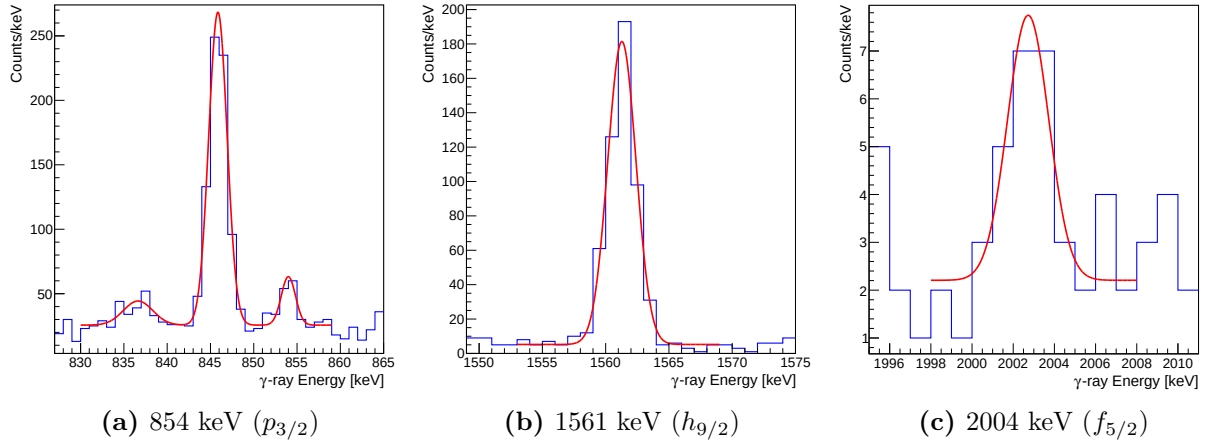


Figure 5.2: Fits to the three know peaks in coincidence with the beta delayed neutron emission of ^{134}In using a gaussian plus background. Events shown in the histogram were within 700 ms of the last beam pulse and coincident with a signal in INDiE. The widths of gaussian fits to each peak were used in setting the gamma ray energy window for generating gamma-gated neutron TOF spectra. Additional gaussians were added to the fit of the $3/2^-$ state because of close contamination due to neutron induced reactions on ^{27}Al and ^{57}Fe support materials.

Histograms of neutron TOF gated on 854 keV and 1560 gammas can be seen in Figure 5.3. In each figure, individual neutron responses can be seen in the blue dotted lines and the sum of the responses shown in red. This run did not accrue enough statistics to observe valid neutrons in coincidence with 2004 keV gamma rays from the $f_{5/2}$ state in ^{133}Sn .

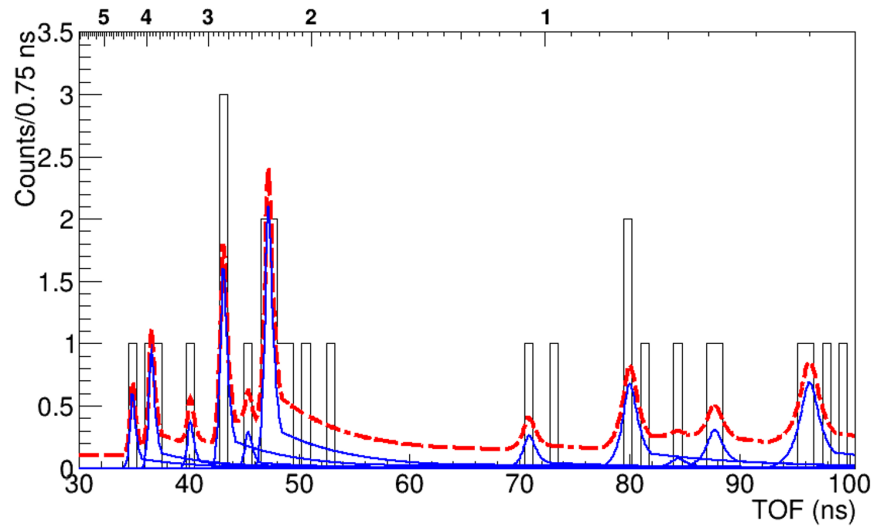
For each gamma gated spectrum, a basic deconvolution was performed by successively adding peaks to the histogram to best describe the few counts along the time of flight axis. In fitting the individual peaks, the t_0 of each analytical response was constrained to be within 1.5 ns of the initial value. A low energy QDC cut was also made to better improve the determination of neutron energies. The total response (sum of all individual responses) with a baseline offset was fit to the gamma gated spectrum between 30 and 150 ns. Peaks were only added between 30 ns and 100 ns because that was the only TOF region which showed statistical significance for neutron-gamma coincidence events.

It should be noted that the width of the analytical neutron response had to be slightly reduced for this step due to the reduced background from implementing the gamma gate and QDC cut. A table containing the extracted TOF maxima and neutron energies for each gamma ray transition can be seen in Table 5.1 and the first level diagram constructed from the fitted neutron peaks can be seen in Figure 5.4. These states are the foundation of the entire neutron time of flight deconvolution.

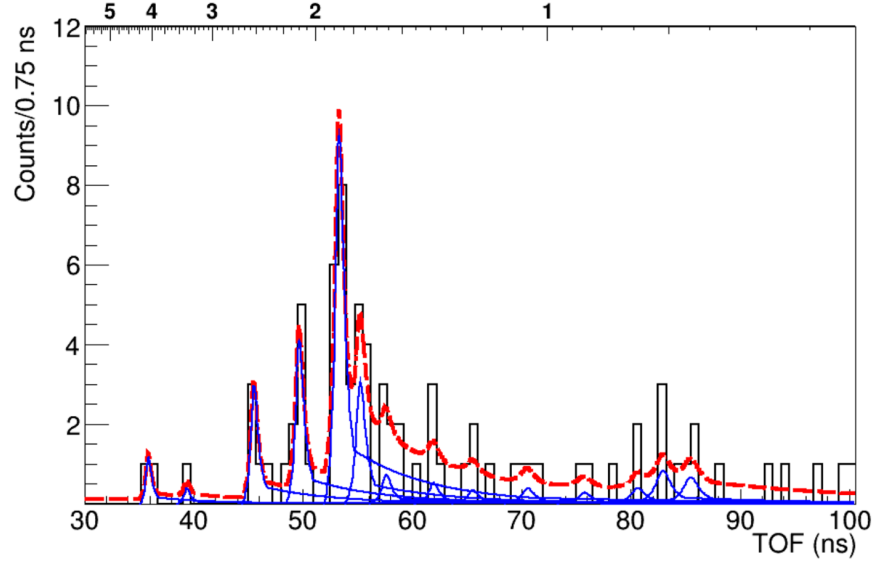
5.2 Full neutron spectrum

Using a sum of the individual neutron responses, an overall analytical response can be fit to the neutron TOF spectrum in order to determine the full feeding scenario. Neutron TOF's were histogrammed using a start signal QDC cut above 250. In some cases, a neutron can bounce between neighboring VANDLE bars, producing identical TOF values in each, which can lead to over counting. In events where neighboring bars produced TOF values within 5 ns of one another, the faster of the two TOF values was kept while the other was disregarded.

Figure 5.5 shows the final fit result from the full spectrum deconvolution and the following discussion of the deconvolution will correspond to colored single neutron responses under the spectrum. To begin fully deconvolving the spectrum, the full intensity of the neutron



(a) 854 keV gated



(b) 1561 keV gated

Figure 5.3: Gamma ray gated neutron TOF histograms showing the individual neutron responses in dashed blue lines and the total response in red lines.

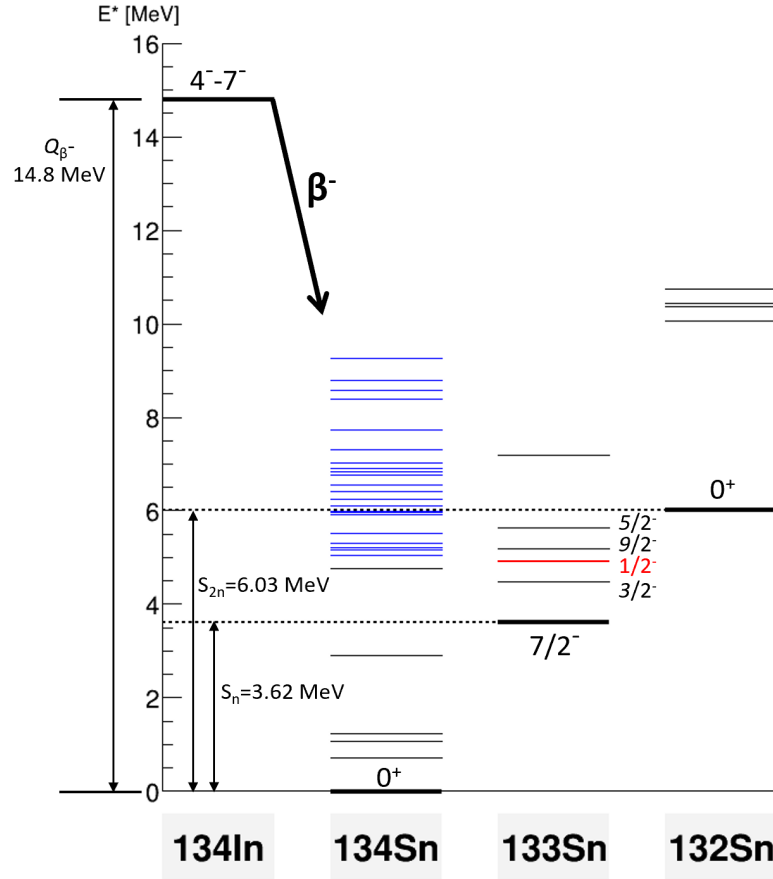


Figure 5.4: Energy level diagram for the ^{134}In beta-delayed neutron emission chain from neutron-gamma level information. Thick black lines represent the ground state energies relative to the ground state of ^{134}Sn . Blue lines signify neutron emitting states observed in this analysis. Low lying ^{133}Sn single particle states are labeled above the ^{133}Sn ground state. The ^{133}Sn $1/2^-$ state marked in red is not observed in coincidence with ^{134}In beta delayed neutron emission.

emission transitions in the previous section were calculated by scaling the individual peaks by the HPGe detector efficiency for the corresponding gamma-ray energy (pink curves). These were the first responses added to the full analytical response, with TOF fixed for each peak while the amplitude was allowed to vary $\pm 20\%$. If a state in Table 5.1 had very low intensity and the calculated ground state transition was closely spaced to other neutron energies with higher intensities, this ground state transition was not included in the analysis as the fitter would suppress the intensity anyway.

Relevant ground state transition energies were calculated from the states found in the gamma-neutron coincidence analysis (dark blue curves). These energies were compared with a parallel extraction of ground state transitions by fitting successive peaks in neutron TOF data from events with high QDC. The TOF values for peaks with large contributions to the high QDC TOF spectra were fixed in the full analytical response (solid dark blue curves).

In a first attempt to deconvolve the neutron TOF spectrum, only the transitions from states extracted from the gamma-neutron coincidence analysis were used. The full analytical response described the neutron TOF spectrum well up to 45 ns, but beyond that, more neutron transitions needed to be added to account for missing portions of the TOF spectrum. Additional peaks were added in regions with the largest discrepancies between the analytical response and data (cyan curves). Neither TOF nor the amplitude were fixed for these responses. The TOF variable range was constrained by the uncertainty in TOF for a given neutron energy. The amplitude was allowed to vary between 0.001 and the spectrum value at the respective TOF. The full spectrum deconvolution is shown in Figure 5.5 after the additional peaks were put in. The cyan curves represent states in which no known coincident gamma-ray emission having been observed. These states could possibly be attributed to emission to the 2004 keV $5/2$ state or from two neutron emission. Because of this ambiguity, they were not included in the neutron branching ratio analysis. The ^{134}Sn energy level information from the neutron spectrum deconvolution can be seen in Table 5.2

Table 5.1: Gamma-Gated Neutron TOFs

1561 keV ($9/2^-$)				854 keV ($3/2^-$)			
TOF	I_n (au)	En	Ex	TOF	I_n (au)	En	Ex
35.84	1.18	4069	9260	34.85	0.60	4303	8790
39.35	0.38	3375	8560	36.57	0.96	3908	8390
45.49	2.97	2525	7710	40.10	0.37	3250	7740
49.64	4.10	2121	7310	43.10	1.61	2813	7230
53.29	9.24	1840	7030	45.35	0.29	2541	7030
55.22	3.07	1714	6900	47.19	2.11	2347	6830
57.59	0.73	1575	6760	70.86	0.26	1040	5530
61.91	0.52	1363	6550	80.01	0.68	816	5300
65.50	0.34	1218	6410	84.37	0.08	734	5220
70.53	0.39	1050	6240	87.72	0.30	679	5160
75.73	0.27	911	6100	96.35	0.68	563	5050
80.60	0.39	804	5990				
82.90	0.83	760	5950				
85.46	0.66	715	5900				

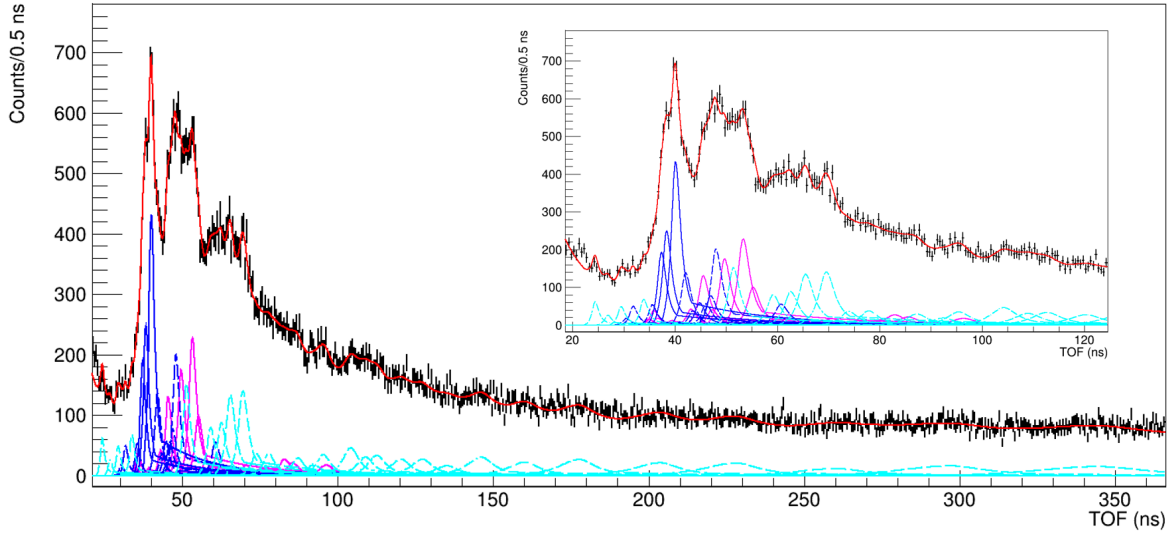


Figure 5.5: The full spectrum deconvolution using all available neutron-gamma gated neutron energies (red), neutron energies from calculated transitions to the ^{133}Sn ground state from neutron-gamma gated levels (dark blue), and additional transitions added by hand (cyan). The dashed lines are individual transitions where the peak location was allowed to fluctuate in the fit.

5.3 Feeding Intensities

Feeding intensities, I_β , to single particle states in ^{133}Sn were calculated by integrating the individual neutron responses that contribute to the total deconvolution. Excitation energies were calculated for states in ^{134}Sn using the deconvolved spectra and coincident gamma ray energy. Closely spaced states ($<50\text{keV}$) that have separate feedings to the $f_{7/2}$, $p_{3/2}$, and $h_{9/2}$ states were grouped to show the relative feeding from the intermediate daughter state. These intensities are shown in Figure 5.6. Uncertainties in the feeding intensities were derived from the uncertainty in the fit amplitude of the individual neutron peaks in the overall spectrum and the uncertainty of the neutron detection efficiency.

5.3.1 Shell Model Calculations

From the data shown in Figure 5.6, the beta delayed neutron emission of ^{134}In populates highly excited states in the ^{134}Sn emitter nucleus approximately $\sim 7.0\text{ MeV}$ above the ground state. Large-scale shell-model (LSSM) calculations for highly excited states in moderate to heavy nuclei tend to suffer from high level density and large numbers of near-degenerate levels. Shimizu et al. developed a LSSM solver, KSHELL, utilizing high order parallelization in order to remediate the large computational demand for storing the large number of eigenstates [37].

The residual interactions, $jj77_vmu$, used for shell model calculations of states and beta decay strengths in ^{134}Sn are built around a ^{88}Sr core ($Z=38, N=50$) [38, 39]. The two highest orbitals below the $Z=50$ shell, $2p_{1/2}$ and $1g_{9/2}$, are included in the interaction space to include core excitations of the $Z=50$ shell for positive parity states in ^{134}Sn . Deeply bound neutron states down to $1g_{9/2}$ are included in the neutron valence space to include the states with a neutron hole created by Gamow-Teller beta decay transitions. Figure 5.9 shows the valence orbitals for both protons and neutrons in the green shaded area outlined in magenta.

Excitation levels were calculated for various spin states using $jj77_vmu$ interactions in ^{134}Sn and can be seen in the left panels of plots in Figure 5.7. Beta decay rates, λ , to states populated in Gamow-Teller and First Forbidden transitions are shown in the right panels in Figure 5.7. Two different calculations were made based on possible ground state spins of

Table 5.2: Deconvoluted ^{134}Sn Levels using levels from neutron gamma ray coincidence data. I_β is given in arbitrary units.

Ex [MeV]	$7/2^- I_\beta$ (au)	Error	$9/2^- I_\beta$ (au)	Error	$3/2^- I_\beta$ (au)	Error
9.34	838.2	152.35	688.3	50.12	—	—
8.77	571.8	171.02	—	—	403.2	148.24
8.31	308.7	434.64	235.9	115.62	325.8	200.50
7.81	437.2	276.09	22734	1013	179.4	64.28
7.37	3362	421.4	4376	240.5	598.8	39.68
7.18	4753	535.2	4860	337.1	106.6	27.89
6.88	8290	782.25	2072	120.6	903.6	262.72
6.76	401.5	729.88	497.8	212.84	—	—
6.56	2751	582.0	502.9	161.13	—	—
6.40	900.9	474.57	237.6	88.12	—	—
6.20	935.2	665.25	474.8	33.39	—	—
6.07	836.9	478.99	329.3	26.43	—	—
5.97	3216	383.3	619.4	46.84	—	—
5.04	1257	617.1	—	—	316.7	19.16

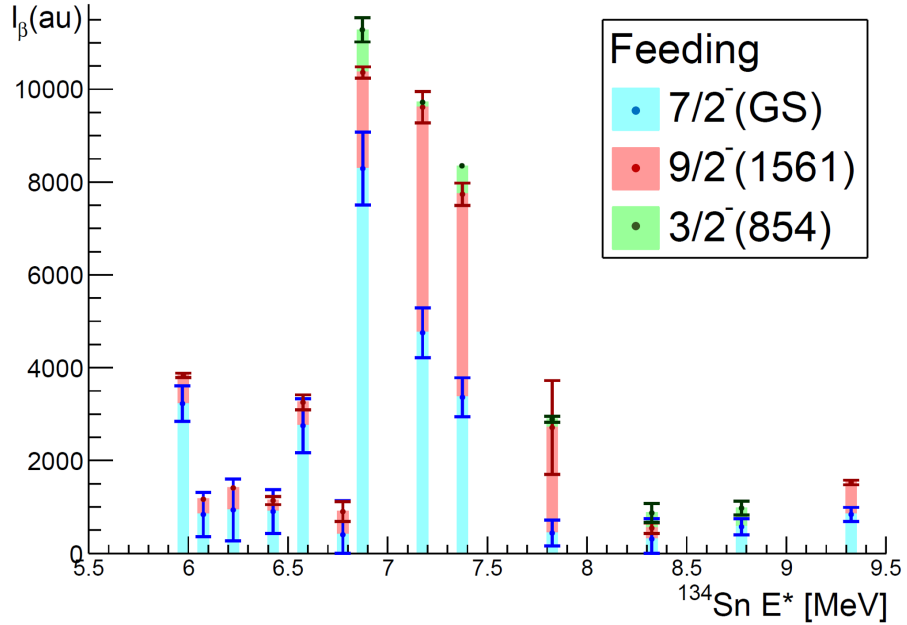


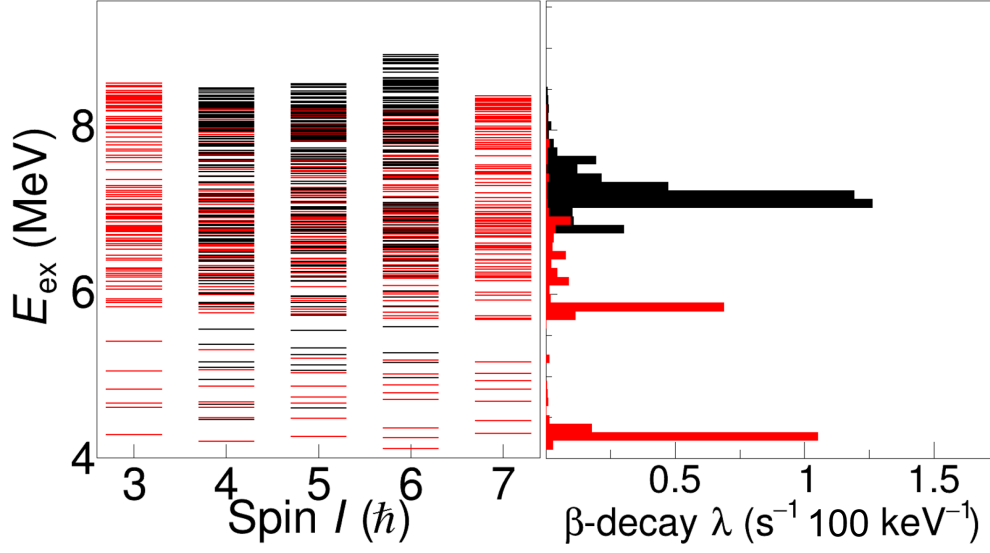
Figure 5.6: Feeding intensities, I_β , as a function of excitation energy of levels in ^{134}Sn . The different color segments of each level indicate the relative branching ratios of a ^{134}Sn level to single particle states in ^{133}Sn . Errors bars are determined from error in fit and the uncertainty in the neutron detection efficiency.

the precursor nucleus. The Gamow Teller beta decay rate calculations (black) in Figure 5.7 reasonably reproduce the I_β distribution in ^{134}Sn around 7 MeV seen in the experimental data shown in Figure 5.6. The shape and position of the Gamow-Teller distribution in Figures 5.7a and 5.7b show little dependence on the spin. These figures indicate that the transitions to excited states around 7 MeV can be of Gamow-Teller type.

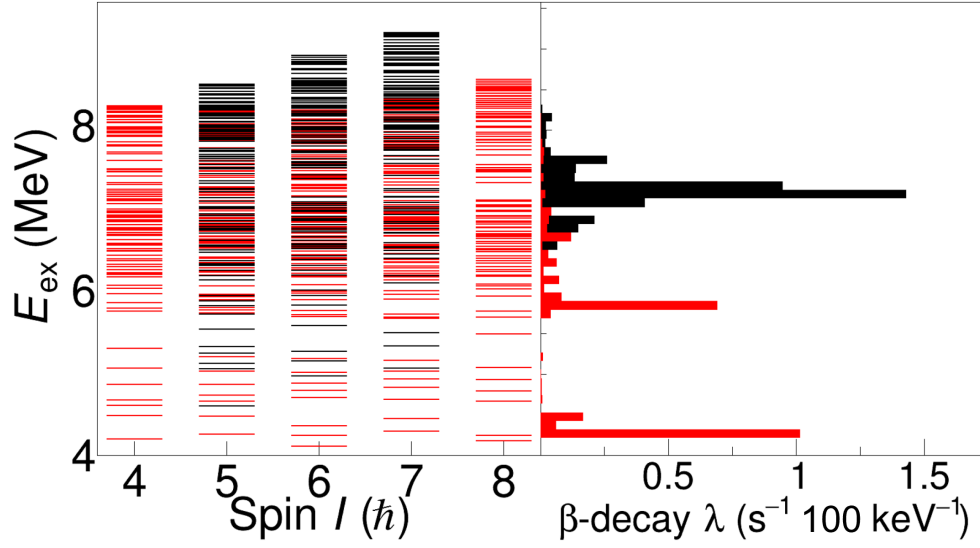
To determine with certainty if a state was populated through GT or FF transitions, $\log ft$ values need to be calculated [40]. ^{134}Sn excited states are assumed to decay exclusively through neutron or gamma emission such that no neutron-gamma competition is accounted for in determining the relative feeding to each state. The total beta decay feeding intensity is calculated by scaling the integrated feeding of neutron emitting levels by the inverse of ^{134}In neutron emission probability. A measured P_n value of ^{134}In from an experiment using a neutron counting detector has not been published so $\log ft$ values were calculated for a variety of neutron emission probabilities ranging from 60% to 90%. Results from $\log ft$ calculations of the states shown in Figure 5.6 are shown in Figure 5.8 for each value of P_n value. Gamow Teller transitions typically have a $\log ft$ values around 4.0-5.0, making four states of particular interest for studying neutron emission in this work: 6.88 MeV, 7.18 MeV, 7.37 MeV, and 7.81 MeV. Their specific $\log ft$ values can be found in Table 5.3. These four states will be further studied to determine possible nuclear structure effects on neutron emission.

5.3.2 Calculations with Hauser-Feshbach

State of the art statistical model calculations were performed using a stripped-down version of the COH codebase released by Kawano et al. [16]. This code, BEOH, published by S. Okumura et al. [41], was specifically developed to calculate neutron emission branching ratios for a single excited state in a compound nucleus based on the initial energy, spin, and parity of the state. For each ^{134}Sn state specified in Section 5.1.1, neutron emission branching ratios to excited states in the granddaughter nucleus ^{133}Sn were calculated based on inputs for the spin and parity of the ^{134}Sn state. States believed to be populated by Gamow-Teller or First Forbidden transitions were investigated independently based on spin and parity constraints. The grouping of states as either Gamow Teller or First Forbidden are substantiated in Section 5.3.1.



(a) $^{134}\text{In} J^\pi = 5^-$



(b) $^{134}\text{In} J^\pi = 6^-$

Figure 5.7: 100 Lowest lying negative (black) and positive (red) parity states in ^{134}Sn using KSHELL and the $jj77_vmu$ interactions. Beta decay rates in the right hand portion of each plot were calculated assuming a ground ^{134}In state spin $J^\pi = 5^-$ and $J^\pi = 6^-$ for the left and right plots respectively. Calculations were performed using KSHELL LSSM solver and $jj77_vmu$ interactions.

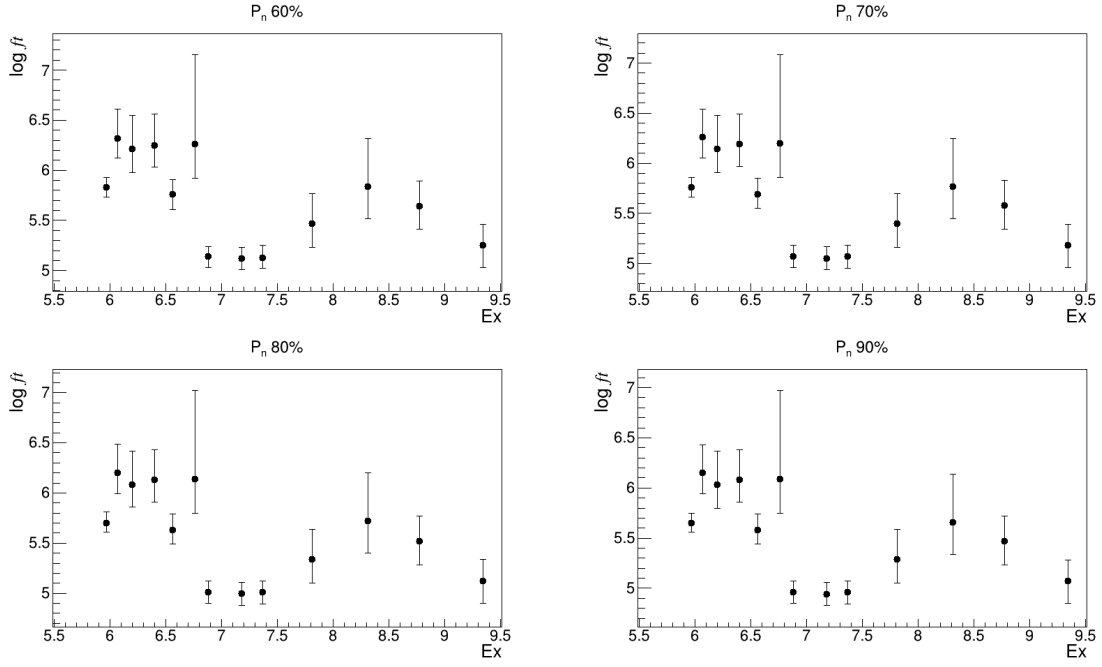


Figure 5.8: Plots showing $\log ft$ values of ^{134}Sn excited levels using beta decay feeding intensity information determined experimentally. Calculations were done for various values of ^{134}In P_n due to the lack of a reliable published value.

Table 5.3: $\log ft$ Results for GT States

^{134}Sn E^* / P_n	60%	70%	80%	90%
6.88 MeV	$5.14^{+0.10}_{-0.11}$	$5.07^{+0.11}_{-0.11}$	$5.01^{+0.11}_{-0.11}$	$4.96^{+0.11}_{-0.11}$
7.18 MeV	$5.12^{+0.11}_{-0.11}$	$5.05^{+0.12}_{-0.11}$	$5.00^{+0.11}_{-0.12}$	$4.94^{+0.12}_{-0.11}$
7.37 MeV	$5.13^{+0.12}_{-0.11}$	$5.07^{+0.11}_{-0.12}$	$5.01^{+0.11}_{-0.12}$	$4.96^{+0.11}_{-0.12}$
7.81 MeV	$5.47^{+0.30}_{-0.24}$	$5.40^{+0.30}_{-0.24}$	$5.34^{+0.30}_{-0.24}$	$5.29^{+0.30}_{-0.24}$

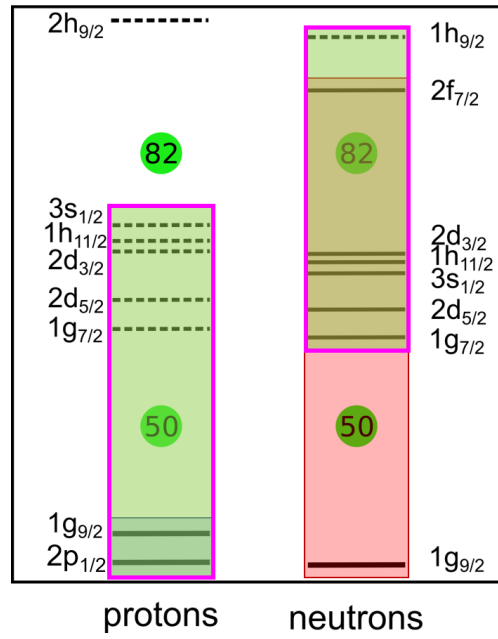


Figure 5.9: Proton and neutron valence orbitals used in $jj77_vmu$ residual interactions for KSHELL calculations (Shaded green area outlined in magenta).

Branching ratios to excited states in ^{133}Sn as a function of ^{134}Sn excitation energy were calculated for different spin and parities. The plots of negative parity states can be seen in shaded histograms in Figure 5.10 with the four data for the supposed Gamow-Teller states overlaid as the darker color points with errors. The histograms show smooth variations as a function of ^{134}Sn excitation energy. Likewise, the positive parity states are shown in Figure 5.11 with data overlaid for states assumed to be populated in First Forbidden transitions.

For each of the four Gamow-Teller states proposed in Section 5.3.1, the percent error and χ^2/Ndf as a function of spin was calculated to determine the most likely spin for each state. The two best cases for χ^2/Ndf and percent error are shown in Table 5.4. For states where percent error and χ^2/Ndf were minimal for the same spin, the spin with the next lowest χ^2/Ndf was included. Although no χ^2/Ndf or percent error value indicates strong agreement with statistical model predictions, the minimum error values for all states except the 6.88 MeV agree to a similar spin scenario. The possible parent spin must be with ± 1 unit of angular momentum if these states are assumed to be populated in Gamow-Teller transitions. Spins 5^- and 6^- are most prevalent, so the assumption in a Hauser-Feshbach statistical model approach would be $J^\pi = 5^-$ or $J^\pi = 6^-$ for the ^{134}In ground state. Spins 7^- and 8^- are unlikely due the presence of only one 7^- agreement and no 8^- agreement. For similar reasons, a 4^- spin assignment is not viable either. The 6.88 MeV state has a minimum χ^2/Ndf for $J^\pi = 3^-$, far outside agreement with the other states. If one is to look at the upper left plot in Figure 5.10 at the data points corresponding to 6.88 MeV, they could assume that this is probably not an accurate prediction. This situation could be an indication, along with the relatively large error values for all states, that the statistical model may not provide an accurate prediction of neutron emission in this scenario.

One would believe that it has been shown that the intermediate excited emitter states in ^{134}Sn behave as compound nuclei, but there is one caveat; neither shell model calculations nor experimental data exhibit high enough level density to satisfy the Hauser-Feshbach approximations made in Ref. [16]. There must be a large overlap between numerous states of different structure but same J^π in order to use the Hauser-Feshbach statistical model and treat the neutron emission as independent of nucleon arrangement. In a microscopic explanation, a large superposition of states in ^{134}Sn would allow the nucleus to rearrange itself

• $7/2^-$ (GS)
 • $9/2^-$ (1561)
 • $3/2^-$ (854)

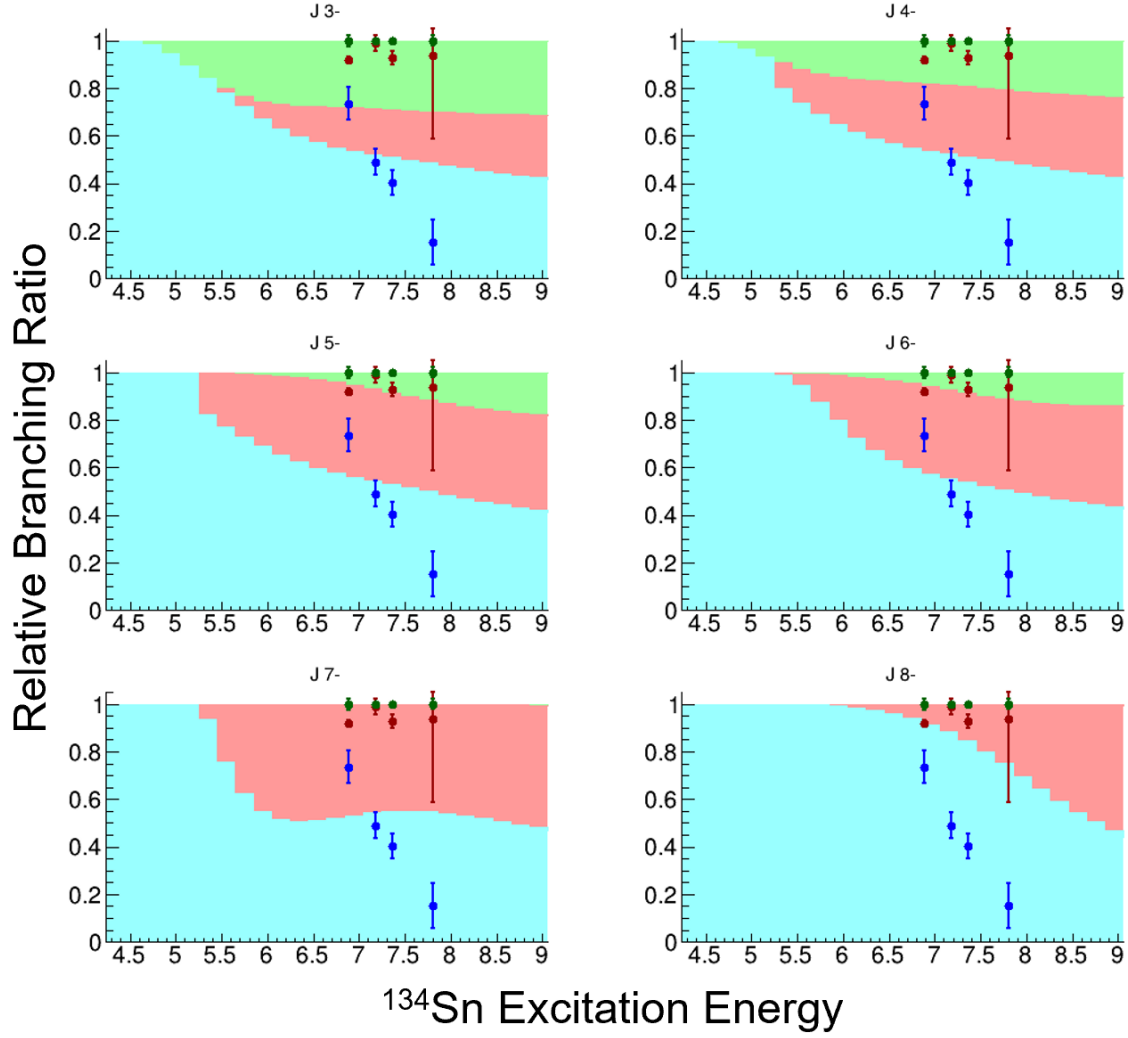


Figure 5.10: Energy dependence of neutron emission branching ratios to single particle states in ^{133}Sn for negative parity states. Each plot represents a different spin assignment of the neutron emitting state in ^{134}Sn .

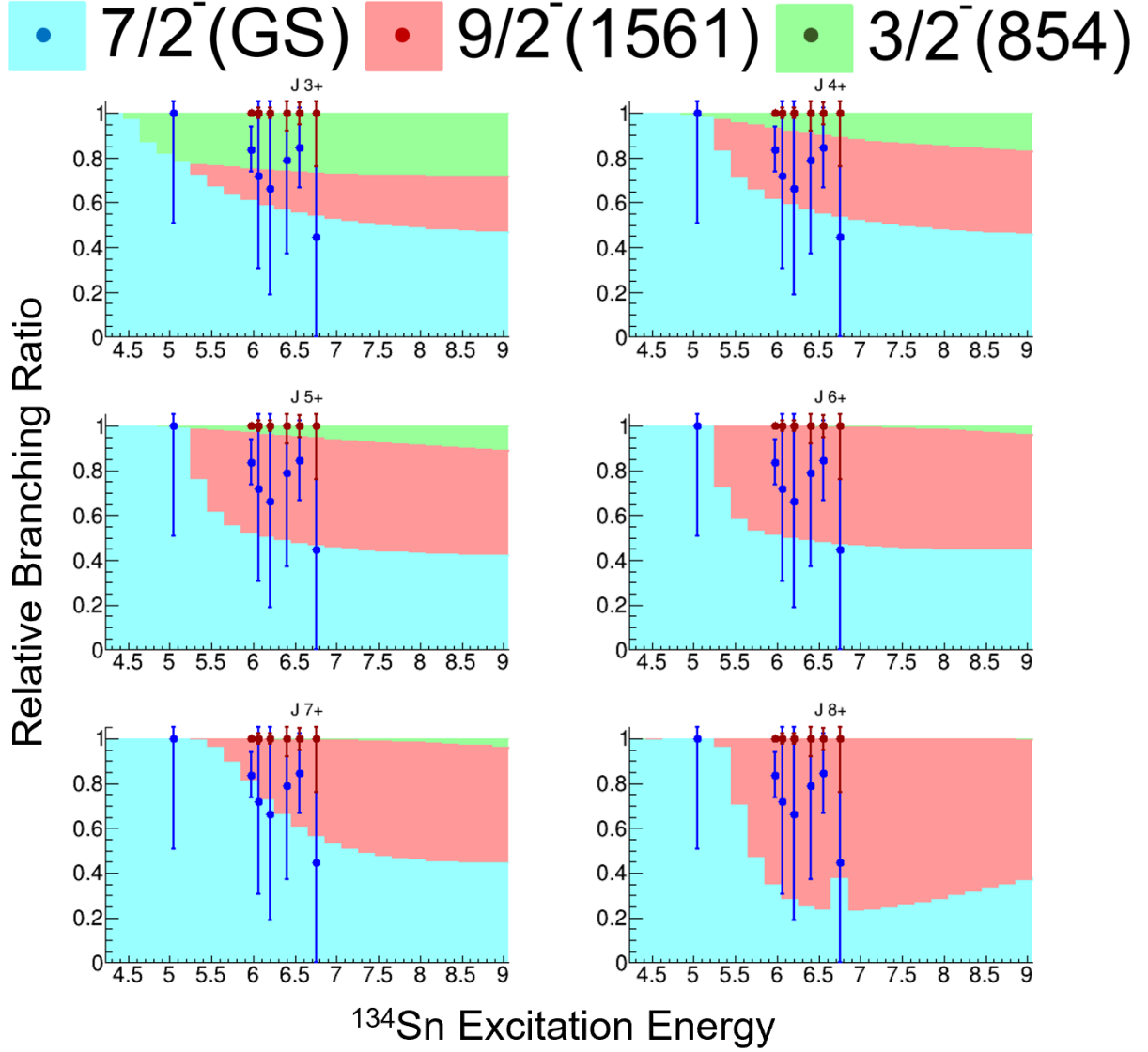


Figure 5.11: Energy dependence of neutron emission branching ratios to single particle states in ^{133}Sn for positive parity states. Each plot represents a different spin assignment of the neutron emitting state in ^{134}Sn .

internally to a configuration more suitable for neutron emission with subsequent population of a single particle state in ^{133}Sn . A calculation of possible neutron emitting states in ^{134}Sn was carried out using NuShellX [42], another LSSM solver with similar performance to KSHELL. Residual interactions were calculated using a $Z=38, N=82$ closed core with valence space up to $Z=82$ for protons and up to $N=126$ for neutrons. This valence space should produce all available neutron emitting states in ^{134}Sn that are similar to states in ^{133}Sn . Figure 5.12 shows all the positive (red) and negative (parity) states from this calculation. Comparing the level densities between 6.5 MeV and 8.0 MeV in Figures 5.7a and 5.7b with those in Figure 5.12, it can be easily asserted that for a given spin, the level overlap between the negative parity states populated in beta decay and negative parity neutron emitting states is minimal. Therefore, it is not conducive to automatically treat this process as occurring through a compound, equilibrated system. Since the statistical model can't be applied in the scenario of beta decay to regions of low level density above the neutron separation energy, a different model must be designed which accounts for the arrangement of nucleons within the nucleus. This model should also be able to reproduce statistical model calculations and experimental measurements for nuclei in regions of high level density.

A nuclear structure based treatment will be presented in the next section that connects the statistical model to the low level density observed in ^{134}In beta delayed neutron emission.

5.4 Doorway State Interpretation

Perhaps the most relevant assumption in the use of the Hauser-Feshbach statistical model for calculating neutron branching ratios is that the states populated in beta decay are in a region of high enough level density that multiple states overlap. The assumed eigenstate superposition foundational to substantiate claims of the absence of structure information in the neutron emission spectrum [43]. However, if it can be shown that if the level density is not high enough to constitute a continuum, one can assume there may exist a resurgence of nuclear structure dependence in the neutron emission probabilities [44]. Proposed here is a rudimentary model accounting for the particular arrangement of nuclei after a precursor nucleus has undergone beta decay.

Table 5.4: χ^2 Results for GT States

Ex [MeV]	J^π	χ^2/Ndf	Error
6.88	3	27.5	24
	6	102.0	21
7.18	7	5.3	34
	5	136.4	30
7.37	5	11.9	12
	6	13.6	13
7.81	6	6.7	39
	5	6.8	39

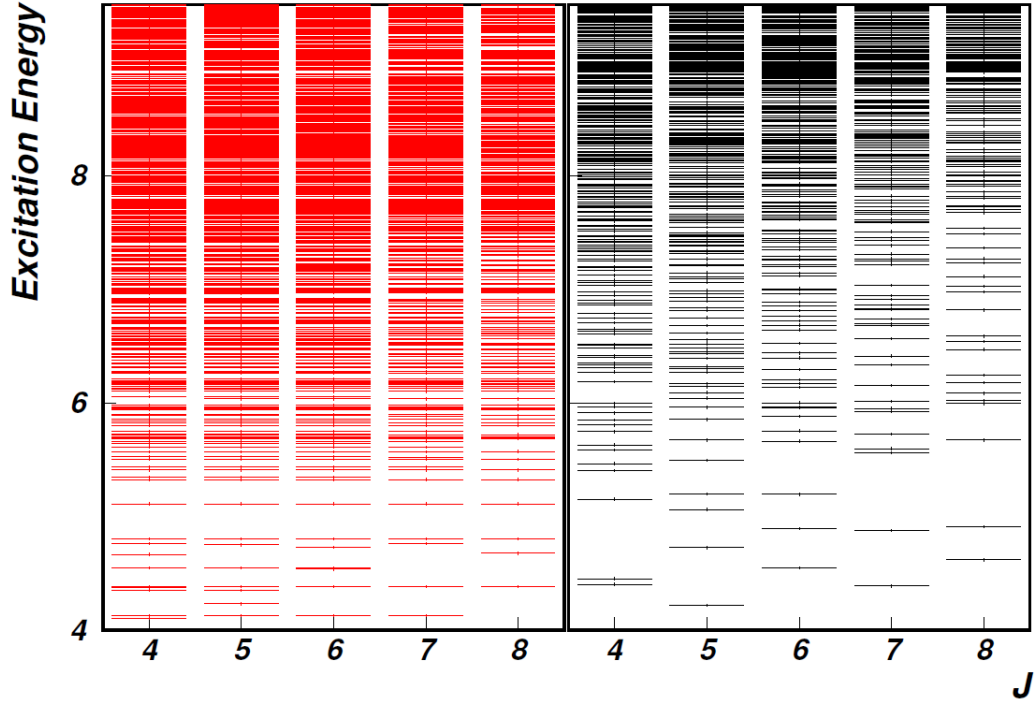
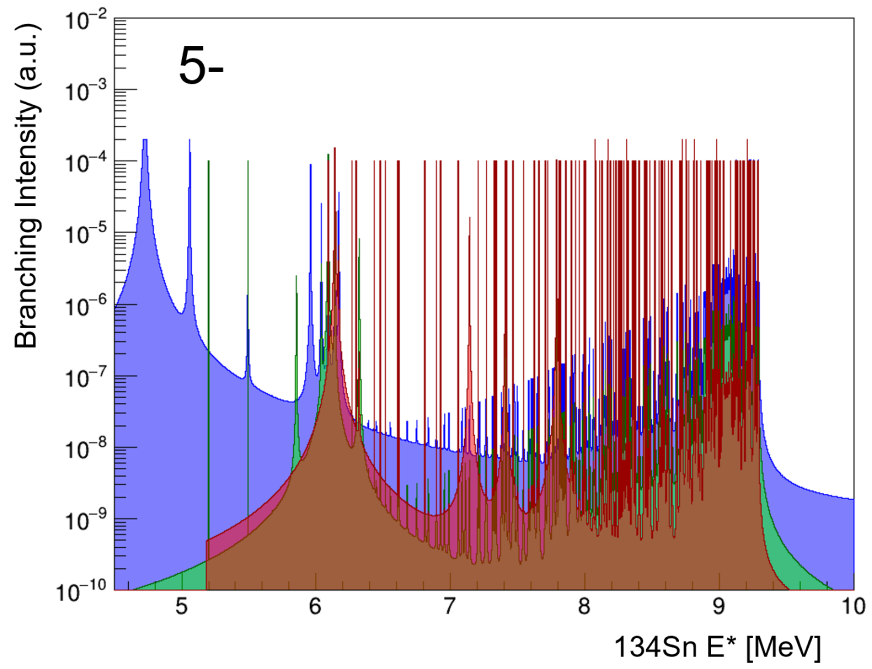


Figure 5.12: NuShellX calculation of all positive (red) and negative (black) parity states for different spins in ^{134}Sn using a $Z=38, N=82$ closed core with valence space up to $Z=82$ for protons and up to $N=126$ for neutrons. These states are all possible neutron emitting states with no neutron hole excitation.

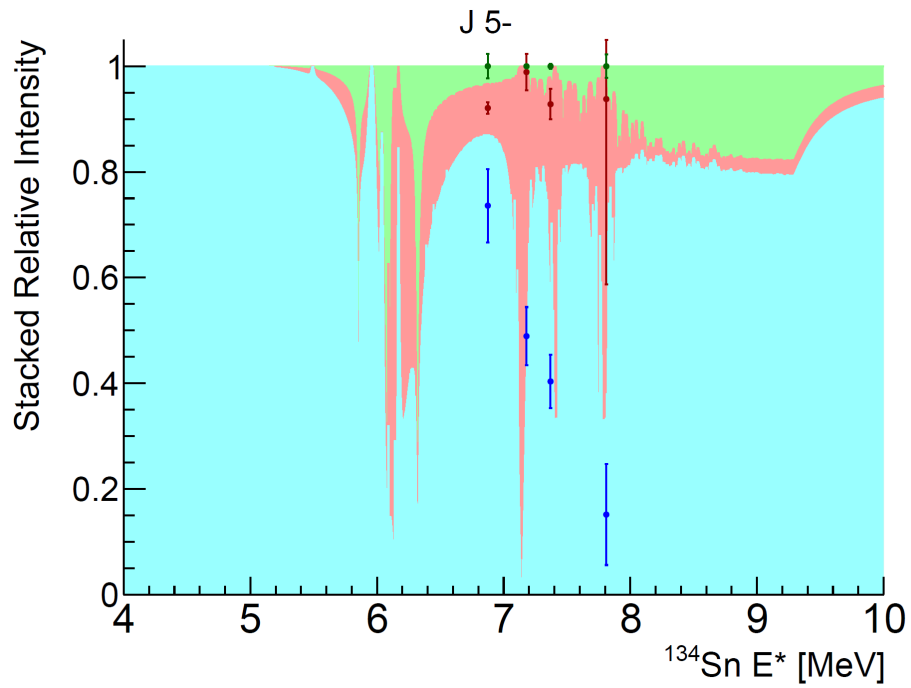
Calculations using NuShellX have shown that ^{134}Sn states with a neutron hole populated in the Gamow Teller beta decay of ^{134}In have zero spectroscopic overlap with the single particles observed in ^{133}Sn [45]. A definition of spectroscopic factors is found in References [46, 47] but it can be explained shortly here as wavefunction overlap between specific states in the initial and final nucleus. Here, the initial nucleus is the neutron emitter in an excited state and the final nucleus is the daughter. Calculated spectroscopic factors for states in the ^{134}Sn emitter nucleus and the final ^{133}Sn single particle states are negligibly small such that the initial and final states can be considered orthogonal. In a nucleus with high level density near the Gamow Teller window, the compound nucleus can easily rearrange itself to accommodate the neutron emission so the sampling of neutron emitting states can be considered uniform. In a system with low level density, the nucleus can still rearrange itself due to the compound nature of the state, but there are fewer states for it evolve into before the neutron emission. The states populated in Gamow Teller transitions now have a larger preference for emitting through states with larger spectroscopic overlap. This entire process can be likened to the mechanism of doorway states observed in reaction experiments [48, 49].

The modeling of this process in ^{134}In beta delayed neutron emission is two fold, beginning with calculations of the spectroscopic overlaps between neutron emitting states and the single particle states in ^{133}Sn . Once the neutron emitting states are calculated, the widths of the neutron emitting states are calculated using a Koning-Delaroche optical potential [50] which are then folded with a state's spectroscopic overlap to generate the Breit-Wigner distribution for each. Figures 5.14a and 5.14a shows the superposition of all 5^- and 6^- states in ^{134}Sn respectively, which emit neutrons to either the $7/2^-$, $3/2^-$, or $9/2^-$ state in ^{133}Sn .

The plots in Figures 5.13 and 5.14 show the effect of the nuclear structure dependence on the neutron emission branching ratios. Figures 5.13a and 5.14a displays how the structure is manifested from the overlap of the distributions for each individual state but it does not reflect actual feeding intensities. The large peaks in the absolute intensity are the result of strong wave function overlaps of the neutron emitting state with a single particle state in the final nucleus. The branching ratio plots in Figure 5.13b and 5.14b provide more insight into how the relative intensities for fixed spin and parity can change as a function of energy. Figures 5.15 and 5.16 shows the feeding intensity from positive and negative parity ^{134}Sn

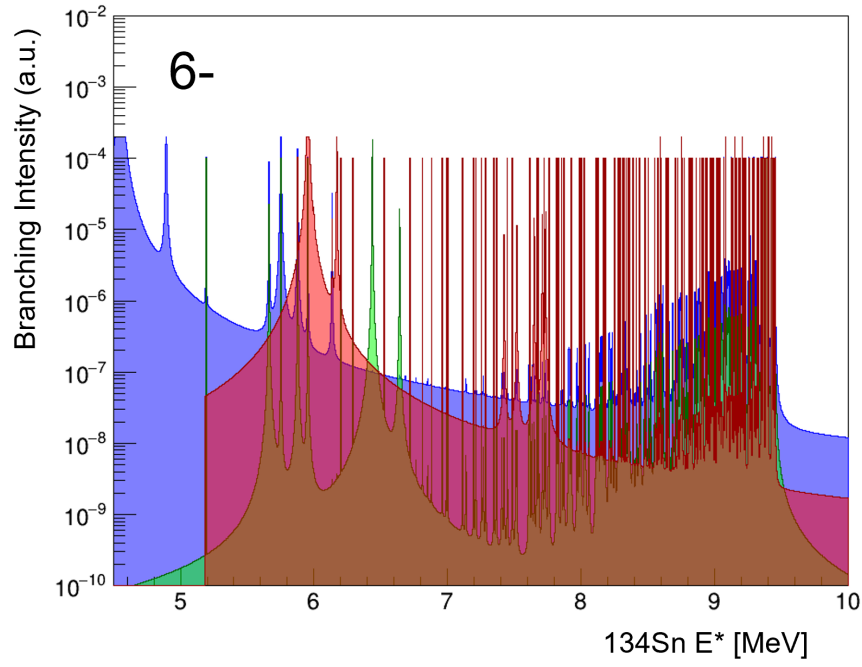


(a) Absolute Intensities

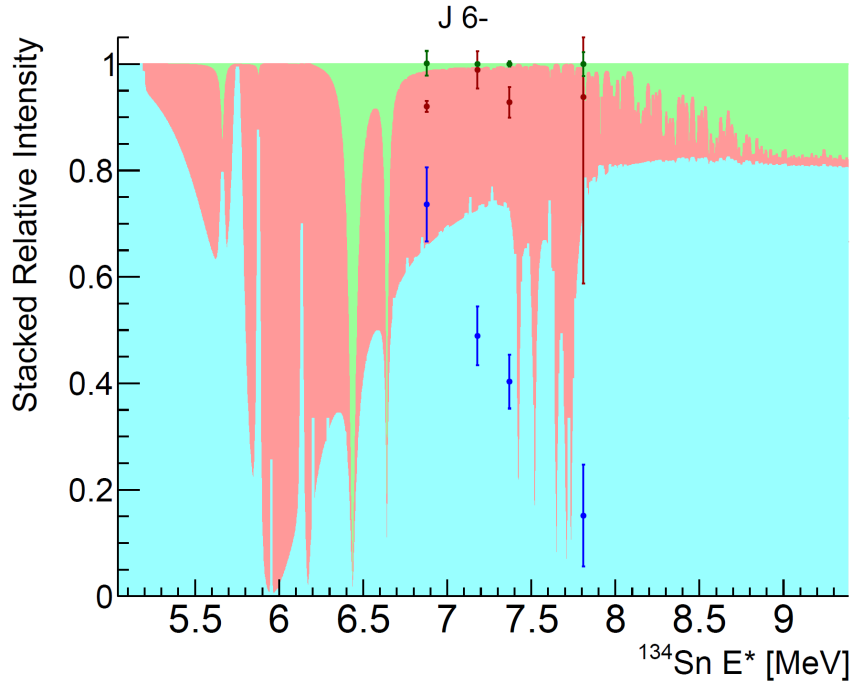


(b) Branching Ratios

Figure 5.13: Calculation showing the absolute and relative branching intensities from a 5^- ^{134}Sn state to the $7/2^-$ (blue), $3/2^-$ (green), and $9/2^-$ (red) states in ^{133}Sn .



(a) Absolute Intensities



(b) Branching Ratios

Figure 5.14: Calculation showing the absolute and relative branching intensities from a 6^- ^{134}Sn state to the $7/2^-$ (blue), $3/2^-$ (green), and $9/2^-$ (red) states in ^{133}Sn .

states for a given energy, E^* , on the y-axis to a corresponding single particle state in ^{133}Sn designated on the x-axis. The brighter colors indicate a stronger preference for transitions to the states specified on the x-axis. The plots on the right in previously mentioned figures best illustrate the situation in which low level density causes strong variations in emission branching ratios. Not only does the feeding intensity drastically change as a function of energy for a single state on the x-axis, but also the relative branching ratio for each ^{133}Sn single particle state varies wildly as a function of energy, as seen in Figures 5.13b and 5.14b.

Another success of this model is shown by calculations of the positive parity states. Whereas the negative parity neutron emitting states predicted by NuShellX exhibit low level density, the positive parity states shown in red in Figure 5.12 have moderate to high level density for energies between 6 MeV and 8 MeV. Calculations using the doorway interpretation for positive parity states show minimal structure in the neutron emission intensities for the 6 MeV to 8 MeV energy range. Due to minimal statistics, the forbidden transitions were not studied in this dissertation, but the model already shows behavior similar to a statistical model for regions with high level density, as one should expect.

The neutron emission framework explained above resolves the issue addressed for neutron emission from regions of low level density. It is founded on the same assumption that the nucleus is high enough energy to equilibrate before emitting a neutron, but only to specific states which have strong spectroscopic overlap with the final states in ^{133}Sn . As Shell Model calculations and residual interactions become more accurate, this structure-based formalism will be studied to estimate its predictive power. If strong fluctuations of branching ratios are observed in experimental data, it may indicate the effect of nuclear structure on the neutron emission process. A full experimental study of ^{134}In beta delayed neutron emission was recently approved by the ISOLDE PAC for 120 hours of beamtime. This experiment will be run with a new high resolution neutron detector detailed in the next chapter which will be vital to the determination of the level density and relative branching ratios.

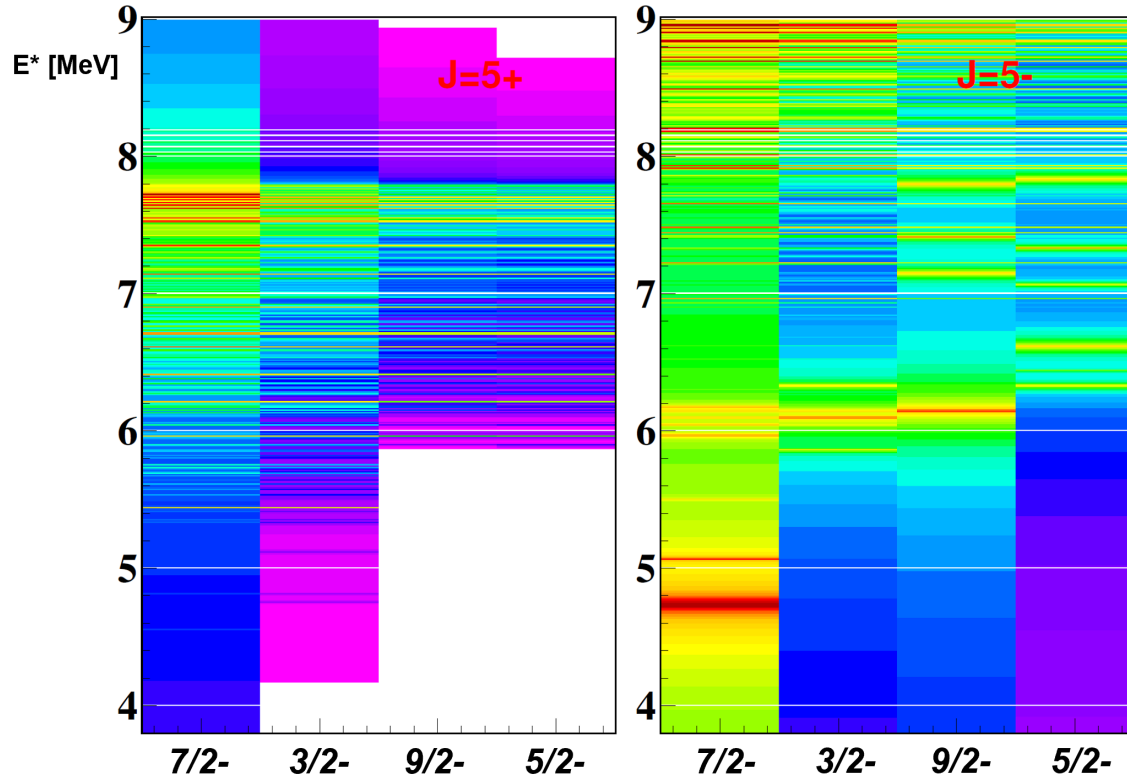


Figure 5.15: Histogram representing the feeding intensity from a $J^\pi = 5^+$ (left) $J^\pi = 5^-$ (right) ^{134}Sn state at energy E^* to the different single particle states in ^{133}Sn labeled on the x-axis using the formalism described in Section 5.4. Brighter/lighter shading indicates stronger feeding.

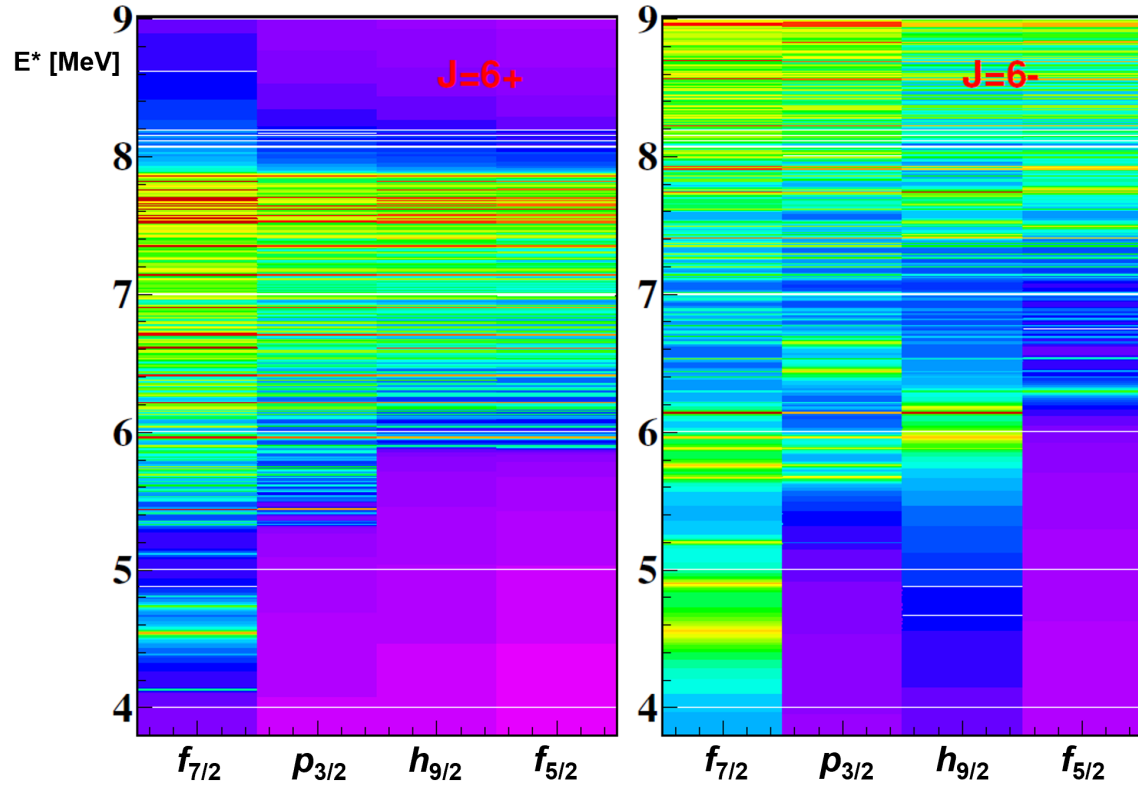


Figure 5.16: Histogram representing the feeding intensity from a $J^\pi = 6^+$ (left) $J^\pi = 6^-$ (right) ^{134}Sn state at energy E^* to the different single particle states in ^{133}Sn labeled on the x-axis using the formalism described in Section 5.4. Brighter/lighter shading indicates stronger feeding.

Chapter 6

Development of a New Generation Detector for High Resolution Neutron Spectroscopy

The Facility for Rare Isotope beams (FRIB) will be online in the fall of 2021, making it possible to explore neutron rich isotopes that have yet to be discovered or studied. In the wake of the discoveries of new isotopes, many of these neutron rich isotopes will be multi-neutron emitters, necessitating the development of a state-of-the-art neutron detector array. The Neutron dEtector with multi-neutron (Xn) Tracking (NEXT) is designed to improve current neutron time-of-flight detector technologies by minimizing the uncertainty of neutron interaction localization and the use of neutron-gamma ($n\text{-}\gamma$) discriminating materials. Appendix B provides more information on neutron energy calculations from TOF measurements and how energy resolutions depend on the time of flight and distance uncertainties.

6.1 Segmented Detector Design and Concept

Compared to previous neutron TOF detectors [31, 51, 52], NEXT will be based on similar technologies. The entire NEXT array will consist of many individual detectors of plastic scintillator coupled to fast photomultipliers used to measure neutron energies through time

of flight. However, recent advancements in fast timing position sensitive detectors and n- γ discriminating scintillator will be adapted to improve the energy resolution in TOF setups.

6.1.1 Improving Energy Resolution

The energy resolution of a neutron time of flight detector is dictated by the uncertainty in the time of flight, ΔT , and the uncertainty in the interaction position, ΔL , and is described by the equation below.

$$\left(\frac{\Delta E}{E}\right)^2 = \left(\frac{2\Delta T}{T}\right)^2 + \left(\frac{2\Delta L}{L}\right)^2 \quad (6.1)$$

There are three ways to generally improve the energy resolution of a neutron detector: reduce ΔL , the position uncertainty, reduce the flight path length, L , or reduce the TOF resolution, ΔT . Detector configurations must balance these three different parameters with neutron detection efficiency to properly optimize the needs of a specific experiment. Intrinsic neutron detection efficiency roughly scales with detector thickness ($\epsilon_n \propto \Delta L$). Therefore, for fixed L , the detector efficiency is directly proportional to the energy resolution. Typical thicknesses for plastic-scintillator-based neutron TOF detectors are about 23 cm, which is a good trade-off between position resolution and efficiency [31, 51, 52].

A single NEXT detector will be designed to attain the upmost timing and position resolution without sacrificing the intrinsic detection efficiency. Ideally the detector would have ~ 500 ps timing resolution and sub-cm position resolution. This would allow an improvement of the energy resolution as can be seen in the left panel of Figure 6.1. This graph shows different calculations of neutron energy resolution as a function of neutron energy depending on different values for flight path distance, position uncertainty, and TOF uncertainty. The right plot shows a calculated neutron energy spectrum from the beta delayed neutron emission of ^{85}As as measured by VANDLE (red) and NEXT (blue). In this calculation, typical VANDLE position and TOF uncertainties were used and uncertainties for NEXT were proposed performance capabilities. The flight path length is 100 cm for VANDLE and 50 cm for NEXT, displaying NEXT's potential ability to attain better energy resolution even at closer distances.

6.1.2 n- γ discrimination with PSD plastic

Another important method to improve neutron energy calculations is by rejecting interactions in the scintillator from particles that are not of interest, namely gamma rays. Scattered gamma rays are a common source of background in scintillating neutron detectors. Figure 6.2 shows the background reduction in a neutron TOF spectrum from a $d(^{12}\text{C}, n)$ reaction [4]. There are several commercially available solid-state scintillators which can provide strong n- γ discrimination and timing, such as stilbene, anthracene, and para-terphenyl. Due to the limited ability of machining these scintillators into large, segmented arrays, these are presently not preferable or economically feasible as a material for the proposed detector. When a viable n- γ discriminating plastic scintillator, Eljen 299 (EJ-299) [53], was first developed [54], the material was not hard enough to facilitate machining and had to be cast directly into the final detector geometry. However, recent improvements to the EJ-299 polymer matrix increased physical stability and pulse-shape discrimination (PSD) capabilities [55]. This new plastic scintillator, Eljen 276 (EJ-276) [56], has n- γ discrimination capabilities comparable to liquid scintillators and is now firm enough for machining of segments with appropriate thickness and geometry to construct a high-resolution neutron time-of-flight detector.

Fast and Slow Decay components

In setups such as VANDLE [31] or INDiE [57] which utilize non-discriminating plastic scintillator, the material exhibits the same light response to neutrons as gamma rays, meaning the same molecular states are populated no matter which scatters in the medium. Scintillator light is produced by de-excitations of the molecular electron configurations. Spin singlet states decay with very short lifetimes (~ 5 ns) while the triplet spin states have a much longer lifetime (~ 1 ms). These states can mix through intersystem crossing and bimolecular interactions. A schematic representing various scintillator processes is shown in Figure 6.3a. Intersystem crossing can occur two ways, the first being the spontaneous transformation of a S_0 state to a T_1 state. This process is very rare and is independent of exciting particle type. The second process occurs through bimolecular interactions wherein two T_1 states

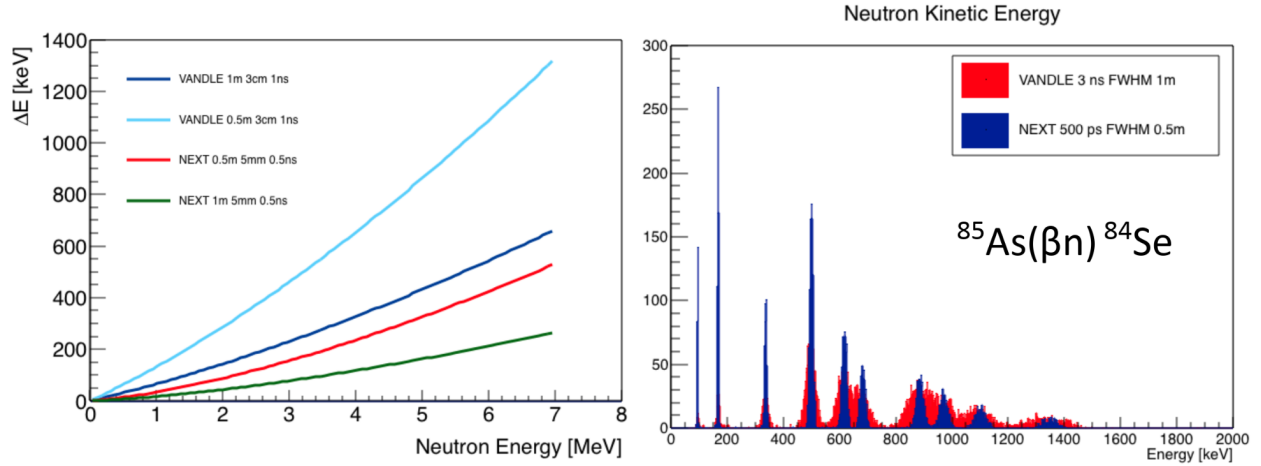


Figure 6.1: (Left) Energy resolutions as a function of energy. The legend is labeled as neutron flight path length (L), position uncertainty (ΔL), and timing uncertainty (ΔToF). (Right) Simulated neutron kinetic energy spectrum of beta delayed neutron emission. The red spectrum is simulated with current VANDLE capabilities and the blue spectrum is simulated with NEXT design goals.

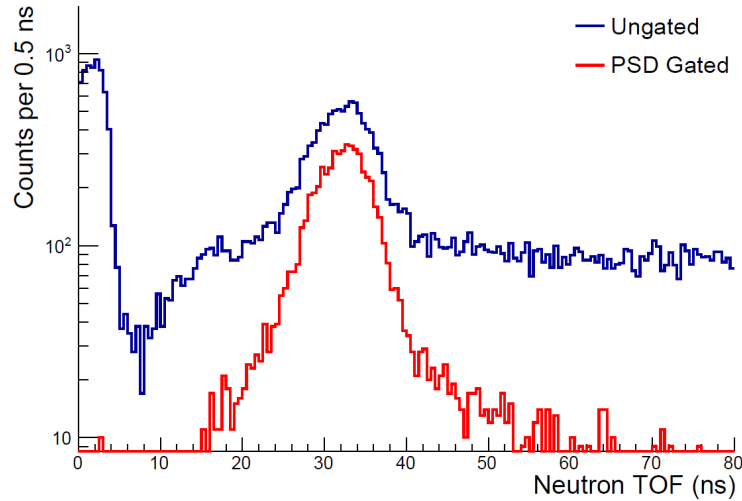


Figure 6.2: Two histograms showing neutron time of flight spectra from a $^{12}\text{C}(\text{d},\text{p})$ reaction before (blue) and after (red) gamma ray events were removed using Pulse Shape Discrimination. Adapted from C. Thorsberry [4].

interact and convert to one S_0 state and one S_1 . This type of de-excitation is called delayed fluorescence and the half life is ~ 50 ns, attributing a larger slow component to the total decay of all the excited molecules (see Figure 6.3b).

Pulse Shape Discrimination Analysis

Heavier particles (protons and heavier) typically convert more of their deposited energy as T_1 states in the scintillator as compared to lighter particles (electrons, muons, etc.) [5]. Knowing this behavior and the fact that the lifetime of the delayed fluorescence of T_1 states is $\sim 10\times$ that of S states, the two particles can be discerned from one another by analyzing the signal decays through multiple methods. Many methods exist for pulse shape analysis and each has its pros and cons but none are quite as robust as the Charge Comparison Method. The Charge Comparison Method discriminates between neutrons and gamma rays through calculations of the slow decay component to the overall integration of the pulse. Since neutrons deposit their energy by scattering protons within the scintillator medium, they should exhibit the stronger slow decay component, making the ratio of the slow component integral to the overall integral should be greater. The equation for the CCM ratio is given below [58]:

$$R_{S/T} = \frac{\sum_{i=delay}^N y(i)}{\sum_{i=0}^N y(i)} \quad (6.2)$$

This value, $R_{S/T}$, is plotted against the total integral or pulse amplitude to show the separation of ratio values for neutrons and gamma rays. The measure of the scintillator or PSD method's capability to discriminate between the two particles is the Figure of Merit, $FoM \equiv \frac{\Delta S}{\Gamma_n + \Gamma_\gamma}$, where ΔS is the separation of the means of the two distributions and $\Gamma_{n,\gamma}$ are the respective FWHM of the two distributions [5]. Plots of neutron gamma discrimination using CCM can be seen in Figures 6.11 and 6.19.

6.1.3 Conceptual Design

The NEXT array is based on multi-layered modules of PSD plastic scintillator with position sensitive photodetectors on both ends of a single module. Each detector consists of eight

~ 6 -mm-thick layers, with an approximate effective thickness of 4.8 cm. These dimensions were driven, among other factors, by the availability of small form factor photosensors. Figure 6.4 shows a possible multi-layered module configuration, with segmentation along the horizontal and vertical directions, wherein the vertically aligned segments with respect to the incoming particle are denoted as columns or layers and the horizontally aligned segments along the incoming particle trajectory are rows. The best timing and position resolution are achieved by orienting the higher segmentation along the direction of incident particles. The photosensors considered are either an array of silicon photomultipliers (SiPMs) or flat panel multi-anode photomultiplier tubes (MAPMTs). To reduce the number of acquisition channels, an Anger Logic readout will be used in conjunction with the photosensors [59]. Analysis of the position-sensitive Anger Logic response from detected scintillation light will determine the specific layer in which the neutron scattered, reducing the uncertainty in the neutron flight-path length, ΔL .

6.2 NEXT Simulations

In order to investigate the light collection efficiency as well as the timing capabilities of the different layer geometries, *NEXTsim*, a GEANT4-based code was developed [60, 61]. The *NEXTsim* code uses GEANT4 version 10.1 Patch 3 and outputs to ROOT [62] files for further analysis. The software simulates the interaction of neutrons, gamma rays, and charged particles in the matter they traverse. The physics model (referred to as *Physics List* in the GEANT4 context) employed is the recommended QGS_BERT_HP, which includes the standard electromagnetic and high-precision models for neutron scattering, elastic and inelastic, as well as capture and fission. This model is based on the G4NDL evaluated neutron data library [63].

Neutron-induced scintillation is simulated using the associated light response from energy deposited in the scintillator by a scattered neutron. This relationship for organic scintillators is detailed in Ref. [64] and has been scaled appropriately to the light output and scintillation efficiency for EJ-276. The G4OpticalPhysicsList is included to treat the transport of each photon until it escapes the active volume, is absorbed, or is detected. For each event,

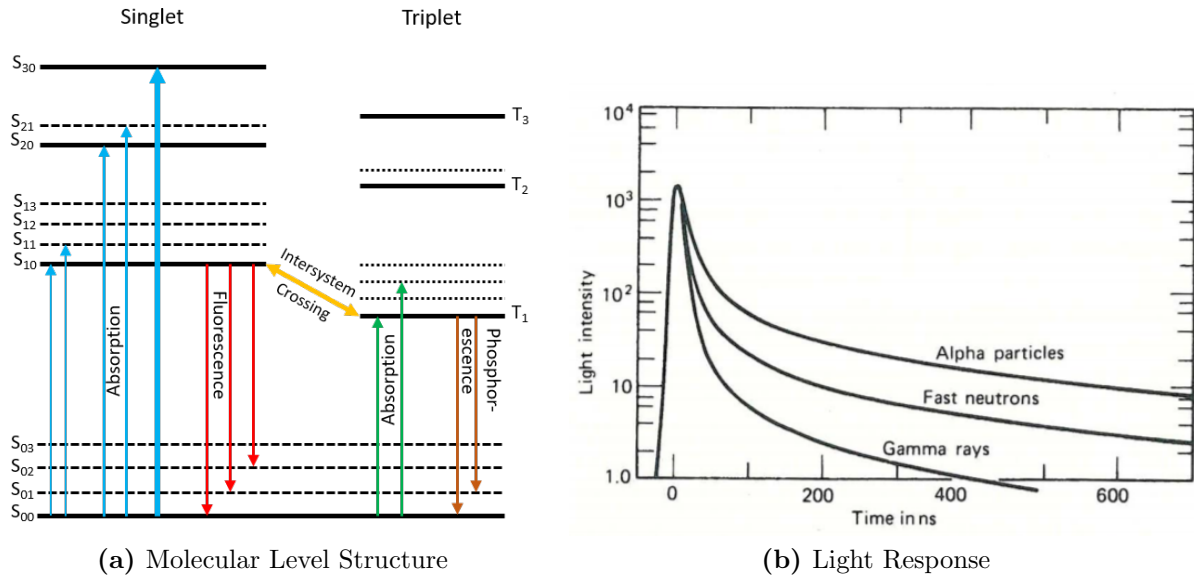


Figure 6.3: Molecular π -electron level structure (left) and the scintillator response (right) of different exciting particles due to different mixtures of initial singlet and triplet states. Adapted from G. F. Knoll [5].

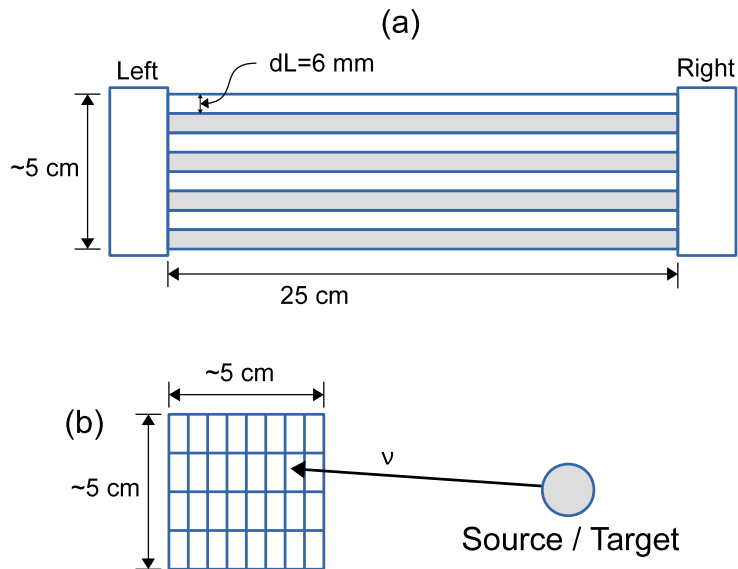


Figure 6.4: Schematic showing a potential segmentation configuration for a single NEXT module. (a) A top-down view of the detector segmentation along the thickness of the detector. (b) Side view of a prototype showing the individual segments within the detector, each optically separated from one another, along a neutron's flight path. Vertically aligned segments in (b) are designated as columns and horizontally aligned segments are designated as rows.

the position and timing information for each neutron scatter within the detector volume is recorded along with relevant photon information, such as the minimum and average photon arrival time along with the position information of all detected photons at the photosensor surface.

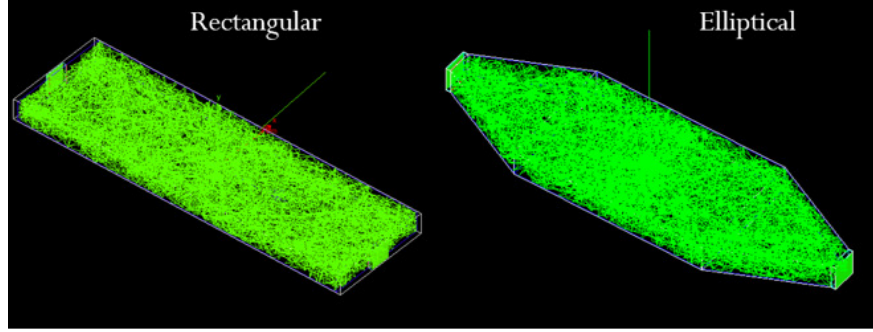
Different geometries and wrappings considered for NEXT modules displayed in Figure 6.5a can be generated, e.g., rectangular bars and elongated octagonal bars (bars in which the corners were cut at an angle to reflect scintillation light towards the photosensors). The ends of each scintillator segment are coupled to photosensitive surfaces with a thin layer of optical grease. Any of the available geometries, scintillator, and wrapping materials can be chosen via macro-driven commands.

6.2.1 Simulation of light collection efficiency

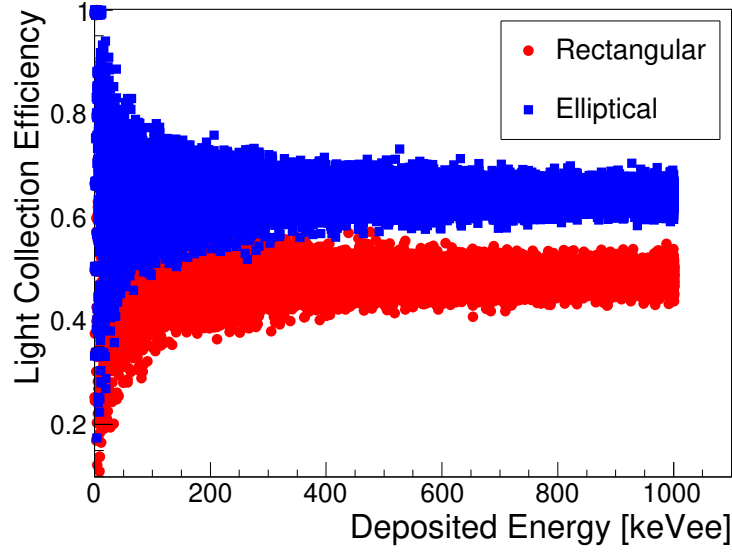
The different 6-mm-thick geometries originally considered for single NEXT layers shown in Figure 6.5a were studied using *NEXTsim* in order to determine the light collection efficiency when wrapped in aluminized Mylar and coupled to two photosensors, one on each end. Figure 6.5b shows the results of the light collection efficiency, calculated as the ratio between the number of detected and produced photons, as a function of the energy deposited in the scintillator from 1 MeV neutrons in a pencil beam incident on the center of the detector. In this case, the photosensors are considered ideal meaning every photon hitting the sensitive surface will be detected. The average efficiency of the rectangular geometry is 50%. The average efficiency of the octagonal geometry is higher and reaches 68% due to the directional scattering of scintillation light towards the photosensors. Octagonal geometries were originally considered for one dimensional layer readouts but further tests were not conducted after it was decided that NEXT must have two dimensional segmentation to maintain adequate timing resolution.

6.2.2 Simulation of photosensor response

The photosensor response to the detected scintillation light was also added to the simulations for better comparisons to experimental timing tests. A Single Photo-Electron (SPE)



(a)



(b)

Figure 6.5: (a) Visualization of a 1 MeV neutron event in *NEXTsim* for two aluminized Mylar-covered geometries considered for a NEXT layer with single photosensors on either end. Green lines correspond to optical photons produced in the scintillation. (b) The light collection efficiency for the two geometries when observing 1 MeV neutrons. The detector in the octagonal geometry observes, on average, 68% of all photons produced in these events compared to 50% in the rectangular geometry.

response function, specific to each photosensor, is folded with the optical-photon arrival-time distribution to obtain realistic photomultiplier signals. The SPE response functions for SiPMs and PMTs were taken from [65]. The total response is the sum of the SPEs of each photon detected by the photosensor weighted by the product of the anode gain and quantum efficiency. The resultant light-response pulse is given a baseline offset and electrical noise, and is then “digitized” by placing it into discrete bins on the y-axis (e.g., from 0 to 65535 to represent a 16-bit digitizer) and discrete time bins on the x-axis (e.g., 4 ns for a 250 MSPS system). The digitized pulses are then integrated to obtain the representative light yield of the event and are processed with a polynomial constant fraction discrimination (PolyCFD) algorithm [4] as described in Section 4.1.2 and Appendix B.1. The PolyCFD algorithm computes a time for each pulse which represents the time-of-flight of the incident neutron aggregated from all collected photons.

6.2.3 Simulation of time-of-flight resolution of the detector

Simulations of 1 MeV neutrons impinging onto 10-cm-long plastic scintillator bars were used to establish the timing resolution dependence on detector thickness. Geometrical cross-sections of $1 \times 6 \text{ mm}^2$, $3 \times 6 \text{ mm}^2$, and $6 \times 6 \text{ mm}^2$ were studied with the varying dimension parallel to the neutron trajectory. The neutron’s first scattering time was used to directly measure the neutron TOF. This method provides the most direct information to indicate the timing uncertainty associated with the thickness of the detector. The TOF distributions can be seen in Figure 6.6 where an increase in the thickness of the scintillator bar results in a broadening of the TOF resolution. This effect is due to the uncertainty in the interaction position along the neutron path within the scintillator and the non-negligible flight time of the neutron.

To test the timing resolution of a digitized photosensor response when using bars of different thicknesses, scintillator plates with cross-sections $1 \times 6 \text{ mm}^2$, $3 \times 6 \text{ mm}^2$, $6 \times 6 \text{ mm}^2$, and $12 \times 6 \text{ mm}^2$ were modeled and the light output and high-resolution-timing (HRT) of each plate response is computed as in Section 6.2.2. The neutron TOF is computed as the average of PolyCFD HRT for the left and right photosensors. Figure 6.7 shows the normalized TOF distributions for each plate overlaid on one another. The difference in TOF

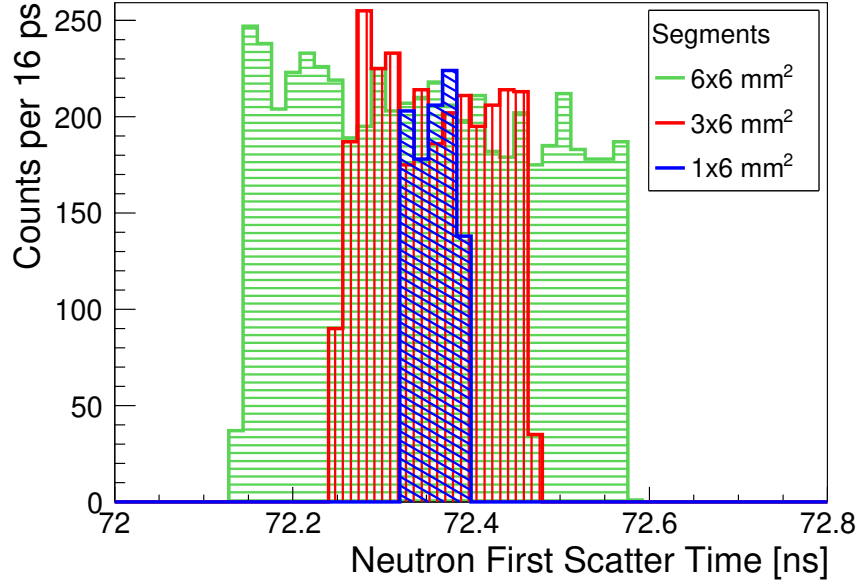


Figure 6.6: Distributions of the times-of-flight for a pencil beam of 1 MeV neutrons impinging onto scintillator bars of varying thickness at a distance of 1 m. TOF was calculated as the neutron’s first scattering time in the scintillator.

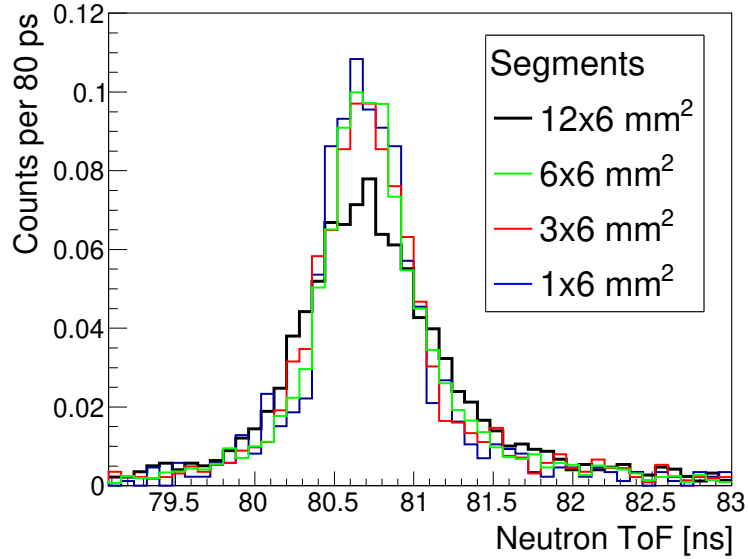


Figure 6.7: Distributions of the times-of-flight for a pencil beam of 1 MeV neutrons scattering in scintillator plates 1 m away. The PolyCFD analysis [4] was applied to both photosensor responses for each event to calculate high-resolution times in order to compute the neutron flight times. Normalized TOF distributions are shown for 10 cm long plates with geometric cross-sections of $1 \times 6 \text{ mm}^2$ (blue), $3 \times 6 \text{ mm}^2$ (red), $6 \times 6 \text{ mm}^2$ (green), and $12 \times 6 \text{ mm}^2$ (black).

distributions between Figs. 6.6 and 6.7 is due to the contributions of the photon arrival time distribution accounted for in Figure 6.7. The FWHM TOF resolution for the 1 mm, 3 mm, and 6 mm thick plates are all within 7% and average to 600 ps. The TOF resolution of the 12 mm plate was 54% larger as compared to the average of the other plates. When full photon statistics and a complete digitized analysis are considered, the TOF resolutions of the scintillator segments with varying thicknesses are dominated by the photon collection and trace analysis up to ~ 6 mm thickness, beyond which the detector geometry begins to contribute to the TOF resolution. It was also concluded from simulations that the detection efficiency of a plate scales linearly with its thickness, i.e. the efficiency of the 6×6 mm² plate is two times larger than the 3×6 mm² plate. This result means that, in addition to exhibiting six times greater efficiency, the 6×6 mm² plate exhibits approximately the same detector time resolution as the 1×6 mm² plate when coupled to a realistic acquisition system.

Based on the loss of TOF resolution for the 1 mm and 3 mm layers when using the full photosensor response, seen in Figure 6.7, it was decided that the minimum layer thickness of a prototype using EJ-276 plastic scintillator should not be less than 6 mm; thinner tiles would not provide any further benefit to TOF measurements due to the limited timing resolution of the data acquisition system.

6.3 Designing a new Detector

The NEXT project is a ground up redesign of the same approach to neutron spectroscopy as VANDLE [31]. The first step towards building a prototype was to categorize all available constituent parts: scintillator, scintillator wrapping, and detector type. Using the information gathered from single segment simulations, single component testing began with 6 mm thick pieces of Eljen 200 plastic scintillator [53].

6.3.1 SiPMs: Small Form Factor, High Gain

When considering position sensitive readouts, silicon photomultipliers were the first choice for designing a new detector. SiPMs are small form factor sensors made from single photon

avalanche diodes, available in microcell densities between 100~1000 per mm². When reversed bias beyond the silicon diode breakdown voltage, a single photon avalanche diode converts a single photon into a breakdown current of approximately 10⁶ electrons. This produces a similar effect to a standard photomultiplier tube, but without the large size and high voltage that is necessary to produce sufficient gain.

SensL Technologies, now owned by OnSemiconductors, is one of the largest producers of high-quality SiPMs in the world. The SensL J-series SiPM offers the best timing with smallest form factor, making it an ideal choice for a compact segmented detector [6]. Single SiPMs can be individually purchased and are easily adaptable to modular detector designs for which there are two approaches to reading out the signal from the SiPM. In a standard readout shown on the left in Figure 6.8, SiPMs have very fast rise times (~ 2 ns) but have a characteristically long signal decay on the order of half a microsecond. SensL suggests passing the signal through a RC pre-amplifier in order to truncate the decay, making the signal decay over 100 ns [6]. The pre-amplifier circuit also helps filter out high frequency noise in the sensor from thermal breakdowns and potential sources of electrical crosstalk.

The pre-amplifier circuit can be tuned to have different effects on the signal, mainly rise time and amplitude, these behaving inversely. RC pre-amplifier filters with large feedback resistors (R1 in the right diagram in Figure 6.8) will have a large amplitude but slower rise time as compared to small feedback resistors which have fast rise times but small amplitudes. Fast timing with digitized pulses generally requires fast rise times, so these were studied to compare to past design capabilities. A 6x6 mm² bar of Eljen 200 wrapped in white polytetrafluoroethylene (PTFE) thread seal tape was coupled to SiPMs at both ends. A ⁹⁰Sr source was placed in the center of the EJ200 bar. SiPMs with and without RC feedback amplifiers were tested to see how the feedback circuits affected the signals and timing. The signals from both setups were passed through an ORTEC[®] 535 fast amplifier to increase the signal amplitude. The signals were digitized with a XIA LLC. 250 MHz 16 bit Pixie16 digitizer before being processed with the timing analyzer [66]. The PolyCFD timing algorithm described in Appendix B.1 was used for high resolution timing of all digitized signals.

Figure 6.9 shows that the on-board circuitry improves the timing resolution from 548 ps to 489 ps. This was the first proof of principle test to determine if the final configuration could be designed with arrays of SiPMs as the position sensitive detector. Unfortunately, SiPMs currently can't be easily coupled to a reduced channel resistive network readout which makes them incapable of currently being adapted to a full scale NEXT detector [67]. However, this work played a critical role in the development of other small scale beta detectors for fast timing purposes.

6.3.2 Eljen 276 Scintillator Tests

The new Eljen 276 scintillator bars were received in 12x6 mm² cross sections, some were 127 mm (5 in) long and the others were 254 mm (10 in) long. Each length came with two types of wrapping: Lumirror[™] or 3M ESR[™]. Because there are not many publications on the timing performance of Eljen 276 (along with these wrappings), stringent tests had to be performed to ensure this plastic can meet the design goals of NEXT. Two Hamamatsu R11265U-M4 series PMTs were used on either end of a bar (see Figure 6.10) to detect the scintillation. The same digitizers and timing methods from the SiPM tests were used to determine the PSD and timing capabilities of EJ276.

The n- γ discrimination capability of each wrapping was tested using a ²⁵²Cf source placed behind a 2 in lead block to attenuate the gamma-ray flux. The method used pulse shape discrimination was the Charge Comparison Method (CCM) which was described in Section 6.1.2. A digital CCM was used to measure the digitized events from the PMTs and the results are shown in Figure 6.11. For each analysis, the delay in the CCM was set to the same value and an energy cut was made between 400-500 keV. The FoMs for the Lumirror[™], PTFE, and ESR bars were 0.820 ± 0.012 , 1.042 ± 0.016 , and 0.977 ± 0.015 , respectively. The difference in FoM between the PTFE-wrapped and Lumirror[™] covered bars shows the optical adhesive worsens PSD capabilities. Of the two possible prototype reflective coverings, ESR was better at maintaining PSD so further tests of EJ-276 segments were only done with ESR reflective layers.

Axial timing tests were performed using a ⁹⁰Sr source on top of the ESR wrapped EJ276 bars. The Lumirror[™] covered detector was not tested for timing capabilities due to the poor

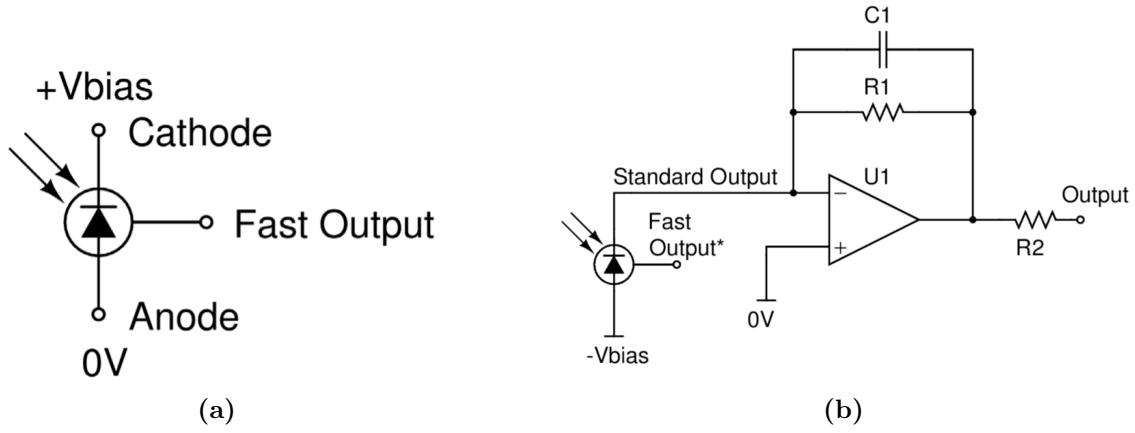


Figure 6.8: Two readout circuits suggested by SensL for the J-series SiPM. The left circuit is for standard SiPM readout. The right circuit is used to decrease the signal decay time and filter out high frequency noise in the sensor [6].

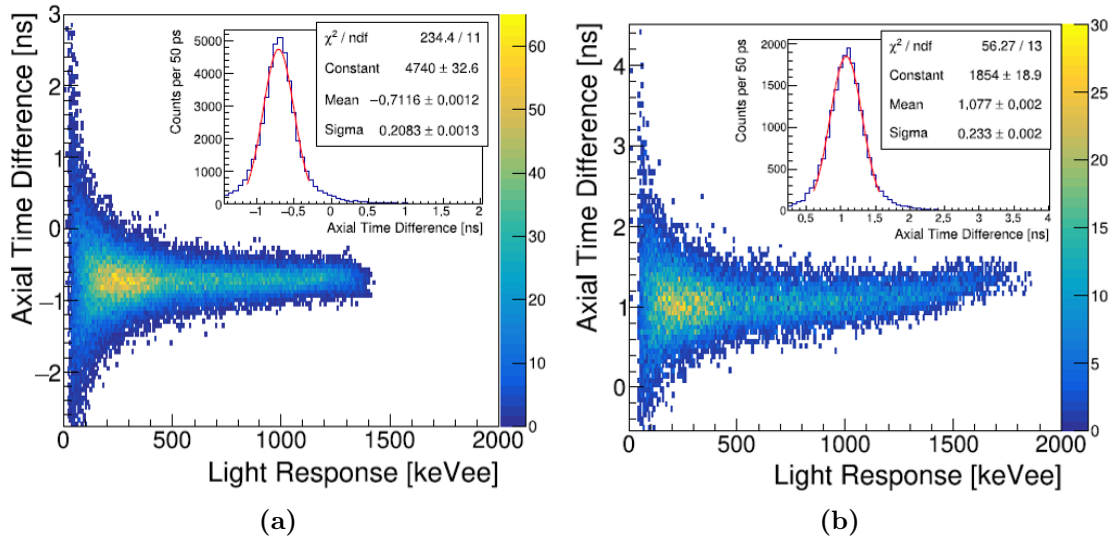


Figure 6.9: Position resolution measurements from SiPMs with RC feedback circuits (left) and no on-board circuitry (right). The insets show the one dimensional projection onto the y-axis with the gaussian fits used to calculate the timing resolution. The source used in this setup was ^{90}Sr .

n- γ discrimination compared to the ESR covered bar. Figure 6.12a shows the axial timing resolution for a single 254x12x6 mm³ bar of Eljen 276 wrapped with ESR. From a fit to the histogram of time differences, the timing resolution of the EJ-276 bar coupled to PMTs is 552 ps. In a time of flight setup using a short EJ200 detector and a ²⁵²Cf fission source, the TOF resolution was calculated to be 538 ps. A two dimensional histogram of TOF vs the light response can be seen in Figure 6.12b. The inset in this figure shows the projection onto the y-axis. The axial and TOF timing test shows that a NEXT module built from 6 mm thick layers of EJ276 can meet the design goals set out at the beginning of this proposal.

6.4 NEXT Prototype

ESR-covered EJ-276 segments were shown to meet NEXT design goals, leading to the assembly of 48×50.8×254 mm³ segmented detectors. An individual segment or cell is 6×12.7×254 mm³. A whole detector has 4×8 scintillator cells, shown in Figure 6.13, the higher segmentation being along the direction of incident particles. A full NEXT prototype is made up of one 4×8 segmented scintillator coupled to Hamamatsu H12700A Multi-Anode PMTs (MAPMTs) on each end of the segmented scintillator. The H12700A MAPMTs have an 8×8 segmentation (6×6 mm² anodes), each anode having an individual readout and a readout for each dynode. A Vertilon Anger Logic interface board (Model SIB064B-1730) [68] was used to reduce the position sensitive readout from 64 individual position signals to 4 position signals, one at each corner of the SIB064B-1730 resistive network, and a single readout for the last dynode. This substantially reduces the total number of required DAQ channels.

The scintillation position is reconstructed using the weighted average of the 4 corner resistive network signals based on their respective integrated signals [59]. Figure 6.13 shows the reconstructed scintillator segmentation using the Anger Logic position measurement of the MAPMTs detecting scintillation light produced from ⁶⁰Co gamma rays. The MAPMT common dynode signal is connected directly to the acquisition and used for all timing and PSD analyses. The scintillator cell-dependent analysis calculates neutron energies on a

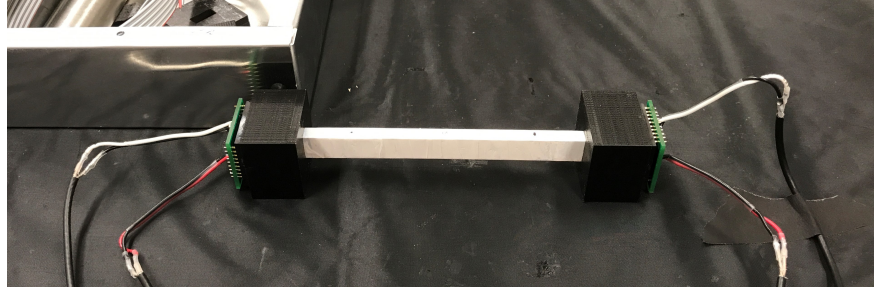


Figure 6.10: A bar of EJ276 with Lumirror wrapping between two Hamamatsu R11265U-M4 PMTs.

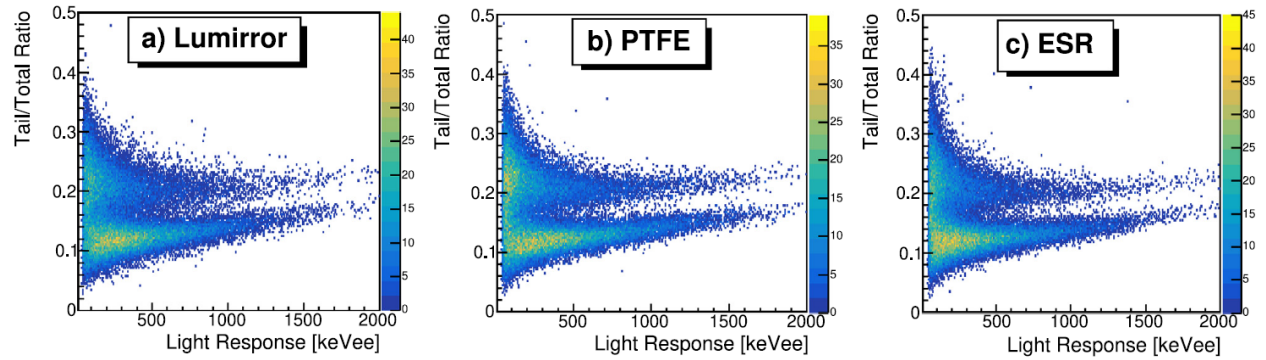
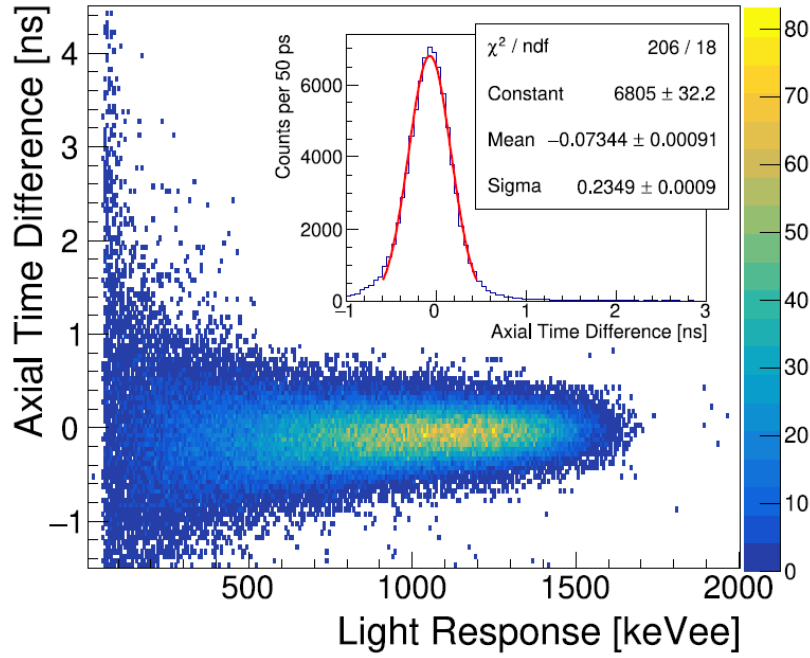
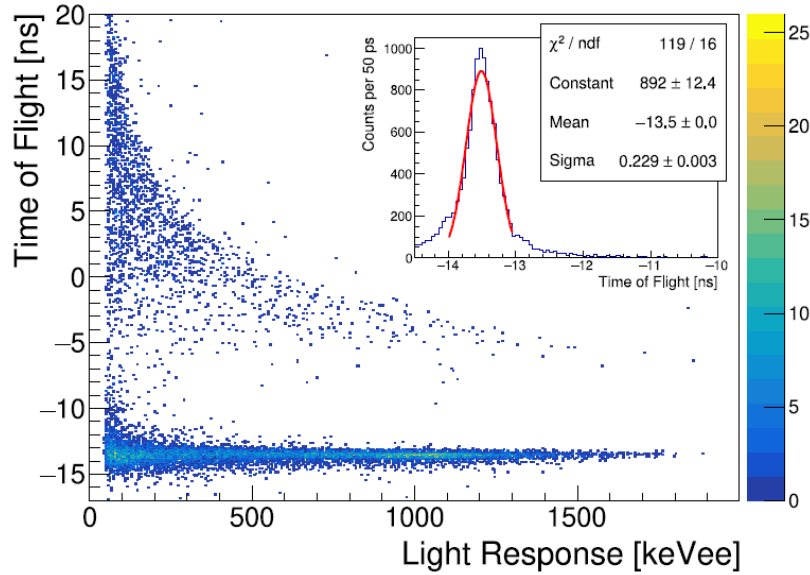


Figure 6.11: CCM ratio plots for the three different types of wrapping. Figure of Merit calculations were made for cuts between 400-500 keV: (a) FoM = 0.82 (b) FoM = 1.04 (c) FoM = 0.97

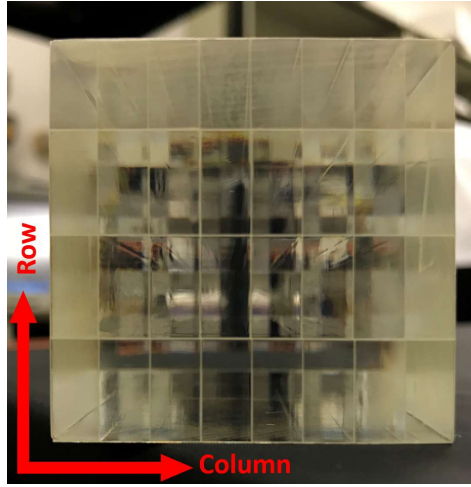


(a)

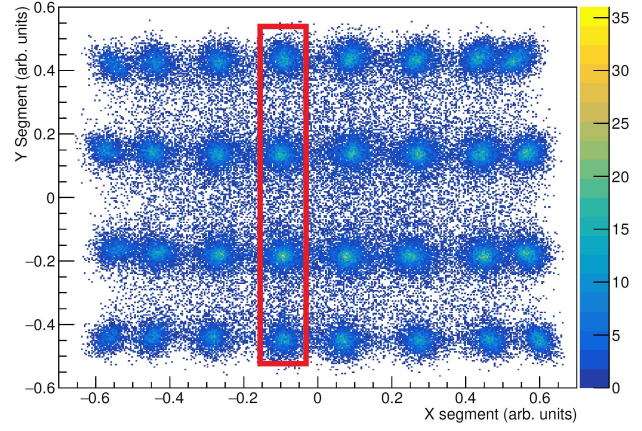


(b)

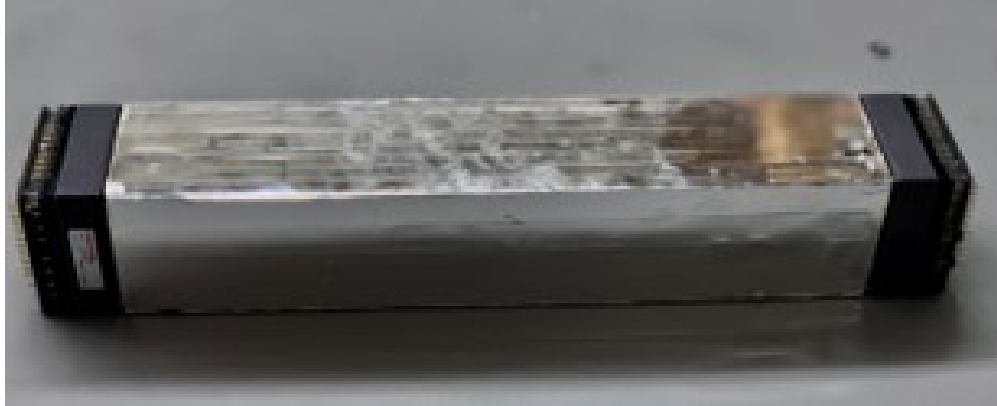
Figure 6.12: (Top) 2D histogram of the time difference between the left and right PMT signals plotted against the energy deposited in the scintillator from ^{90}Sr beta decay. The projection onto the time difference axis is shown in the inset. (Bottom) ^{252}Cf time of flight spectrum using a small EJ200 based start detector and the 5 in EJ276 detector shown in Figure 6.10. The inset shows the projection onto the y-axis with the gaussian fit to the peak.



(a)



(b)



(c)

Figure 6.13: The top left figure is an image of one end of a 4×8 segmented scintillator. The top right figure shows the reconstructed cells using the position sensitive signals from the Vertilon interface board. A single column is outlined by the red rectangle in the bottom figure. The detector is always arranged such that the higher segmentation is along the incident particle flight path for the best position and timing resolution. The bottom picture is a NEXT prototype consisting of $2 \text{ in} \times 2 \text{ in} \times 10 \text{ in}$ segmented scintillator wrapped in 3M^{TM} ESR coupled to Hamamatsu MAPMTs on each end.

segment-by-segment basis using reconstructed high-resolution positions for the particle flight path.

6.4.1 Study of neutron multiple scattering

If a neutron scatters multiple times within the detector, the neutron energy may be incorrectly determined. The *NEXTsim* code was used to evaluate the probability and effects of multiple scattering events in the different columns (layers) of the detector. A multi-layer detector was modeled using $6 \times 12.7 \times 254$ mm³ scintillator cells arranged in a 4×8 segmented detector, the same design as shown in Figure 6.4. An 8×8 multi-anode photosensor (6×6 mm² anodes), similar to commercially available designs, was coupled to each end. The simulation tracks the neutron while it traverses the entire detector. In plastic scintillator, a neutron can scatter either a proton or carbon nuclei, of which only a proton scatter produces detectable light. Because there is no way to determine if a carbon scatter, often referred to as a dark scatter, occurred in an actual experiment, both types of scatters were included in simulations to correctly replicate multiple scattering effects seen in a prototype. Figure 6.14 shows first and second scattering layer differences in the multi-layered detector obtained from the simulation of a 1 MeV neutron knife beam (uniformly distributed along a vertical line at the center between the two ends of the detector). Of all the neutrons that interact within the detector, 69.5% will scatter more than once in the scintillator. Relative to the first interaction point, the majority of multiply-scattered neutrons (57%) forward scatter, while only $\sim 6\%$ of events scatter backwards.

Neutron multiple scattering will have a large effect on the reconstructed scintillation position within the detector using a center-of-mass (CoM) analysis for detected photons. The optical photon CoM (segment position) is computed by taking the weighted average of the X and Y positions of all photons detected at the surface of the photosensor. Each detected photon position is weighted using the product of the gain of the anode at which it was detected and the quantum efficiency of the photosensor for a given wavelength. The photon CoM analysis is analogous to the Anger Logic position algorithm proposed for the NEXT prototype. Ideally, the reconstructed photon CoM should be within the same column as the neutron scatter CoM, defined as the average X and Y interaction position weighted by

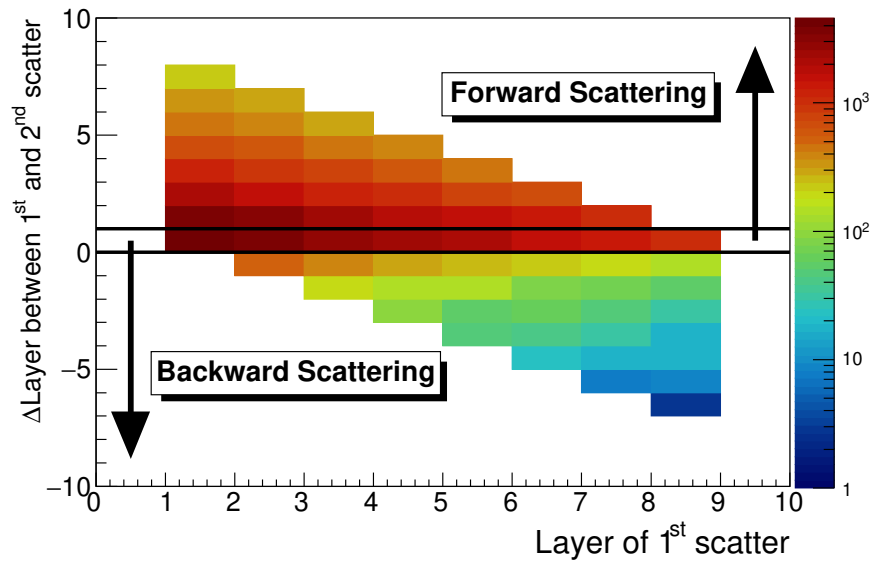


Figure 6.14: Two-dimensional histogram showing 1 MeV neutron multiple scattering between layers of a NEXT detector. The x-axis denotes the layer number of the first neutron interaction and the y-axis denotes the difference in layer number between the first and second neutron interaction layer. Forward scattering events (above the two black lines) comprise about 57% of events while backward scattering events (below black lines) are about 6.1%. The remaining events (between black lines) are a result of scattering more than once in the same layer.

the imparted energy for each scatter within the detector. From the same simulated 1 MeV neutron data analyzed to study the forward and backward scattering, Figure 6.15 shows four separate histograms representing the difference between photon and neutron CoM positions for events with 1, 2, 3, and 4 neutron scatters. A single layer thickness is 6 mm, represented by the magenta lines aligned at ± 3 mm in Figure 6.15. Events in which the reconstructed photon and neutron CoM positions are within the same layer comprise 91%, 86%, 86%, and 87% of all events with 1, 2, 3, and 4 neutron scatters, respectively.

To determine the overall effect of neutron multiple scattering on the detector performance, 1 MeV neutrons in a knife beam were simulated along a 75 cm flight path to a detector. The weighted average photon arrival time for each photosensor was used as a TOF measurement to calculate the incident neutron energies. In Figure 6.16, the black histogram represents the calculated neutron energies for all simulated 1 MeV neutrons which scattered at least once in the detector, with relative contributions from single- (red) and multiple-scattering (blue) events. The maxima of the black, red, and blue distributions are 0.992, 0.994, and 0.990 MeV, respectively. The change in peak location between singly- and multiply-scattered neutrons shows the relationship between timing and reconstructed positions for multiple-scattering events is not as strongly correlated as for single-scattering events and typically results in lower reconstructed neutron energies.

Simulations of the NEXT prototype have shown that such detectors should be capable of measuring neutrons with improved energy resolution. The NEXT prototyping process was guided by single-segment simulations which minimized the effort needed to fully test every configuration with an experimental setup. Going forward, the *NEXTsim* framework will be continually developed to provide first estimates of new detector capabilities and simulate complete experiments with more sophisticated detector arrangements.

6.4.2 Time-of-flight measurements

To measure the prototype time-of-flight resolution for a single column (as outlined in red in the bottom of Figure 6.13), a collimated ^{60}Co source was used. Figure 6.17 shows the TOF distribution for a single 6 mm column. From a Gaussian fit to the distribution, the TOF resolution is $\Delta TOF = 543$ ps after applying a 30 keVee threshold. Once the prototype was

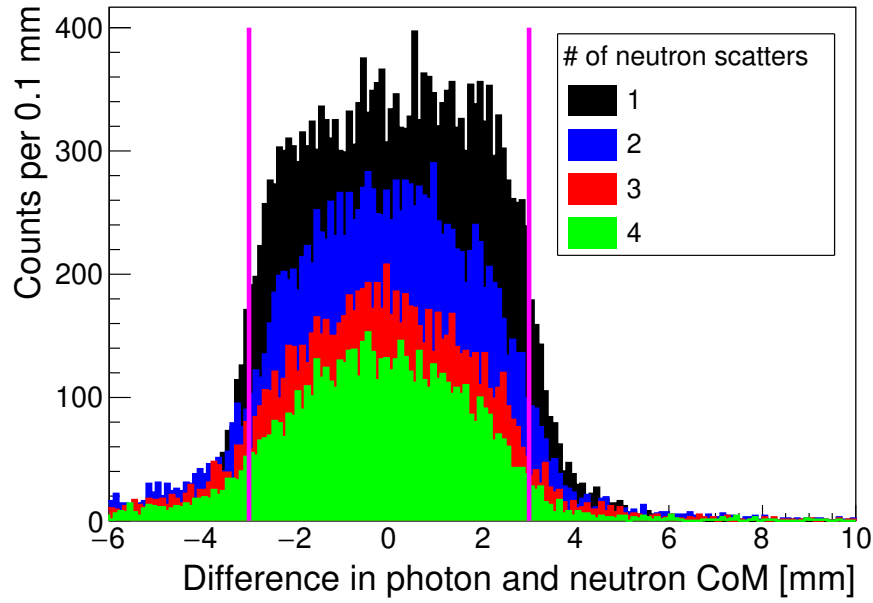


Figure 6.15: Differences between reconstructed photon center-of-mass scatter position and neutron center-of-mass position shown here for 1 (black), 2 (blue), 3 (red), and 4 (green) scatters of 1 MeV neutrons within the detector. The magenta lines represent the width of a single layer thickness. Events outside the lines would be considered improperly reconstructed.

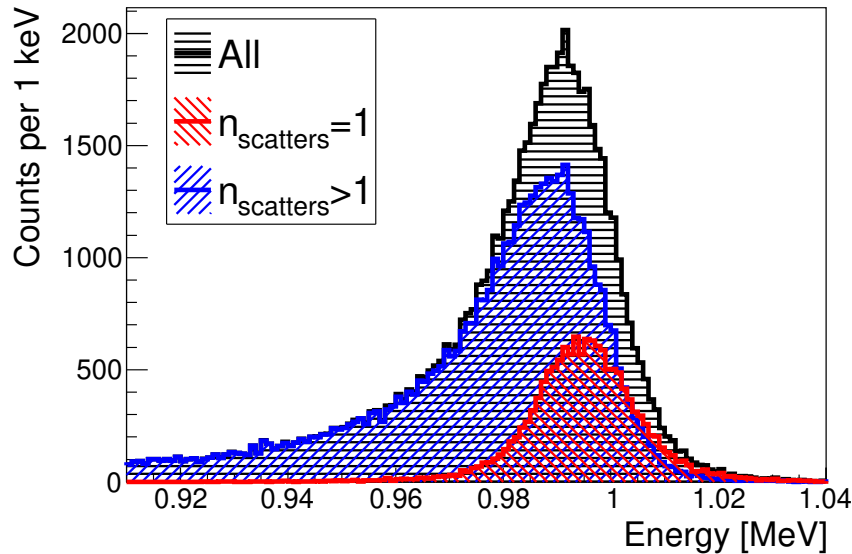


Figure 6.16: Calculated neutron energy distributions for simulated 1 MeV neutrons over a 75 cm flight path. TOF was calculated using the weighted average photon arrival time for each photosensor. All simulated events in which a neutron scattered at least once are shown in the black histogram with relative contributions from single- and multiple-scattering events shown in the red and blue histograms, respectively.

established to have ~ 500 ps TOF resolution for a single column, a proof-of-principle neutron energy measurement was made using a ^{252}Cf source. The source was placed ~ 44 cm from the front face of the prototype. The neutron yield, shown in Figure 6.18, was calculated using time-of-flight and high-resolution-position information. Using the PSD information shown in Figure 6.19, a cut was applied to select only neutron events. The data were fit with the Watt equation (red line in Figure 6.18) using fixed Mannhart parameters [69]. An additional multiplicative factor was also used to scale the fit to the data. The disagreement at low neutron energy with respect to the fit is likely due to a stringent detection threshold in simulated efficiency data which was folded with the Watt equation.

6.4.3 Neutron-gamma discrimination

The MAPMT single photon response is different than that of the fast timing PMTs used to initially test EJ-276 and is not uniform across all anodes in MAPMT. This response affects the overall pulse shape, potentially affecting PSD capabilities. PSD can only be calculated using the dynode signals as the four position signals lose n- γ information after passing through the resistive network. Figure 6.19 displays the prototype PSD capabilities using the CCM, the inset showing the PSD projection for the same energy cut (400-500 keVee) used in the single bar reflective-layer tests. In this energy window, the FoM is 1.08 ± 0.02 . The NEXT prototype does not show any noticeable effect on PSD due to segmentation or multi-anode readout.

6.5 Monoenergetic Neutron Tests

NEXT's defining characteristic is high-precision, position-dependent timing correlations. When neutrons pass through the segmented detector, there is a non-negligible amount of time taken to traverse the thickness of a single column. Therefore, TOF measurements for monoenergetic neutrons should correspond to the position within the detector the neutron interacted, i.e., the average TOF for each successive column should shift by the time it

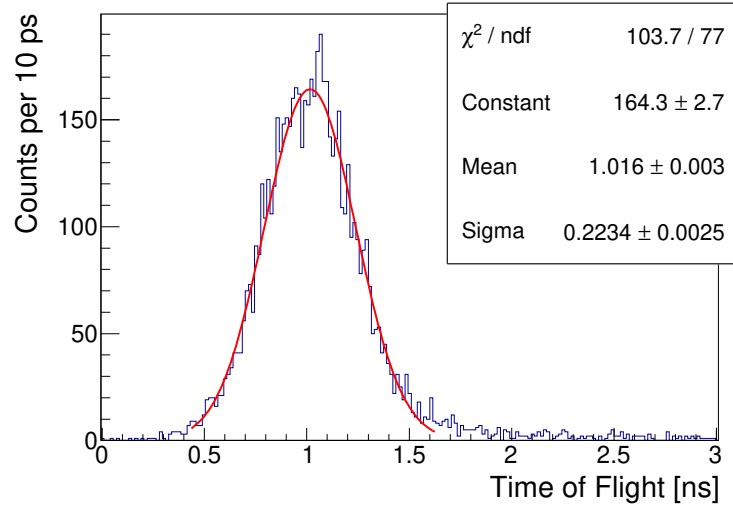


Figure 6.17: Time-of-flight resolution for a single NEXT prototype column (outlined in red in Figure 6.13) using a collimated ^{60}Co source at a flight distance of ~ 44 cm. The Gaussian fit to the distribution shows the time resolution is 525 ps (30 keVee threshold).

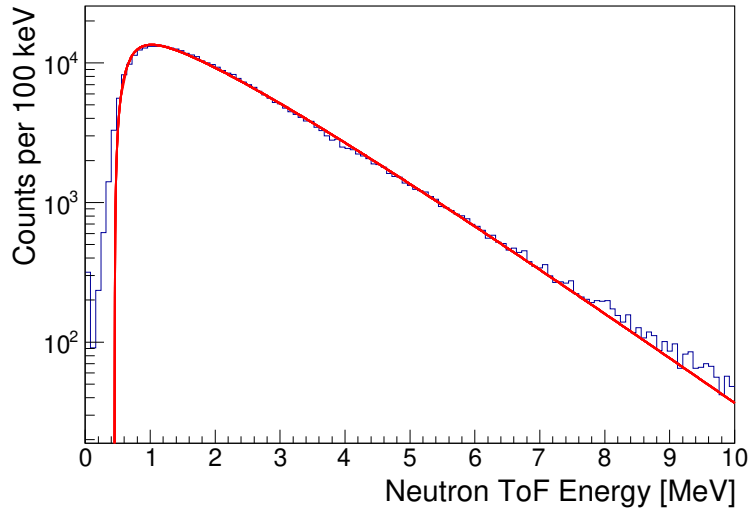


Figure 6.18: ^{252}Cf neutron energy spectrum as measured with the NEXT prototype using the segment-dependent analysis (blue). The red line shows the expected neutron yield with a 100 keVee detection threshold.

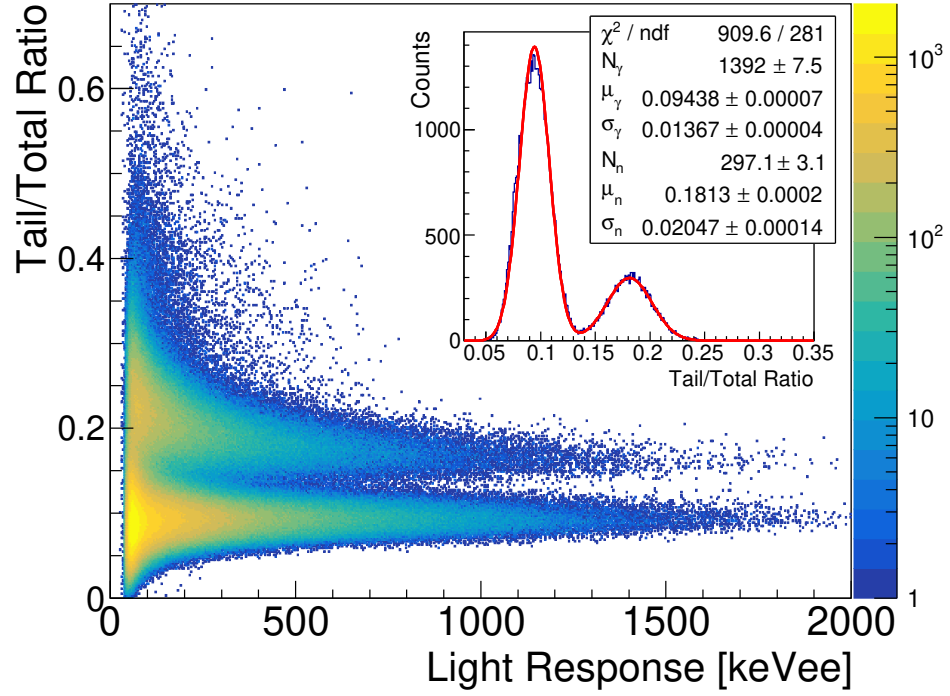


Figure 6.19: PSD from the common dynode signal of the PSPMT. The distribution has been corrected by adjusting the gamma-ray portion to have no linear dependence on light response. The inset shows the PSD projection in the light response range of 400-500 keVee. The FoM for this energy range is 1.08 ± 0.02 .

takes a neutron to traverse a single column thickness. In order to benchmark the timing-position correlation for the NEXT prototype, monoenergetic neutrons were measured at the University of Kentucky Accelerator Laboratory (UKAL).

6.5.1 Experimental Setup at UKAL

At UKAL, monoenergetic neutrons are generated with ${}^3\text{H}(p, n){}^3\text{He}$, ${}^2\text{H}(d, n){}^3\text{He}$, or ${}^3\text{H}(d, n){}^4\text{He}$ reactions. An in-depth overview which describes the neutron production and energy selection at UKAL can be found in Ref. [70]. The ${}^3\text{H}(p, n){}^3\text{He}$ reaction was used to generate neutrons with energies in the 0.25 to 1.5 MeV range, but only ~ 1 MeV neutrons will be discussed below as an example of NEXT’s position-dependent timing characteristics. Analysis at other energies were carried out by other graduate students working with NEXT.

NEXT was positioned behind stacked copper, polyethylene/lead, and paraffin/lithium carbonate collimators and aligned at 55° with respect to the proton beam direction, corresponding to 1.03(3) MeV neutrons. Neutron TOFs were measured as the difference between the HRT of the proton beam pickoff signal upstream of the tritium target and the average HRT of the dynode timing signals from the NEXT prototype. Specialized XIA LLC Pixie-16 firmware allowed the acquisition to be run in triple coincidence mode [3], requiring a start signal (proton beam pickoff) and two stop signals (left-right dynode timing signals) within a pre-determined coincidence window.

6.5.2 Simulating TOF propagation

Ideally, the shift in the mean of the TOF distributions for each successive column along the neutrons’ trajectory would be constant. A simulation replicating UKAL NEXT measurements was completed to provide an estimate of the detector response to ~ 1 MeV neutrons. 1.03 MeV neutrons in a cylinder beam with radius 25.4 mm were simulated along a 3.08 m flight path to the front of a NEXT prototype. Only 1.03 MeV neutrons were simulated because the neutron energy distribution of the NEXT UKAL setup has not been fully studied. Using the full NEXT*sim* capabilities (GEANT4 interactions and photosensor response), neutron TOFs from the simulation were calculated and the mean of each column’s

TOF distribution was plotted against the column number corresponding to the reconstructed photon CoM, as described in Section 6.4.1. In doing so, a position map similar to what is shown in Figure 6.13b can be made using simulated data and the same position criteria applied to experimental data can also be applied to the simulated data.

Figure 6.20 shows the expected prototype position-dependent timing behavior when detecting ~ 1 MeV neutrons. In order to plot the simulated data on the same scale as the experimental data shown in Figure 6.21, the data points have been shifted so that the TOF-axis offset of the first-order fit is zero. The same methods used to make cuts on the resistive network event positions in the experimental data were used to determine the column ID from optical photon center-of-mass calculations in the simulated data. The error bars on the data in Figure 6.20 are the statistical uncertainty in the mean for each column. 1.03 MeV neutrons traverse a single cell thickness (6 mm in simulations) in 0.429 ns based on neutron TOF calculations, represented by the dashed red line. The average shift in the mean TOF per column (δ_{TOF}) is equal to the slope of a first order polynomial fit to data. The first row in Table 6.1 shows the shift in TOF per column, $\delta_{TOF}=0.415$ ns, extracted from a linear fit to the simulated data.

δ_{TOF} from the simulated data agrees with the calculated δ_{TOF} within $\sim 3\%$, but the data are not well described with a linear fit. This deviation is largely due to neutron multiple-scattering effects. Events where a neutron scatters more than once in separate scintillator segments are more likely to have reconstructed positions in the inner segments. The TOF vs column relationship should be linear for all single-neutron-scatter events. This relationship becomes non-linear in multiple-scattering events at the inner segments due to the delayed arrival time of photons from subsequent scatters. In-depth NEXT_{sim} simulations will be used to correct for these effects in experimental data.

6.5.3 Experimental results

To demonstrate the feasibility of NEXT, analyses were completed for ~ 1 MeV neutrons detected in three different segmented NEXT prototypes: EJ276-10 (10-inch EJ-276 4×8 array), EJ276-05 (5-inch EJ-276 4×8 array) and EJ200-10 (10-inch EJ-200 4×8 array). For 1.03(3) MeV neutrons, the mean of the TOF distributions should shift by 0.429 ns for each

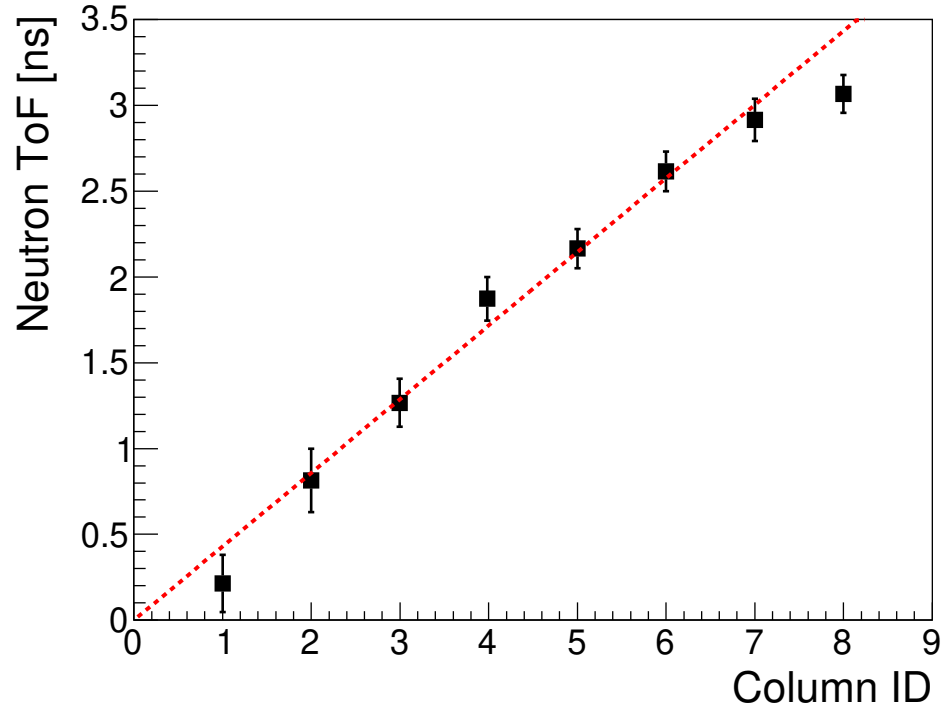


Figure 6.20: Mean TOFs for each segment from simulated 1.03 MeV neutrons, mimicking the UKAL experimental setup using the *NEXTsim* framework. The dashed red line shows the expected position dependence of the TOF measurements for 1.03 MeV neutrons. The error associated with each point is the statistical uncertainty in the mean of the Gaussian fit to the TOF distribution for each segment.

successive column. By making the appropriate position cuts, the mean TOF for each column was extracted using a Gaussian fit to 1.5σ width for the TOF distribution maximum. δ_{TOF} for each prototype was determined from a first-order polynomial fit to the average TOF vs. column ID data shown in Figure 6.21. To ensure the plot for each prototype lies on the same scale, each data set was shifted such that the TOF-axis offset of their respective first-order fit is zero.

The δ_{TOF} values from the fits for each prototype are shown in Table 6.1. Overall, each detector exhibited the expected position-dependent timing characteristics, with a clear shift in TOF measurements from column to column and a similar higher-order behavior over the linear fit also evident in the simulations. Future work with this detector will address more results from continued analysis on this data set as well as other TOF data acquired for different neutron energies.

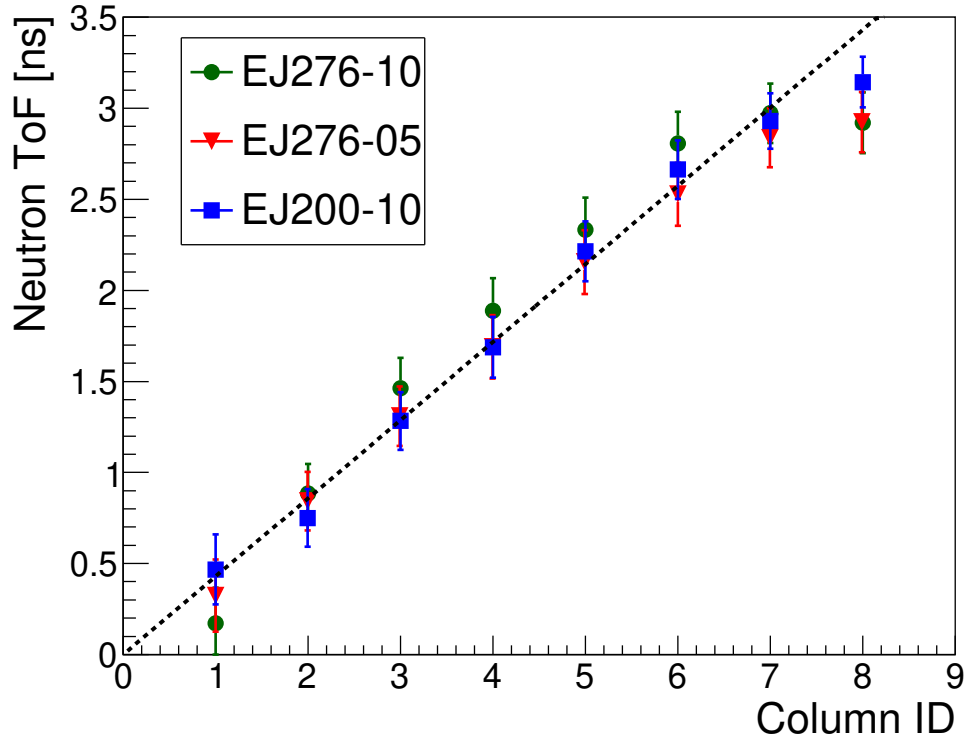


Figure 6.21: Plots showing the TOF shift per segment for each prototype: EJ276-10 (green), EJ276-05 (red), and EJ200-10 (blue). Data shown correspond to TOF measurements for ~ 1 MeV neutrons. The data have been shifted such that the TOF-axis offset of the linear fit to each data set is zero. Errors are calculated as the combined uncertainty of the statistical uncertainty in the mean and the timing variations between the four rows in a single column. The black dashed line represents the expected δ_{TOF} based on TOF calculations for 1.03 MeV neutrons.

Table 6.1: Slopes from first-order polynomial fits to simulated and experimental TOF data for 1.03(3) MeV neutrons, yielding δ_{TOF} in $[ns/col]$. Three different prototypes were used to collect data. The *NEXTsim* slope was calculated from a simulation of the EJ276-10 prototype. The slope uncertainties are given as the error in the fit.

Prototype	$\delta_{TOF} [ns/col]$
<i>NEXTSim</i>	0.415 ± 0.018
EJ276-10	0.439 ± 0.013
EJ276-05	0.402 ± 0.013
EJ200-10	0.424 ± 0.010

Chapter 7

Summary

The work presented in dissertation detailed a study of the underlying nuclear processes which occur during beta delayed neutron emission. Using neutron-gamma coincidence spectroscopy, an accurate level structure of neutron emitting states ^{134}Sn was made and compared with start of the art Shell Model calculations. The level densities from experimental data and Shell Model calculations did not provide a supporting case for the use of a Hauser-Feshbach statistical approach to predicting neutron emission branching ratios for this scenario. A new neutron emission model which involves the wavefunction overlap of ^{134}Sn states populated in ^{134}In beta decay with those which are considered neutron emitting was proposed. This model will continue to be adapted to test applicability to future measurements of ^{134}In beta delayed neutron emission and other nuclei as well.

A significant portion of the work outlined in this dissertation went towards the development of a new high resolution neutron detector. The prototyping phase was motivated by introducing novel technologies such as neutron-gamma discriminating plastic scintillator and position sensitive electronics while keeping the price per detector down in order to manufacture a full-scale detector array. When a NEXT prototype was finally developed, experiments were conducted to test the position-timing correlations of the detector. For ~ 1 MeV neutrons, NEXT was proven to have a strong position-timing correlation which would drastically improve neutron energy resolutions.

Although this dissertation only covers the development of NEXT up to the proof of principle tests, continued oversight and support was provided for the continued research using

the NEXT detector. Efficiency tests were run at University of Ohio's Edward Accelerator Laboratory using $^{27}\text{Al}(\text{d},\text{n})$ and $^9\text{Be}(\text{d},\text{n})$ reactions. Since then, two experiments have been run using an fully functional array of NEXT modules, one at Argonne National Lab observing ^{106}Nb βn emission, and the other at the National Superconducting Cyclotron Laboratory studying βn emitters near ^{29}F .

Bibliography

- [1] H. Ohm, W. Rudolph, and K.-L. Kratz. Beta-delayed neutron emission following the decay of ^{17}n . *Nuclear Physics A*, 274(1):45 – 52, 1976. [x](#), [10](#), [31](#), [34](#)
- [2] M.R. Mumpower, R. Surman, G.C. McLaughlin, and A. Aprahamian. The impact of individual nuclear properties on r-process nucleosynthesis. *Prog. Part. Nucl. Phys.*, 86:86–126, 2016. [xii](#), [13](#), [17](#), [19](#)
- [3] XIA LLC. *Pixie-16 Setup Guide for the VANDLE Detector System*, version 1.3 edition, Ferbruary 2016. [xii](#), [25](#), [27](#), [94](#)
- [4] Cory R. Thornsberry. *Proton Transfer Reactions Studied Using the Versatile Array of Neutron Detectors at Low Energy (VANDLE)*. PhD thesis, University of Tennessee, 2018. [xii](#), [xvi](#), [xvii](#), [27](#), [29](#), [70](#), [71](#), [77](#), [78](#), [117](#)
- [5] Glenn F. Knoll. *Radiation Detection and Measurement*. Wiley, fourth edition, 2010. [xvi](#), [72](#), [74](#), [116](#)
- [6] SensL, ON Semiconductor, Cork, Ireland. *J-Series User Manual*, December 2016. [xvii](#), [80](#), [82](#)
- [7] K. Heyde. *Basic Ideas and Concepts in Nuclear Physics*. Institute of Physics, third edition, 2004. [2](#)
- [8] K. Grotz & H.V. Klapdor. *The Weak Interaction in Nuclear, Particle and Astrophysics*. Adam Hilger, 1990. [3](#)
- [9] Maria Goeppert Mayer. On closed shells in nuclei. ii. *Phys. Rev.*, 75:1969–1970, Jun 1949. [4](#)
- [10] Maria Goeppert Mayer. Nuclear configurations in the spin-orbit coupling model. i. empirical evidence. *Phys. Rev.*, 78:16–21, Apr 1950.
- [11] Otto Haxel, J. Hans D. Jensen, and Hans E. Suess. On the ”magic numbers” in nuclear structure. *Phys. Rev.*, 75:1766–1766, Jun 1949. [4](#)
- [12] Maria Goeppert Mayer. The shell model (nobel lecture). 1963. [4](#)

- [13] Roger D. Woods and David S. Saxon. Diffuse surface optical model for nucleon-nuclei scattering. *Phys. Rev.*, 95:577–578, Jul 1954. [4](#)
- [14] K. L. Jones, A. S. Adekola, D. W. Bardayan, J. C. Blackmon, K. Y. Chae, K. A. Chipps, J. A. Cizewski, L. Erikson, C. Harlin, R. Hatarik, R. Kapler, R. L. Kozub, J. F. Liang, R. Livesay, Z. Ma, B. H. Moazen, C. D. Nesaraja, F. M. Nunes, S. D. Pain, N. P. Patterson, D. Shapira, J. F. Shriner, M. S. Smith, T. P. Swan, and J. S. Thomas. The magic nature of ^{132}Sn explored through the single-particle states of ^{133}Sn . *Nature*, 465:454–457, 2010. [4](#), [11](#)
- [15] Kohji Takahashi. Application of the Gross Theory of β -Decay to Delayed Neutron Emissions. *Progress of Theoretical Physics*, 47(5):1500–1516, 05 1972. [6](#)
- [16] T. Kawano, P. Möller, and & W.B. Wilson. Calculation of delayed-neutron energy spectra in a quasiparticle random-phase approximation-Hauser-Feshbach model. *Phys. Rev. C*, 78(054601), 2008. [6](#), [9](#), [15](#), [53](#), [57](#)
- [17] M.R. Mumpower, T. Kawano, and & P. Möller. Neutron- γ competition for β -delayed neutron emission. *Phys. Rev. C*, 94(064317), 2016.
- [18] R. Yokoyama, R. Grzywacz, B. C. Rasco, N. Brewer, K. P. Rykaczewski, I. Dillmann, J. L. Tain, S. Nishimura, D. S. Ahn, A. Algora, J. M. Allmond, J. Agramunt, H. Baba, S. Bae, C. G. Bruno, R. Caballero-Folch, F. Calvino, P. J. Coleman-Smith, G. Cortes, T. Davinson, C. Domingo-Pardo, A. Estrade, N. Fukuda, S. Go, C. J. Griffin, J. Ha, O. Hall, L. J. Harkness-Brennan, J. Heideman, T. Isobe, D. Kahl, M. Karny, T. Kawano, L. H. Khiem, T. T. King, G. G. Kiss, A. Korgul, S. Kubono, M. Labiche, I. Lazarus, J. Liang, J. Liu, G. Lorusso, M. Madurga, K. Matsui, K. Miernik, F. Montes, A. I. Morales, P. Morrall, N. Nepal, R. D. Page, V. H. Phong, M. Piersa, M. Prydderch, V. F. E. Pucknell, M. M. Rajabali, B. Rubio, Y. Saito, H. Sakurai, Y. Shimizu, J. Simpson, M. Singh, D. W. Stracener, T. Sumikama, R. Surman, H. Suzuki, H. Takeda, A. Tarifeño Saldivia, S. L. Thomas, A. Tolosa-Delgado, M. Wolińska Cichocka, P. J. Woods, and X. X. Xu. Strong one-neutron emission from two-neutron unbound states in β decays of the r -process nuclei $^{86,87}\text{Ga}$. *Phys. Rev. C*, 100:031302, Sep 2019. [6](#), [9](#)

- [19] Walter Hauser and Herman Feshbach. The inelastic scattering of neutrons. *Phys. Rev.*, 87:366–373, Jul 1952. [8](#)
- [20] L. Wolfenstein. Conservation of angular momentum in the statistical theory of nuclear reactions. *Phys. Rev.*, 82:690–696, Jun 1951. [8](#)
- [21] Weisskopf V.F. *The Statistical Theory of Nuclear Reactions*, pages 80–114. U. S. Govt. Print. Off., Washington, 1947. [8](#)
- [22] K.-L. Kratz, W. Rudolph, H. Ohm, H. Franz, M. Zendel, G. Herrmann, S.G. Prussin, F.M. Nuh, A.A. Shihab-Eldin, D.R. Slaughter, W. Halverson, and H.V. Klapdor. Investigation of beta strength functions by neutron and gamma-ray spectroscopy: (i). the decay of ^{87}Br , ^{137}I , ^{85}As and ^{135}Sb . *Nuclear Physics A*, 317(2):335 – 362, 1979. [9](#)
- [23] P. Tidemand-Petersson, R. Kirchner, O. Klepper, E. Roeckl, D. Schardt, A. Pochocki, and J. ylicz. β -delayed particle emission from neutron-deficient Te , I , Xe , Cs and Ba isotopes. *Nuclear Physics A*, 437(2):342 – 366, 1985. [9](#)
- [24] R. E. Azuma, L. C. Carraz, P. G. Hansen, B. Jonson, K. L. Kratz, S. Mattsson, G. Nyman, H. Ohm, H. L. Ravn, A. Schröder, and W. Ziegert. First observation of beta-delayed two-neutron radioactivity: ^{11}Li . *Phys. Rev. Lett.*, 43:1652–1654, Nov 1979. [10](#)
- [25] P. Hoff, P. Baumann, A. Huck, A. Knipper, G. Walter, G. Marguier, B. Fogelberg, A. Lindroth, H. Mach, M. Sanchez-Vega, R. B. E. Taylor, P. Van Duppen, A. Jokinen, M. Lindroos, M. Ramdhane, W. Kurcewicz, B. Jonson, G. Nyman, Y. Jading, K.-L. Kratz, A. Wöhr, G. Løvholden, T. F. Thorsteinsen, and J. Blomqvist. Single-neutron states in ^{133}Sn . *Phys. Rev. Lett.*, 77:1020–1023, Aug 1996. [10](#), [11](#), [44](#)
- [26] M. Madurga and R. Grzywacz. Neutron unbound single particle states in ^{133}Sn from the beta decay of ^{133}In , Oct 2016. [13](#), [24](#)
- [27] R. Grzywacz and M. Madurga. Beta delayed neutron emission from ^{134}In to neutron single particle states in ^{133}Sn , Oct 2017. [13](#)

- [28] A. Tolosa-Delgado, J. Agramunt, J.L. Tain, A. Algora, C. Domingo-Pardo, A.I. Morales, B. Rubio, A. Tarifeo-Saldivia, F. Calvio, G. Cortes, N.T. Brewer, B.C. Rasco, K.P. Rykaczewski, D.W. Stracener, J.M. Allmond, R. Grzywacz, R. Yokoyama, M. Singh, T. King, M. Madurga, S. Nishimura, V.H. Phong, S. Go, J. Liu, K. Matsui, H. Sakurai, G.G. Kiss, T. Isobe, H. Baba, S. Kubono, N. Fukuda, D.S. Ahn, Y. Shimizu, T. Sumikama, H. Suzuki, H. Takeda, P.A. Sderstrm, M. Takechi, C.G. Bruno, T. Davinson, C.J. Griffin, O. Hall, D. Kahl, P.J. Woods, P.J. Coleman-Smith, M. Labiche, I. Lazarus, P. Morrall, V.F. E. Pucknell, J. Simpson, S.L. Thomas, M. Prydderch, L.J. Harkness-Brennan, R.D. Page, I. Dillmann, R. Caballero-Folch, Y. Saito, A. Estrade, N. Nepal, F. Montes, G. Lorusso, J. Liang, S. Bae, J. Ha, and B. Moon. Commissioning of the broken detector for the measurement of very exotic - delayed neutron emitters. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 925:133 – 147, 2019. [17](#)
- [29] B.A. Marsh. Resonance ionization laser ion sources for on-line isotope separators. *Review of Scientific Instruments*, 85(02B923), 2014. [20](#)
- [30] Nigel Warr. HIE-ISOLDE, June 2016. [21](#)
- [31] W. A. Peters, S. Ilyushkin, M. Madurga, C. Matei, S. V. Paulauskas, R. K. Grzywacz, D. W. Bardayan, C. R. Brune, J. Allen, J. M. Allen, Z. Bergstrom, J. Blackmon, N. T. Brewer, J. A. Cizewski, P. Copp, M. E. Howard, R. Ikeyama, R. L. Kozub, B. Manning, T. N. Massey, M. Matos, E. Merino, P. D. O’Malley, F. Raiola, C. S. Reingold, F. Sarazin, I. Spassova, S. Taylor, and D. Walter. Performance of the Versatile Array of Neutron Detectors at Low Energy (VANDLE). *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 836:122–133, 2016. [24](#), [68](#), [69](#), [70](#), [79](#)
- [32] S. V. Paulauskas, M. Madurga, R. Grzywacz, D. Miller, S. Padgett, and H. Tan. A digital data acquisition framework for the Versatile Array of Neutron Detectors at Low

- Energy (VANDLE). *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 737:22–28, 2014. [25](#)
- [33] L.C. Carraz, P.G. Hansen, A. Huck, B. Jonson, G. Klotz, A. Knipper, K.L. Kratz, C. Miéhé, S. Mattsson, G. Nyman, H. Ohm, M. Poskanzer, A. Poves, H.L. Ravn, C. Richard-Serre, A. Schröder, G. Walter, and W. Ziegert. The 49k beta decay. *Physics Letters B*, 109(6):419–422, 1982. [35](#), [41](#)
- [34] Richard Madey, Frank M. Waterman, Alan R. Baldwin, James N. Knudson, J.D. Carlson, and J. Rapaport. The response of ne-228a, ne-228, ne-224, and ne-102 scintillators to protons from 2.43 to 19.55 mev. *Nuclear Instruments and Methods*, 151(3):445–450, 1978. [41](#)
- [35] R.A. Cecil, B.D. Anderson, and R. Madey. Improved predictions of neutron detection efficiency for hydrocarbon scintillators from 1 mev to about 300 mev. *Nuclear Instruments and Methods*, 161(3):439–447, 1979. [41](#)
- [36] Miloslava Baginova, Pavol Vojtyla, and Pavel P. Povinec. Investigation of neutron interactions with ge detectors. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 897:22 – 31, 2018. [44](#)
- [37] Noritaka Shimizu, Takahiro Mizusaki, Yutaka Utsuno, and Yusuke Tsunoda. Thick-restart block Lanczos method for large-scale shell-model calculations. *Computer Physics Communications*, 244:372–384, 2019. [51](#)
- [38] C. Yuan and Zhengyu Xu. Private Correspondence. 2019. [51](#)
- [39] Zhengyu Xu et al. To be submitted. 2020. [51](#)
- [40] Sota Yoshida, Yutaka Utsuno, Noritaka Shimizu, and Takaharu Otsuka. Systematic shell-model study of β -decay properties and gamow-teller strength distributions in $a \approx 40$ neutron-rich nuclei. *Phys. Rev. C*, 97:054321, May 2018. [53](#)

- [41] Shin Okumura, Toshihiko Kawano, Patrick Jaffke, Patrick Talou, and Satoshi Chiba. $^{235}\text{U}(n,f)$ Independent fission product yield and isomeric ratio calculated with the statistical Hauser-Feshbach theory. *Journal of Nuclear Science and Technology*, 55(9):1009–1023, 2018. [53](#)
- [42] B.A. Brown and W.D.M. Rae. The shell-model code nushellx@msu. *Nuclear Data Sheets*, 120:115 – 118, 2014. [60](#)
- [43] J.C. Hardy, B. Jonson, and P.G. Hansen. The essential decay of pandemonium: β -delayed neutrons. *Nuclear Physics A*, 305(1):15 – 28, 1978. [60](#)
- [44] S.G. Prussin, Z.M. Oliveira, and K.-L. Kratz. Does the simple statistical model describe delayed neutron emission?: The cases of ^{85}as , ^{87}br , ^{135}sb and ^{137}i . *Nuclear Physics A*, 321(2):396 – 414, 1979. [60](#)
- [45] Robert Grzywacz. Private Correspondence. 2020. [62](#)
- [46] Angelo Signoracci. Introduction to NUSHELLX and transitions. 2012. [62](#)
- [47] B. Alex Brown. Lecture Notes in Nuclear Structure Physics. 2017. [62](#)
- [48] H. Feshbach, A.K. Kerman, and R.H. Lemmer. Intermediate structure and doorway states in nuclear reactions. *Annals of Physics*, 41(2):230 – 286, 1967. [62](#)
- [49] N. Auerbach and V. Zelevinsky. Doorway states in nuclear reactions as a manifestation of the super-radiant mechanism. *Nuclear Physics A*, 781(1):67 – 80, 2007. [62](#)
- [50] A.J. Koning and J.P. Delaroche. Local and global nucleon optical models from 1 kev to 200 mev. *Nuclear Physics A*, 713(3):231 – 310, 2003. [62](#)
- [51] R. Harkewicz, D. J. Morrissey, B. A. Brown, J. A. Nolen, N. A. Orr, B. M. Sherrill, J. S. Winfield, and J. A. Winger. β -decay branching ratios of the neutron-rich nucleus ^{15}B . *Phys. Rev. C*, 44:2365–2371, Dec 1991. [68](#), [69](#)
- [52] A Buță, T Martin, C Timiș, N Achouri, J.C Angélique, C Borcea, I Cruceru, A Genoux-Lubain, S Grévy, M Lewitowicz, E Liénard, F.M Marqués, F Negoită, F de Oliveira,

- N. A Orr, J Péter, and M Sandu. TONNERRE: an array for delayed-neutron decay spectroscopy. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 455(2):412–423, 2000. 68, 69
- [53] Eljen Technology. Plastic Scintillators, 2016. 70, 79, 116
- [54] Natalia Zaitseva, Benjamin Rupert, Iwona Pawelczak, Andrew Glenn, H Paul Martinez, Leslie Carman, Michelle Faust, Nerine Cherepy, and Stephen Payne. Plastic scintillators with efficient neutron/gamma pulse shape discrimination. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 668:88–93, 03 2012. 70
- [55] N. P. Zaitseva, A. M. Glenn, A. N. Mabe, M. L. Carman, C. R. Hurlbut, J. W. Inman, and S. A. Payne. Recent developments in plastic scintillators with pulse shape discrimination. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 889:97–104, 2018. 70
- [56] Eljen Technology. *Eljen 276 Data Sheet*, October 2017. 70
- [57] R. Lica. Beta-decay spectroscopy at the isotope decay station. http://isolde-ids.web.cern.ch/isolde-ids/doc/RLica_ISOLDE.pdf, 2016. 70
- [58] G. Ranucci. An analytical approach to the evaluation of the pulse shape discrimination properties of scintillators. *Nucl. Inst. Meth. A*, 354:389–399, 1995. 72
- [59] H. O. Anger. Scintillation camera with multichannel collimators. *J. Nucl. Med.*, 5:515–531, 1964. 73, 83
- [60] S. Agostinelli, J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, D. Axen, S. Banerjee, G. Barrand, F. Behner, L. Bellagamba, J. Boudreau, L. Broglia, A. Brunengo, H. Burkhardt, S. Chauvie, J. Chuma, R. Chytrcek, G. Cooperman, G. Cosmo, P. Degtyarenko, A. Dell’Acqua, G. Depaola, D. Dietrich, R. Enami,

A. Feliciello, C. Ferguson, H. Fesefeldt, G. Folger, F. Foppiano, A. Forti, S. Garelli, S. Giani, R. Giannitrapani, D. Gibin, J.J. Gómez-Cadenas, I. González, G. Gracia Abril, G. Greeniaus, W. Greiner, V. Grichine, A. Grossheim, S. Guatelli, P. Gumplinger, R. Hamatsu, K. Hashimoto, H. Hasui, A. Heikkinen, A. Howard, V. Ivanchenko, A. Johnson, F.W. Jones, J. Kallenbach, N. Kanaya, M. Kawabata, Y. Kawabata, M. Kawaguti, S. Kelner, P. Kent, A. Kimura, T. Kodama, R. Kokoulin, M. Kossov, H. Kurashige, E. Lamanna, T. Lampén, V. Lara, V. Lefebure, F. Lei, M. Liendl, W. Lockman, F. Longo, S. Magni, M. Maire, E. Medernach, K. Minamimoto, P. Mora de Freitas, Y. Morita, K. Murakami, M. Nagamatu, R. Nartallo, P. Nieminen, T. Nishimura, K. Ohtsubo, M. Okamura, S. O’Neale, Y. Oohata, K. Paech, J. Perl, A. Pfeiffer, M.G. Pia, F. Ranjard, A. Rybin, S. Sadilov, E. Di Salvo, G. Santin, T. Sasaki, N. Savvas, Y. Sawada, S. Scherer, S. Sei, V. Sirotenko, D. Smith, N. Starkov, H. Stoecker, J. Sulkimo, M. Takahata, S. Tanaka, E. Tcherniaev, E. Safai Tehrani, M. Tropeano, P. Truscott, H. Uno, L. Urban, P. Urban, M. Verderi, A. Walkden, W. Wander, H. Weber, J.P. Wellisch, T. Wenaus, D.C. Williams, D. Wright, T. Yamada, H. Yoshida, and D. Zschiesche. Geant4—a simulation toolkit. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 506(3):250–303, 2003. [73](#)

- [61] J. Allison, K. Amako, J. Apostolakis, P. Arce, M. Asai, T. Aso, E. Bagli, A. Bagulya, S. Banerjee, G. Barrand, B. R. Beck, A. G. Bogdanov, D. Brandt, J. M. C. Brown, H. Burkhardt, Ph. Canal, D. Cano-Ott, S. Chauvie, K. Cho, G. A. P. Cirrone, G. Cooperman, M. A. Cortés-Giraldo, G. Cosmo, G. Cuttone, G. Depaola, L. Desorgher, X. Dong, A. Dotti, V. D. Elvira, G. Folger, Z. Francis, A. Galoyan, L. Garnier, M. Gayer, K. L. Genser, V. M. Grichine, S. Guatelli, P. Guèye, P. Gumplinger, A. S. Howard, I. Hřivnáčová, S. Hwang, S. Incerti, A. Ivanchenko, V. N. Ivanchenko, F. W. Jones, S. Y. Jun, P. Kaitaniemi, N. Karakatsanis, M. Karamitros, M. Kelsey, A. Kimura, T. Koi, H. Kurashige, A. Lechner, S. B. Lee, F. Longo, M. Maire, D. Mancusi, A. Mantero, E. Mendoza, B. Morgan, K. Murakami, T. Nikitina, L. Pandola, P. Paprocki, J. Perl, I. Petrović, M. G. Pia, W. Pokorski, J. M. Quesada, M. Raine, M. A. Reis, A. Ribon,

- A. Ristić Fira, F. Romano, G. Russo, G. Santin, T. Sasaki, D. Sawkey, J. I. Shin, I. I. Strakovsky, A. Taborda, S. Tanaka, B. Tomé, T. Toshito, H. N. Tran, P. R. Truscott, L. Urban, V. Uzhinsky, J. M. Verbeke, M. Verderi, B. L. Wendt, H. Wenzel, D. H. Wright, D. M. Wright, T. Yamashita, J. Yarba, and H. Yoshida. Recent developments in Geant4. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 835:186–225, 2016. [73](#)
- [62] I. Antcheva, M. Ballintijn, B. Bellenot, M. Biskup, R. Brun, N. Buncic, Ph. Canal, D. Casadei, O. Couet, V. Fine, L. Franco, G. Ganis, A. Gheata, D. Gonzalez Maline, M. Goto, J. Iwaszkiewicz, A. Kreshuk, D. Marcos Segura, R. Maunder, L. Moneta, A. Naumann, E. Offermann, V. Onuchin, S. Panacek, F. Rademakers, P. Russo, and M. Tadel. ROOT—A C++ framework for petabyte data storage, statistical analysis and visualization. *Computer Physics Communications*, 180(12):2499–2512, 2009. 40 YEARS OF CPC: A celebratory issue focused on quality software for high performance, grid and novel computing architectures. [73](#)
- [63] John Apostolakis, Gunter Folger, Vladimir Grichine, Aatos Heikkinen, Alexander Howard, Vladimir Ivanchenko, Pekka Kaitaniemi, Tatsumi Koi, Mikhail Kosov, Jose Manuel Quesada, Alberto Ribon, Vladimir Uzhinskiy, and Dennis Wright. Progress in hadronic physics modelling in Geant4. *Journal of Physics: Conference Series*, 160(1):012073, 2009. [73](#)
- [64] V. V. Verbinski, W. R. Burrus, T. A. Love, W. Zobel, N. W. Hill, and R. Textor. Calibration of an organic scintillator for neutron spectrometry. *Nuclear Instruments and Methods*, 65(1):8–25, 1968. [73](#)
- [65] Woon-Seng Choong. The timing resolution of scintillation-detector systems: Monte Carlo analysis. *Phys. Med. Biol.*, 54(21):6495, 2009. [77](#)
- [66] XIA LLC. Nuclear Spectroscopy Products, 2020. [80](#)
- [67] Vincent Palermo, Vertilon Coportation. Private Correspondence. 2019. [81](#)
- [68] Vertilon Corporation. *SIB064B-1018 User Guide*, July 2018. [83](#)

- [69] W. Mannhart. Status of the Cf-252 fission neutron spectrum evaluation with regard to recent experiments. In *INDC(NDS) 220*, pages 305–336. International Atomic Energy Agency (IAEA), 1989. [91](#)
- [70] J. Hartman, A. Barzilov, E. E. Peters, and S. W. Yates. Measurements of response functions of EJ-299-33A plastic scintillator for fast neutrons. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 804:137–143, 2015. [94](#)

Appendices

A Summary of Analytical Neutron Response

In order to properly deconvolve a neutron time of flight spectrum, detailed simulations are required to reproduce the characteristic detector response to monoenergetic neutrons in the experiment environment. Neutrons readily scatter off material in an experiment hall and depending of the atomic composition of this material, the change in velocity of the neutron can either relatively small or can so large that the neutron is effectively stopped. The shape of the neutron response at a given energy is not only dependent on the atomic mass of the material in the room, but also the relative positioning with respect to the neutron detector. In the ^{134}In beta delayed neutron emission experiment, most of the other detector subsystems were directly opposite the neutron detector wall. From Geant4 simulations of the experiment setup, it was determined that the long tail in neutron time of flight seen in Figure 4.6 occurs because of the low A material directly opposite the detector. By characterizing the neutron response at different energies, the underlying long TOF behavior of higher energy neutrons can be properly accounted for as background under lower energy neutrons. The piecewise functional form fit to the simulated responses is

$$\frac{1}{A} \cdot f(t) = \begin{cases} \frac{1}{A} \cdot \left[\frac{\sigma_0^2}{(t-t_0)^2 + \sigma_0^2} (a_0 + 1) - a_0 \right], & -\frac{1}{\sqrt{a_0}} \leq \frac{t-t_0}{\sigma_0} \leq 0 \\ \frac{1}{A} \cdot \frac{\sigma_1^2}{(t-t_0)^2 + \sigma_1^2}, & 0 < \frac{t-t_0}{\sigma_1} \leq k_1 + d_1 \\ \frac{1}{A} \cdot b_1 \exp(-k_1 \frac{t-t_0}{\sigma_1}), & k_1 + d_1 < \frac{t-t_0}{\sigma_1} \leq k_2 + d_2 \\ \frac{1}{A} \cdot b_2 \exp(-k_2 \frac{t-t_0}{\sigma_1}), & k_2 + d_2 < \frac{t-t_0}{\sigma_1} \leq k_3 + d_3 \\ \frac{1}{A} \cdot b_3 \exp(-k_3 \frac{t-t_0}{\sigma_1}), & \frac{t-t_0}{\sigma_1} > k_3 + d_3 \end{cases} \quad (1)$$

with

$$b_1 = \frac{\exp[k_1(k_1 + d_1)]}{1 + (k_1 + d_1)^2},$$

$$b_2 = \frac{\exp[k_1(k_1 + d_1) - (k_1 - k_2)(k_2 + d_2)]}{1 + (k_1 + d_1)^2},$$

$$b_3 = \frac{\exp[k_1(k_1 + d_1) - (k_1 - k_2)(k_2 + d_2) - (k_2 - k_3)(k_3 + d_3)]}{1 + (k_1 + d_1)^2}.$$

By defining the scaling parameters b_1 , b_2 , and b_3 above, the function is guaranteed to be continuous at each boundary. The normalization parameter, A , is the sum of the integrals for each piecewise portion of the function within their respective boundaries.

For the neutron energies listed in Section 4.2.2, the first neutron response fit was for 200 keV neutrons. Initial values of the parameters were adjusted by hand until the response curve best represented the total neutron response of the 200 keV neutrons. Once the first neutron response was fit, the subsequent peaks were fit iteratively in order of increasing energy using the parameter values from the final fit of the previous energy. For a given parameter, the value at given energy was plotted against the corresponding time of flight for that energy. The graph for each parameter was fit with various polynomial of which the best fit was chosen. The results can be seen below in Equation 2. This parameters space was later adjusted by scaling different parameters and increasing the width of the main peak Lorentzian to best match the ^{49}K neutron time of flight spectrum. The adjustments that were made are given in Equation 3. Once the parameter space was finalized, the ^{134}In was deconvolved.

A.1 Response Parameter Space

Parameter Space

$$\begin{aligned}a_0 &= 0.1667 + (-0.00141) \times t_0 + (5.27E - 6) \times t_0^2 \\ \sigma_0 &= 0.2594 + (0.000699) \times t_0 + 0.000202 \times t_0^2 \\ \sigma_1 &= -0.139 + 0.0242 \times t_0 \\ k_1 &= 0.1819 - 0.000118 \times t_0 + (8.215E - 6) \times t_0^2 \\ d_1 &= 75.41 / (t_0 + 17.70) + 1.878 \\ k_2 &= 0.0162 - (4.797E - 5) \times t_0 + (1.887E - 6) \times t_0^2 \\ d_2 &= 8.684 + 0.1331 \times t_0 - (3.685E - 4) \times t_0^2 \\ k_3 &= 0.00335 + (2.108E - 4) \times t_0 - (6.485E - 7) \times t_0^2 \\ d_3 &= 320.057 - 2.324 \times t_0 + 0.00441 \times t_0^2\end{aligned}\tag{2}$$

Parameter Adjustments

$$\begin{aligned}\sigma_E &= 0.9E - 5 \times (14.18 \times t_0^2 - 166.3 \times t_0 + 68135.9); \\ \sigma_0 &= 1. \times \text{sqrt}(\sigma_0 \times \sigma_0 + 0.75 \times \sigma_E \times \sigma_E) \\ \sigma_1 &= 1. \times \text{sqrt}(\sigma_1 \times \sigma_1 + 1. \times \sigma_E \times \sigma_E) \\ k_1 &= 0.4 * k_1 \\ d_1 &= 0.8 * d_1 \\ k_2 &= 1.5 * k_2 \\ d_2 &= 2.1 * d_2\end{aligned}\tag{3}$$

B Neutron Time of Flight Method

Commonly used neutron detection devices, such as ^3He , use neutron capture to detect neutrons. This process has a high efficiency but requires thermalized neutrons, meaning that little to no initial energy information can be determined. An alternate form of detection is through scintillation, namely particle scattering to induce scintillated light from excited molecules. Neutrons incident on the plastic scintillator scatter off protons in the molecular structure. The recoil energy of the protons is then transformed into scintillation via excitation of the atoms in the scintillator [5]. This visible light is detected by light sensitive detectors, photomultiplier tubes or silicon photomultipliers.

Neutrons don't necessarily deposit all of their energy in the plastic scintillator through one interaction. The amount of plastic scintillator needed to fully capture the neutron energy would be excessive and make it nearly impossible to design a modular detector. Instead, plastic scintillators are optimized for fast timing. Plastic scintillators have very fast signal rise and decay times, e.g. Eljen 200 (rise $\sim$ 2ns & decay $\sim$ 30ns) [53]. Neutron energies can then be measured via precise timing measurements. Due to the large neutron mass, beta delayed neutrons emitted from nuclei can be treated classically. Neutron kinetic energies are commonly calculated from time-of-flight (TOF) measurement, given below:

$$E_{TOF} = \frac{1}{2}mv^2 = \frac{1}{2} (939.6\text{MeV}/c^2) \left(\frac{\frac{L}{ToF}}{c} \right)^2 \quad (4)$$

The uncertainty in neutron energy measurements are dependent on the flight path distance and time of flight uncertainties for the neutron. The two sections below will cover how each uncertainty manifests itself in a time of flight detector setup.

B.1 High Resolution Timing

Fast digitizers are extremely useful for experimental setups that require complex analysis of many signals at the same time, while maintaining a modular approach that can be applied to numerous experimental designs. There has been an increase in the availability and performance of fast digitizers due their increasing popularity and numerous applications.

The digitizers used by the UTK Low Energy Nuclear Physics group are produced by XIA LLC. and come in 100 MHz, 250 MHz, and 500 MHz sampling rates. 250 MHz digitizers were used for the ^{134}In beta decay experiment and are currently used in the testing and development of the NEXT detector. The signals are sampled every 4 ns and are converted to integer values by an Analog to Digital Converter (ADC). The digitized signal is passed to a Field Programmable Gate Array (FPGA) that handles the event triggering and coincidence requirements. When a channel (or certain combination of channels) crosses the trigger threshold, the digitized signals are processed by a digital signal processor (DSP) which tags the event with the appropriate information (timestamp, integral, amplitude, etc.). This information is then written in an event buffer and is read by an acquisition computer. These traces are then unpacked for later analysis to perform high resolution timing measurements, energy measurements, and other trace analysis.

The primary use of these signals in the time of flight setup is to extract the time difference between a start and stop signal. However, if the raw time signal from the digitized signal is used, then the timing resolution would only be 4 ns. In order to determine a more precise timing, a digital polynomial constant fraction discriminator (PolyCFD) was developed [4] to calculate a higher precision time measurement. A longer explanation of the PolyCFD can be found in Ref. [4], but the fundamentals will be explained here. The digitized signal trace is fit with a third order polynomial 4 to 5 bins around the maximum in order to approximate the actual maximum of the original analog signal. The average baseline before the signal pulse is subtracted from the maximum of the third order fit to calculate the amplitude. The timing threshold is set as the CFD threshold of the signal amplitude. A first order polynomial is fit between the two points surrounding the threshold and the threshold crossing point is set as the phase of the trace. The high resolution timestamp is set as the Pixie16 timestamp plus the phase.

Figure 1 shows graphically how the trace is analyzed with the green line representing the third order fit to find the maximum, the magenta line representing the first order fit around the threshold, and the red and blue lines representing the phase and threshold crossings.

B.2 Energy Resolution

The energy resolution of a time of flight calculation is dependent on the uncertainty in the distance traveled, L , and the time of travel, ToF . The formula for calculating the energy resolution is given below:

$$\left(\frac{\Delta E}{E}\right)^2 = \left(\frac{2\Delta(ToF)}{ToF}\right)^2 + \left(\frac{2\Delta L}{L}\right)^2 \quad (5)$$

The goal of NEXT is to reduce both the uncertainties in L and ToF in order to improve the resolution. The time of flight uncertainty will be decreased by improving digital high resolution timing methods and the localization uncertainty will be reduced by segmenting the detector into thinner interaction planes.

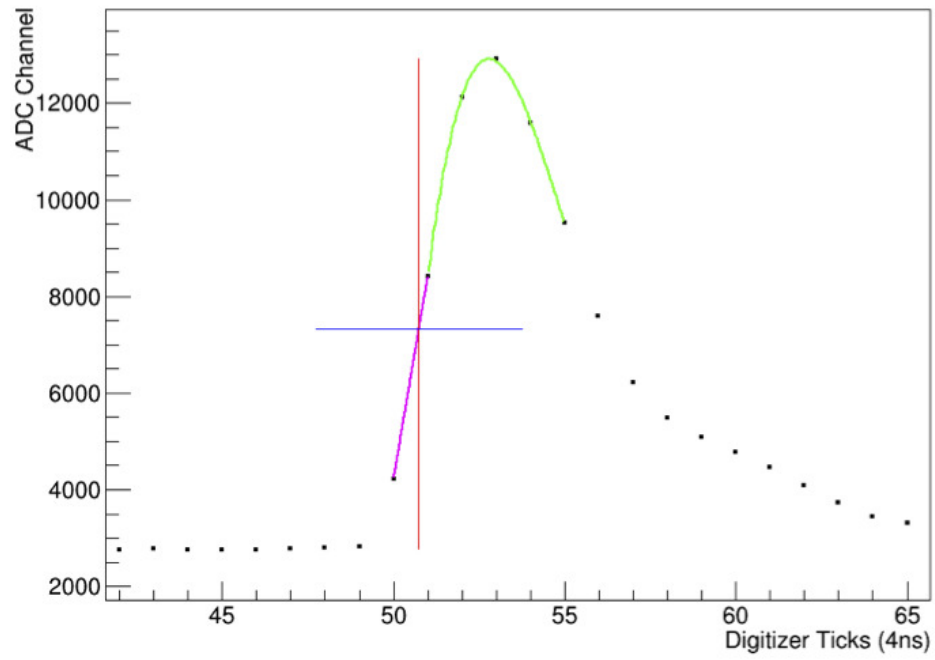


Figure 1: Graphical representation of the PolyCFD method to extract the phase of a trace for higher precision timing measurements.

Vita

Joseph Heideman was born in Montgomery, AL on December 5, 1991. At age 9, his family moved to Charlotte, NC when his father was relocated for his job. Growing up with a passion for sports and tinkering, Joseph began high school in 2006 and joined Auto-Tech and the school's lacrosse team. It was his junior year of high school when he took his first physics class and instantly fell in love. After taking physics courses the last two years of high school, Joseph was accepted to the University of North Carolina at Chapel Hill and declared a Physics major before classes even began. Beginning at the end of his sophomore year, Joseph joined the Medium Energy Physics group at TUNL/Duke University where he first learned computer programming and worked with particle detectors. It was also about this time he met his future wife, Julie, at UNC through their on-campus ministry. Upon receiving his Bachelor of Science in Physics, Joseph began graduate school the following fall at the University of Tennessee Knoxville. After initially joining the High Energy Physics Group at UTK, Joseph switched to Dr. Robert Grzywacz's Low Energy Nuclear Physics group in the fall of 2017 where he began the work outlined in this dissertation.

Joseph and Julie were married in Asheville, NC in June 2016 and welcomed the first family dog, Maple, less than 6 months later. As a family, they thoroughly enjoy spending their time boating the numerous bodies of water surrounding Knoxville and traveling to see extended family in the surrounding southeastern United States. When Joe manages to sneak away by himself, he spends the weekend mornings fishing and playing music with fellow UTK physics graduate students.