

Total Absorption Spectroscopy of Neutron Rich Nuclei Across the N=50 Neutron Shell Closure

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Degree

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To Miguel, your love and support mean the world to me.

I, who erewhile the happy Garden sung
By one mans disobedience lost, now sing
Recovered Paradise to all mankind,
By one mans firm obedience fully tried
Through all temptation, and the Tempter foiled
In all his wiles, defeated and repulsed,
And Eden raised in the waste Wilderness.

Paradise Regain'd, Book One

John Milton

Abstract

Decay spectroscopy of neutron rich nuclei near doubly magic ^{78}Ni [78-Nickel] is relevant to nuclear structure and astrophysics as well as reactor and neutrino physics. β -decay [beta-decay] calorimetry studies are essential to reconstruct the decay strength function and is used to overcome the problems arising from the high density of states leading to nuclear Pandemonium. The Modular Total Absorption Spectrometer, currently located in HRIBF at the Oak Ridge National Laboratory, collected data on 25 fission products of ^{238}U [238-Uranium] during a run in March 2015. Analysis of the $^{84,85,86}\text{Br}$ [84, 85 and 86-Bromine] data from the March 2015 run indicates a significant modification of the β -strength [beta-strength] function when compared with previous measurements for all three nuclei, including the introduction of new high energy states not previously detected. The cases of $^{84,85,86}\text{Br}$ will be discussed in concert with shell model predictions. ^{85}Br [85-Bromine] is a singly magic $N=50$ nucleus. Through the study of $N=49,50,51$ nuclei the decay properties around a neutron shell closure governed by the interplay between core and valence nucleon excitations and Gamow-Teller decay in a ^{78}Ni [78-Nickel] core can be understood and provide a pinpoint for the study of more exotic nuclei.

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Chapter 1

Introduction

1.1 Structure and Applications for Nuclei Around ^{78}Ni

This work studies the β decay of nuclei near doubly magic ^{78}Ni , highlighted in Fig. [1.1](#). Nuclei in this region are both readily produced in experimental facilities world-wide and serve as a probe to test the robustness of models for neutron-rich nuclei. These models are essential for predicting the properties of nuclei active in the stellar r-process. The decay of the less exotic nuclei in this region contribute heavily to decay heat production in nuclear reactors.

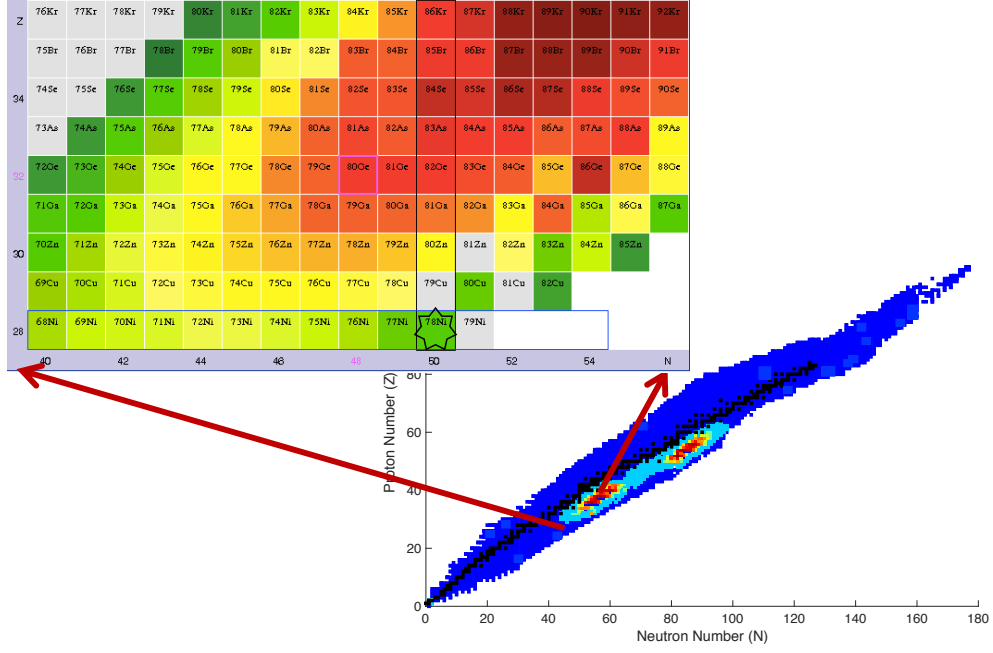


Figure 1.1: Chart of the nuclides with a heat map of the cumulative fission yields from ^{235}U . The area around ^{78}Ni [4] is blown up and ^{78}Ni is marked with a star. Neutron number (N) is plotted on the x axis and proton number (Z) is plotted on the y axis.

1.1.1 R-process Nucleosynthesis

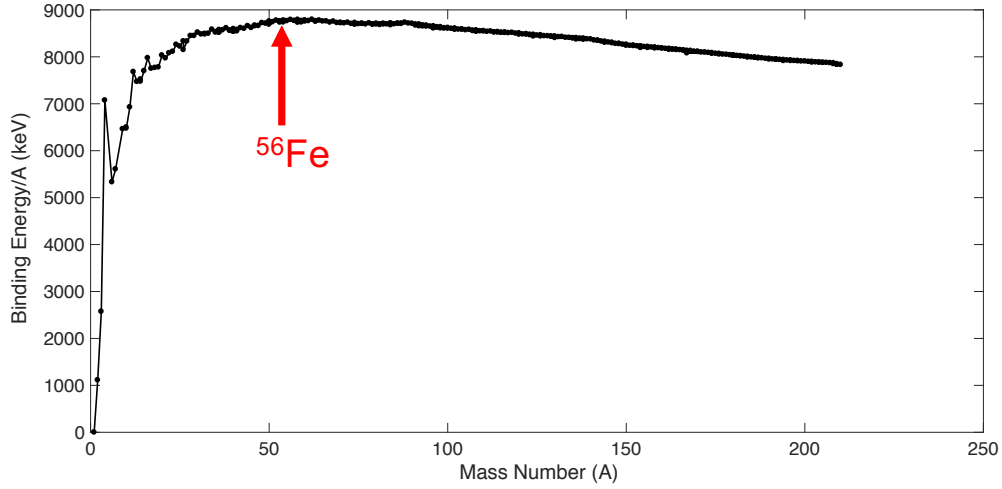


Figure 1.2: Binding energy curve for stable nuclei. Mass number (A) is plotted on the x axis, and binding energy per nucleon in keV is plotted on the y axis. The location of ^{56}Fe at the peak of the curve is highlighted in red.

In a stellar environment, nucleosynthesis is accomplished through nuclear fusion for nuclei up to ^{56}Fe . This is due the fact that the Coulomb-barrier to nuclear fusion increases linearly with Z [20] and binding-energy per nucleon peaks at ^{56}Fe , shown in Fig. 1.2. The significance of the peak in binding energy is that nuclei larger than ^{56}Fe require more energy to fuse than to break apart and are thus formed by methods other than nuclear fusion [20].

The r-process, or rapid neutron-capture process, is one of the largest contributors to nucleosynthesis for those heavy nuclei. The reaction chain is shown in Fig. 1.3 [16]. R-process nucleosynthesis occurs through neutron capture followed by rapid β decay back to stability. The r-process, thought to occur in core-collapse supernovae or neutron star mergers, is driven by enormous neutron fluxes on the order of $4 \cdot 10^{31} \frac{n}{\text{cm}^3 \text{sec}}$ [20, 16]. The temperature of the environment sets the path of r-process. Hot r-process occurs at temperatures of $\sim 10^9$ K. The “cold” r-process, occurring at temperatures of $\sim 10^8$ K, allows for the synthesis of more exotic nuclei [16]. Certain nuclei in the r-process reaction chain are what are termed “waiting points”. Here, the neutron cross-section drops such that the neutron-capture rate of a given nucleus is equal to the rate of γ -induced neutron emission [16]. Thus the process is temporarily in a state of equilibrium. This is because the neutron-capture process in

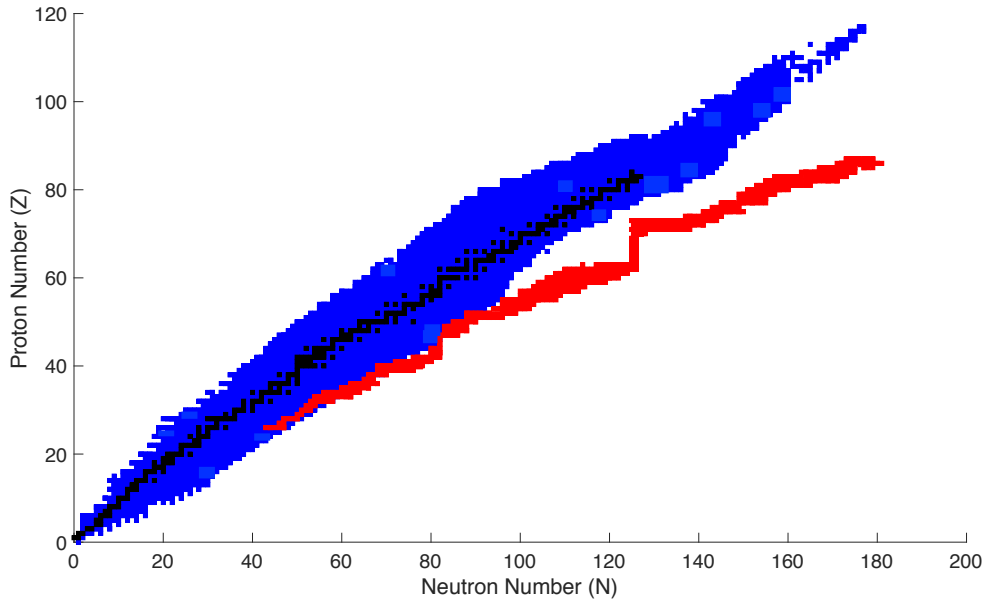


Figure 1.3: A chart of the nuclides with the r-process path outlined in red. Neutron number (N) is plotted on the x axis and proton number (Z) is plotted on the y axis [16].

effect must wait for these nuclei to decay. Following the β decay of these nuclei at “waiting points”, the (n, γ) reaction may resume as the resulting nuclei once again have a sufficiently large neutron cross-section to overcome this state of equilibrium. Nuclei in the r-process path occurring at neutron shell closures, a phenomenon that will be discussed in Chapter 2, are all waiting points. This serves to increase the yield of neutron-magic nuclei. Due to the exotic nature of waiting-point nuclei, better and more accurate data are required to improve predictions of their behavior.

1.2 Practical Applications for Nuclei Around ^{78}Ni and the Implications for Green Energy Production

The nuclei in the region around ^{78}Ni are readily produced as fission products in nuclear reactors. Many of the nuclei in this region are located near the first fission peak shown in Fig. 1.4. Therefore, understanding their behavior is integral to predicting the behavior of nuclear reactors, especially in emergency scenarios when cooling may be lost.

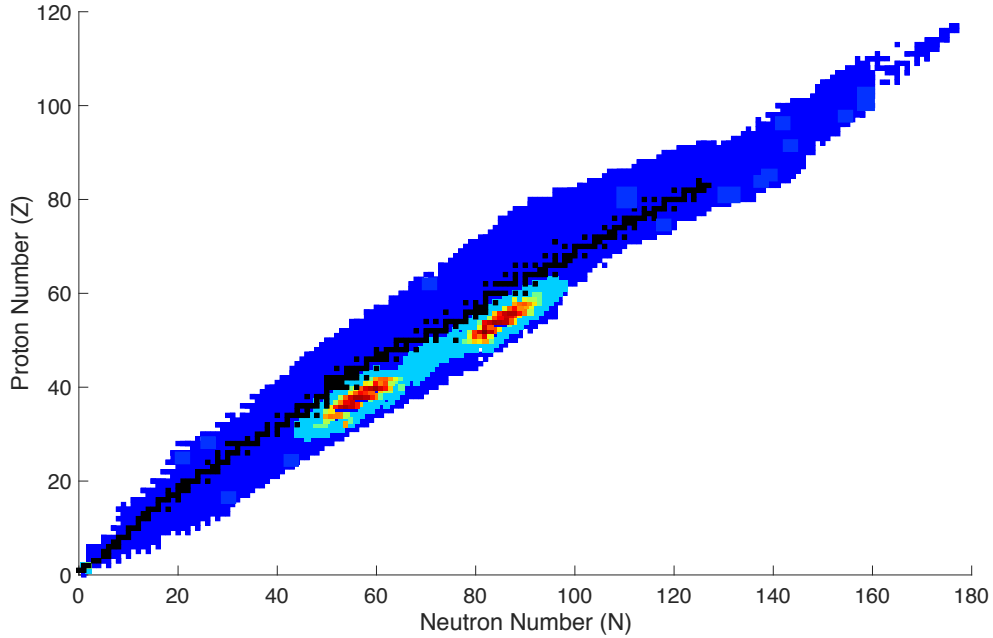


Figure 1.4: Chart of the nuclides with a heat map of the cumulative fission yields from ^{235}U . Neutron number (N) is plotted on the x axis and proton number (Z) is plotted on the y axis. The region being studied in this work is centered around the lower fission peak.

1.2.1 Decay Heat

After the controlled nuclear chain reaction is halted in a nuclear reactor many of the fission products remaining in the reactor are radioactive. These radioactive products decay, emitting energy in the form of neutrons, anti-neutrinos, γ rays and β particles. This emitted energy, termed decay heat due to the fact that it is dissipated as heat in the reactor, varies as a function of time after shut down. Decay heat accounts for $\sim 8\%$ of the total energy generated during reactor operations [60, 40].

Cooling must be maintained on the spent fuel in order to manage decay heat safely. A loss of cooling, such as happened at the Fukushima-Daiichi plant in March, 2011, can result in reactor meltdown. It is therefore imperative to have a thorough understanding of the behavior of decay heat in nuclear reactors.

A report released by the International Atomic Energy Agency (IAEA) estimates that the measurements taken, most of which were performed with low-efficiency high-purity germanium (HPGe) detectors, are missing up to 20% of the γ transitions above 1.7

MeV [60, 40]. These high energy transitions would significantly contribute to decay heat production and are contributions that are currently missed due to insufficient data [9]. This is noteworthy because the most effective way of predicting decay heat is through full decay network simulations with codes such as SCALE [14].

SCALE was developed at the Oak Ridge National Laboratory. It allows for a wide range of calculations pertinent to all parts of the nuclear fuel cycle from reactor physics and criticality safety to shielding and uncertainty analysis based on data from evaluated nuclear data files [14]. For these analyses accurate data are essential.

Total Absorption Spectroscopy (TAS), a method capable of detecting the previously missed high-energy γ transitions, serves as a complement to high resolution spectroscopy. TAS is often performed with large sodium iodide (NaI) detectors and is efficient enough to serve as a β -decay calorimeter. The need for this technique was first outlined in the 1970's by Hardy et al. [26].

Chapter 2

Physics Background

2.1 β Decay of Neutron Rich Nuclei

Nuclear β decay is a result of the weak interaction in nuclei and consequently can have relatively slow decay rates compared to other forms of nuclear transitions and reactions [24]. It is also the dominant decay mode for the majority of nuclides as demonstrated in Fig. 2.1.

There are two types of β decay, β^- which is dominant in neutron-rich nuclei and β^+ and electron capture which is dominant in neutron-deficient nuclei. Nuclear β decay is possible due to the difference in total binding energy between isobars. When plotted for an isobaric chain, binding energy has a parabolic shape as shown in Fig. 2.2. When the minimum of the parabola is reached, the resulting nucleus is termed stable. This stable nucleus is energetically blocked from further decay.

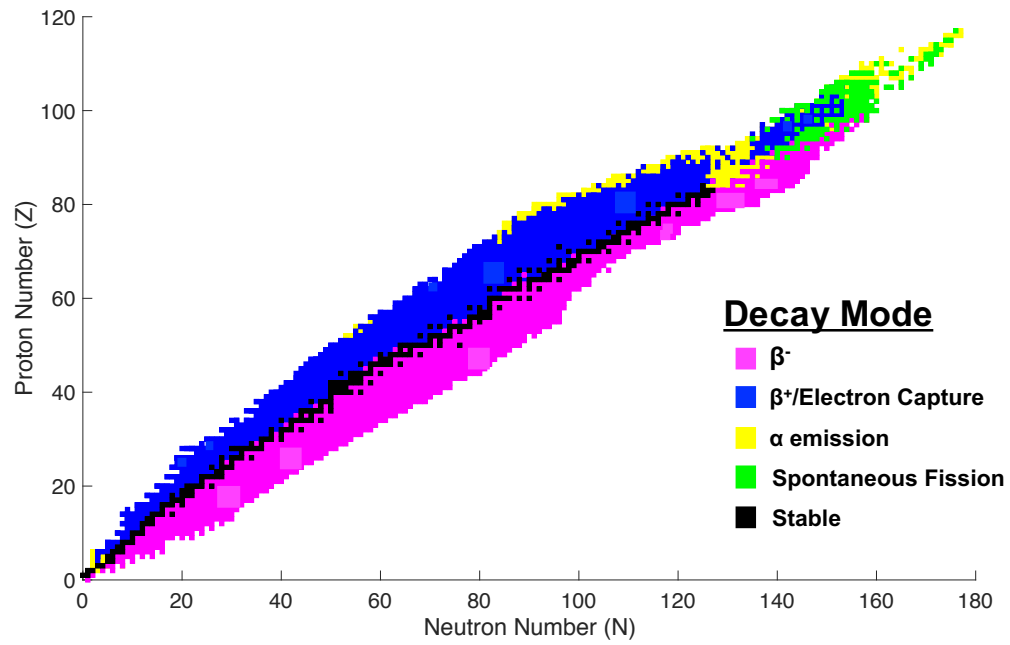


Figure 2.1: Chart of the nuclides depicting the dominant mode of decay for each nucleus. Neutron number (N) is plotted on the x axis and proton number (Z) is plotted on the y axis.

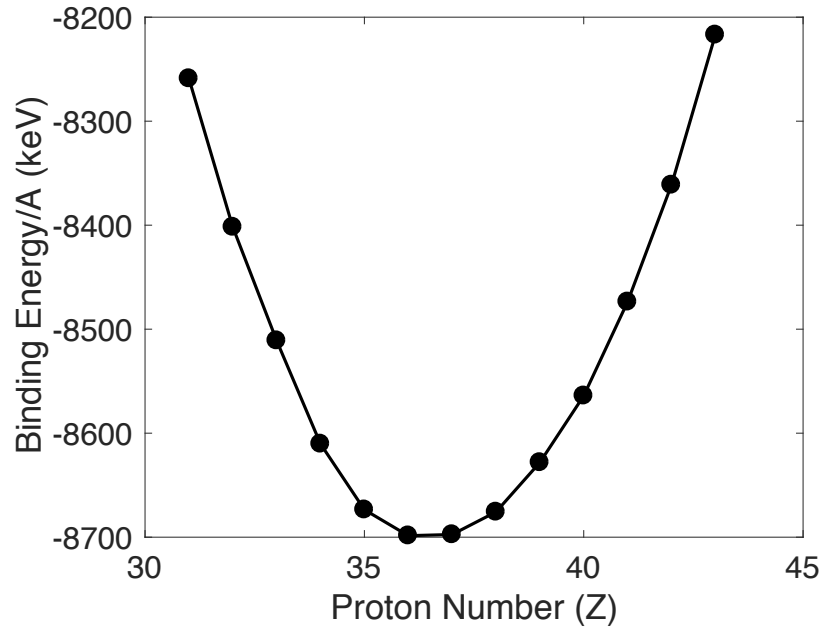


Figure 2.2: Proton number (Z) on the x axis plotted against binding energy per nucleon in keV on the y axis for mass $A = 83$. Please note that binding energy reaches a minimum at $Z = 36$. This point refers to ^{83}Kr , a stable nucleus. This plot shows the binding energy per nucleon curve for odd-mass nuclei. The same plot for even-mass nuclei would exhibit staggering due to the fact that even-even nuclei are more bound than odd-odd nuclei thanks to nuclear pairing effects [13].

As the nuclei that are the subject of this dissertation are located in the neutron-rich region around ^{78}Ni and therefore decay through β^- decay, the focus of the remainder of this discussion will be on β^- decay. In β^- decay, one neutron transforms into a proton and an electron and anti-neutrino are emitted. This serves to preserve charge-parity (CP) invariance as well as conservation of weak isospin [24]. The resulting number of nucleons in the system remains constant. The reaction is shown in Equation 2.1

$${}^A_Z X_N \rightarrow {}^A_{Z+1} X_{N-1} + e^- + \bar{\nu}_e \quad (2.1)$$

where X is an atomic nucleus with Z protons, N neutrons and A nucleons, e^- is the electron and $\bar{\nu}_e$ is the anti-neutrino.

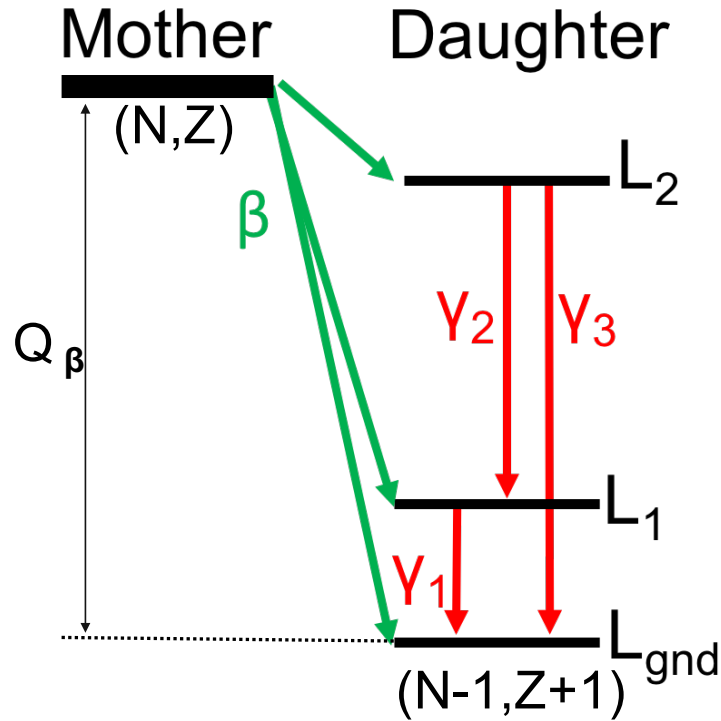


Figure 2.3: A schematic of a fictional nucleus with Z protons and N neutrons, termed the “mother”, decaying via β^- decay to its “daughter” with $Z+1$ protons and $N-1$ neutrons. The daughter then decays via γ -ray emission to the its ground state. The difference in energy between the ground state of the mother and daughter is represented by Q_β and represents the amount of energy available for the decay.

After a nucleus decays via β^- decay, the resulting nucleus, termed the “daughter”, is often left in an excited state. The daughter may then decay to its ground state via γ -ray emission if its energy is below the neutron separation energy, as is the case for the nuclei discussed in this dissertation. If it is energetically favorable, the daughter may decay further via β^- decay. A schematic of β^- decay as described here, represented by a fictional nucleus, is shown in Fig. 2.3.

If after the β^- decay of the mother, the daughter is in an excited state with enough energy to be above the neutron separation energy, the daughter may emit a neutron possibly populating states in another $N - 1$ daughter. Subsequently, the $N - 1$ daughter may decay via γ -ray emission to its ground state. This effect, termed β -delayed neutron emission, is energetically impossible for the nuclei studied in this dissertation.

2.2 The Relationship Between β -decay Matrix Elements and Physical Observables

The summation of transition probabilities representing the individual transitions of the β^- decay reaction yield the mathematical basis from which the observables measured in experiments arise [24]. Therefore, observables such as half-lives and decay rates can be derived from first principles and infer valuable information about nuclear structure. For example the decay rate for a single state $\lambda_{i \rightarrow f}$ for *allowed* decay, discussed in more detail in the following section, can be expressed as a summation of transition probabilities shown in Equation 2.2 [32].

$$\lambda_{i \rightarrow f} = \frac{\ln(2)}{D} \left[B_F^{if} + \left(\frac{g_A}{g_V} \right)^2 B_{GT}^{if} \right] f(Z_f, E_i - E_f) \quad (2.2)$$

This is based on the assumption that the nucleus is non-relativistic. The constants $D = \frac{\ln(2)\bar{K}^{-1}}{g_V^2} = 6144.2(13)s$, $\bar{K} = \frac{m_e^5 c^4}{2\pi\hbar^7}$ and $\frac{g_A}{g_V} = -1.2695(29)$ [32]. B_F^{if} and B_{GT}^{if} represent the two components of allowed decay, the Fermi and Gamow-Teller matrix elements respectively

and are given by Equations 2.3 and 2.4 [24].

$$B_F^{if} = \left| \langle f | \hat{O}_{GT} | i \rangle \right|^2 \quad (2.3)$$

$$B_{GT}^{if} = \left| \langle f | \hat{O}_{GT} | i \rangle \right|^2 \quad (2.4)$$

Here $\hat{O}_{GT}$ represents the axial portion of the β -decay operator $\hat{O}_\beta = \hat{O}_F + \hat{O}_{GT}$ [24] and i and f represent the initial and final states in the mother and daughter nuclei. Maintaining our assumption that the nucleus is non-relativistic, $\hat{O}_{GT}$ is described by the sum of the the spin operator $\sigma(j)$ times the isospin raising operator t_+ over all final states in the daughter as shown in Equation 2.5 [24].

$$\hat{O}_{GT} = \sum_j \sigma(j) t_+(j) \quad (2.5)$$

Finally, $f(Z_f, E_i - E_f)$ corresponds to the phase space factor. This function arises from the fact that the amount of states available for the emitted particles (electron and anti-neutrino) are limited by the size of their phase space. As $f(Z_f, E_i - E_f)$ falls off as a function of energy to the fifth power, this serves to suppress transitions to states at high excitation energies in the daughter. This effect is a result of conservation of energy which dictates the resulting energy imparted to the emitted electron and anti-neutrino is small. The small amount of available kinetic energy corresponds to a small phase space and thus a small number of occupy-able states for the electron and anti-neutrino. The reverse is true for transitions to states at low excitation energies, as they allow for a large phase space for the electron and anti-neutrino and therefore a large number of states are open to the emitted particles.

2.3 Allowed and Forbidden Decays

2.3.1 Allowed Decays

In β decay, allowed decays occur when there is no change in the orbital angular momentum or parity between the nucleon in the mother and the daughter. As stated above, the two types of allowed decays are Fermi and Gamow-Teller (GT). Fermi decay only occurs between

isobaric analog states. Furthermore, Fermi decay requires that the net change of the total angular momentum $\Delta L = 0$ and for the electron and anti-neutrino's spins to couple to $S=0$. In GT decay, the total angular momentum and isospin may change by ± 1 or 0 and the electron and anti-neutrino's spins couple to $S=1$. For neutron-rich nuclei, Fermi decay is unlikely to occur because Coulomb repulsion pushes the energy of the isobaric analog states in the daughter up to a point where they are too high for a neutron to decay into [24]. Therefore, as the Fermi portion of the decay makes no contribution, Equation 2.2 becomes:

$$\lambda_{i \rightarrow f} = \frac{\ln(2)}{D} \left[\left(\frac{g_A}{g_V} \right)^2 B_{GT}^{if} \right] f(Z_f, E_i - E_f) \quad (2.6)$$

For the purposes of this dissertation, it is useful to define the Gamow-Teller strength (B_{GT}) for a given transition as $B_{GT} = \left(\frac{g_A}{g_V} \right)^2 B_{GT}^{if}$.

2.3.2 Forbidden Decays

Alternatively, “forbidden” transitions occur when the emitted particles carry away orbital angular momentum. This imposes a change in parity and/or angular momentum from the initial state in the mother to the final state in the daughter to conserve the total angular momentum of the system. The more orbital angular momentum carried by the emitted particles, the smaller the probability of the decay, thus furthering the suppression of the decay rate through this mode [24]. However, phase space effects may amplify the role of forbidden transitions for the decay of nuclei with large Q_β windows. The resulting rates of forbidden transitions could compete with allowed transitions if the allowed transitions are pushed to high excitation energies in the daughter. This effect is achieved because the phase space factor serves to suppress transitions to high energy states in the daughter.

2.4 The Nuclear Shell Model and Magicity in Nuclei

The shell model of atomic nuclei assumes that nucleons can be treated as if they occupy discrete energy orbitals inside a potential well [24]. Through spin-orbit interactions, energy levels are grouped together forming “shells” with relatively large energy gaps between them.

A nucleus whose protons or neutrons occupy a full shell is termed “magic”. If a nucleus exists at a double shell closure, meaning a closed shell for both neutrons and protons, it is termed “doubly magic”. Shell closures are predicted to occur at nucleon numbers 2,8,20,28,50 and 82 and 126 [38].

The β decay of nuclei is energetically possible because of the differences in binding energies between the parent and daughter nuclei, as discussed above. Nuclear structure plays a key role in determining the decay rate of a nucleus because of the selection rules imposed by operators responsible for the allowed and forbidden transitions and the role of the Pauli exclusion principle which states that no two fermions may be in identical states.

For the nuclei near closed shells, nuclear shell model paints a picture of a nucleus as an inert core with nucleons in valence orbitals. At its most computationally tractable, decay of this nucleus occurs by transitions between neutron and proton valence orbitals. For Gamow-Teller decay, this is always limited to transitions between spin-orbit partners, e.g. $f_{\frac{5}{2}} \rightarrow f_{\frac{7}{2}}$ or $p_{\frac{3}{2}} \rightarrow p_{\frac{1}{2}}$. However, for very neutron-rich nuclei, the condition imposed by the Gamow-Teller operator limiting transitions to those between the aforementioned spin-orbit partners may require the participation of states within the “inert” core. This increased complexity leads to very high energy cross-shell excitations as well as heightened computational complexity.

Further away from closed shells, the number of valence nucleons increases to the point that other collective degrees of freedom such as nuclear deformation and multi-body effects complicate the picture of β decay. The study of a spherical nucleus near a closed shell provides an anchor point for more complicated systems.

Chapter 3

Paradise Regained: Conquering Pandemonium with Total Absorption Spectroscopy

3.1 Tackling the Pessimism of Pandemonium

A seminal paper published by Hardy, Johnson and Hansen in 1977, stated the decay of heavy nuclei with large Q_β values and transitions to levels above ~ 1.7 MeV in the daughter can be described using a purely statistical model of a nucleus dubbed “Pandemonium” [26]. Therefore peaks observed in the electromagnetic decay of the daughter nucleus are described by gross features of the decay and statistical fluctuations in level densities due to groupings of levels and not by structure. This is a rather pessimistic message for nuclear physics as the most extreme interpretation of this rubric renders any apparent structure reported as a result of a measurement meaningless.

However, drawing such extreme conclusions is a misinterpretation of the intent of the paper which was to draw attention to the fact that the decay of such nuclei is likely to be highly fragmented at high energies, see Fig. 3.1, known as the “Pandemonium Effect”. This fragmentation results in many high-energy but low-intensity electromagnetic transitions in the daughter that will be unlikely to be detected with low-efficiency high-resolution γ -ray

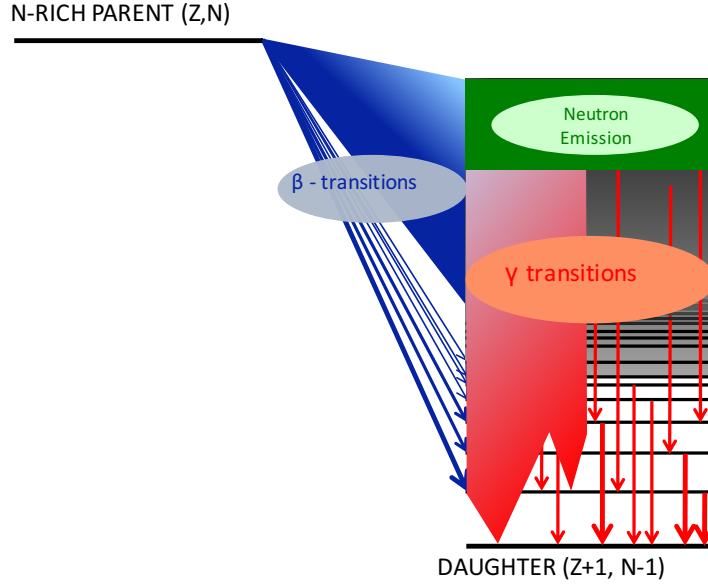


Figure 3.1: A simplified view of fragmentation. Notice the increased density of levels (black) at increased energies close to the neutron separation energy. Figure courtesy of Krzysztof Rykaczewski.

detector systems, a fact that is stressed by Hardy et. al [26]. The solution to this is total absorption spectrometry (TAS), a technique developed and successfully implemented after the publication of the paper by Hardy et al. and is also used in this work.

3.2 Discussion of TAS versus High Resolution Spectroscopy

A typical TAS uses NaI for radiation detection through scintillation in the place of HPGe. NaI is chosen because it is much less expensive than HPGe. The smaller expense coupled to the restrictions on the growth size of HPGe crystals allows for larger volume and thus higher-efficiency detectors. Additionally, HPGe must be maintained at a low operating temperature through the use of liquid nitrogen and therefore would pose significant engineering challenges to the construction of a large detector array.

NaI has poor resolution when compared to HPGe. This is due to the nature of a scintillation detector versus that of a semiconductor detector. Semiconductors, such as HPGe, produce many more “charge carriers”, in this case electrons, due to an incident γ ray

than a scintillation detector is capable of. For scintillation detectors, the “charge carriers” released due to incident γ radiation are photons. The signal width $\sigma = K\sqrt{N}$ where N is the number of charge carriers and K is a proportionality constant [35]. Therefore resolution is directly proportional to the square root of the number of charge carriers produced by a detector.

However, what is lost in resolving individual γ rays is gained in detection efficiency and a more comprehensive understanding of β feeding. Significantly less γ -ray energy can escape undetected because of the larger volume of the active material in the detector. Gains in detection efficiency between a typical HPGe array and a TAS can be as much as an order of magnitude for γ transitions at the same energy. For example, the HPGe clover array Low-energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS) has an efficiency of $\sim 6\%$ at 1 MeV and the Modular Total Absorption Spectrometer (MTAS), a TAS detector, is $\sim 90\%$ efficient at the same energy [3, 59]. Such high efficiency allows for the detection of the high-energy but low-intensity γ transitions associated with Pandemonium that escape unseen in low-efficiency detector systems. Both LeRIBSS and MTAS are located at the Oak Ridge National Laboratory, MTAS is discussed further in Chapter 5.

The TAS method relies on summation of individual γ transitions in the cascade to identify level energy due to the fact that most of the γ rays that de-excite a given level will be deposited in the detector. The resulting TAS spectrum displays level energies and not individual γ rays as would be otherwise typical. See Fig. 3.2.

The resolution of NaI can render TAS incapable of differentiating between a single level or a close grouping of levels at high energy. TAS is, however, capable of establishing the excitation energy and population intensity of the level(s) in the high energy region, where fragmentation is likely; a feat beyond the capability of high resolution spectroscopy.

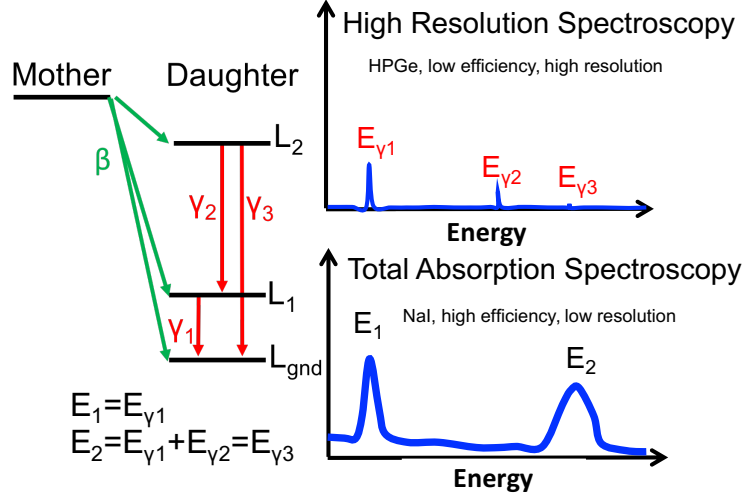


Figure 3.2: An imaginary simple decay scheme with two levels and diagrams of the resulting spectra for high resolution spectroscopy and TAS. Individual γ transitions are visible in the mock high resolution spectra (top). The mock TAS spectra, bottom, shows sums of the γ transitions in the form of level energies.

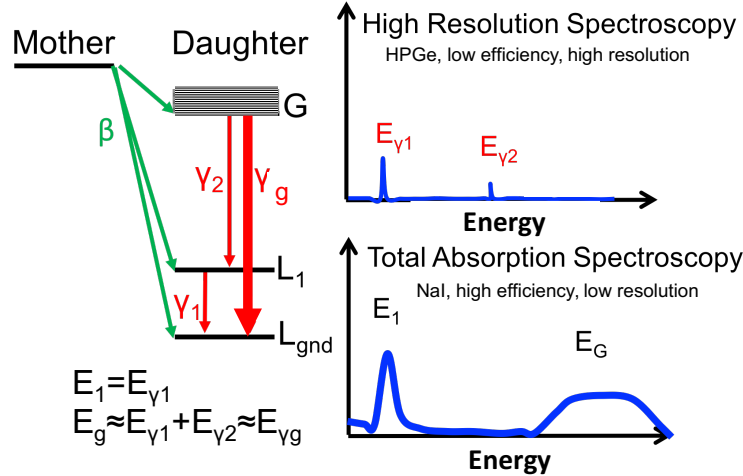


Figure 3.3: A similar decay scheme and associated high resolution and TAS spectra as those in Fig. 3.2 only with added complexity that our imaginary nucleus is fragmented. This results in a group of levels (G) that de-excite via a group of high-energy low-intensity γ transitions γ_g . Note that high resolution spectroscopy will likely miss γ_g . TAS will see G but not be able to differentiate between the levels.

3.3 Pandemonium in the Era of Modern Shell Model

This interpretation of the Hardy et al. paper is further bolstered by the fact that at the time of publication, nuclear properties were predicted using simplified models of the interactions between nucleons only in the most superficial of shells. The reason being that computational capabilities for more complete calculations did not exist at the time. The current iteration of the nuclear shell model is based on a more complete view of nuclear physics involving microscopic interactions between nucleons. By taking advantage of modern computing capabilities as well as more advanced matrix diagonalization methods, nuclear shell model is capable of calculating transitions into the formerly inaccessible and messy regions of Pandemonium.

The Hardy et al. paper is nevertheless pivotal as it was the first recognition of large amounts β -feeding strength to high energy states in the daughter having been missed, up to $\sim 20\%$ above 1.7 MeV. Hardy et al. argue that low efficiency measurements of γ rays resulted in the mis-assignment of β feeding to levels at low excitation energies in the daughter. This strength was in effect taken away from high energy γ transitions that are undetectable for such low efficiency single γ -transition measurements. This mis-attributed strength artificially inflates feeding to low energy states in the daughter and has been confirmed in other experiments with TAS [22, 33, 23, 9, 44].

A nuclear shell model perspective could quantify the high level densities of Pandemonium. High level densities can be reproduced using the nuclear shell model by choosing an appropriate valence space so as to provide a sufficiently large number of final configurations. The decay of very neutron-rich nuclei with large Q_β values that delve into the region of Pandemonium open up the possibility for allowed transitions between spin-orbit partners in the proton and neutron harmonic oscillators at high energies. For cases of very asymmetric neutron-rich nuclei, decay to low lying states necessitates a parity change and therefore is forbidden. The result is forbidden transitions feeding those low-lying states in the daughter are depressed with respect to current high resolution spectroscopy measurements.

Pandemonium driven mis-assignment of β strength and the resulting depression of feeding to low-lying states in the daughter has important implications for decay heat measurements.

A re-examination of data currently in the Evaluated Nuclear Structure Data File (ENSDF) database could be warranted.

Chapter 4

Physics Motivation for the Study of $^{84,85,86}\text{Br}$

4.1 Purpose of Study

This work describes the study of three isotopes of bromine at and around the $N=50$ neutron magic number using TAS. The purpose of this being to update the decay schemes for $^{84,85,86}\text{Br}$ to accurately describe the decay strength that likely has been missed through the use of high resolution spectroscopy as the sole detection method. Specifically, we first determine the β -decay strengths as accurately as possible using experimental data obtained with MTAS. We then use the measured decay strengths to demonstrate the capability of a modified shell model by calculating transitions in the region of excitation energies traditionally attributed to Pandemonium. The results demonstrate an ability to reproduce the main features of the shell model quantifiable decays of $N=49,50$ $^{84,85}\text{Br}$. The data from the decay of $N=51$ ^{86}Br are then used to test the robustness of the calculations involving cross-shell excitation. While the modern shell model can be much more complete than previous iterations, it still lacks the capability to incorporate all microscopic interactions between all nucleons. As such, we use the $^{84,85,86}\text{Br}$ data to test our hypothesis that neutrons outside of the $N=50$ closed shell do not play an active roll in the decay of the nucleus. Our results will allow for confident predictions of even more exotic $N>50$ nuclei.

Beyond testing the predictive power of our modified shell model, the study of $^{84,85,86}\text{Br}$ is important as they are all fission products. In particular, $^{85,86}\text{Br}$ are abundantly produced in the fission of uranium. As such the data from this study will provide information pertinent to the behavior of decay heat in nuclear reactors; decay heat is discussed previously in 1.2.1.

4.2 Nuclear Structure of $^{84,85,86}\text{Br}$

Taking a more microscopic look, a thorough study of the β decay of $^{84,85,86}\text{Br}$, with $N=49,50,51$, will yield an understanding of decay properties governed by the interplay between core and valence nucleons and Gamow-Teller decay in a ^{56}Ni core. This will provide information about the evolution of nuclear structure across the $N=50$ shell gap.

4.2.1 β -Decay of $^{84,85}\text{Br}$

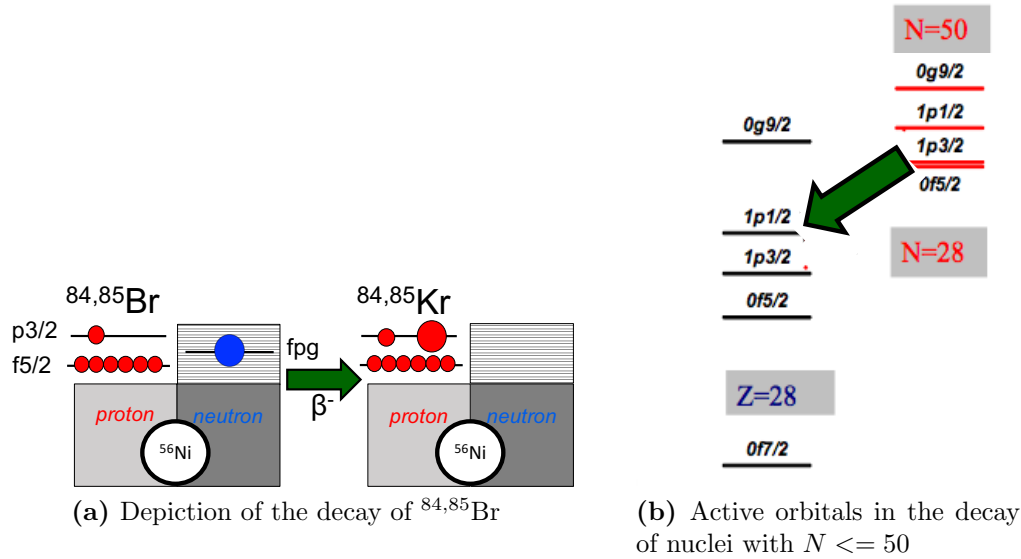


Figure 4.1: a) Representation of β decay of $^{84,85}\text{Br}$. The diagram illustrates that the decay occurs in the valence space above a ^{56}Ni core. b) Orbitals involved in the decay of $^{84,85}\text{Br}$.

Bromine nuclei, $Z=35$, have seven protons occupying the $0f_{5/2}1p_{1/2,3/2}$ shells outside of a ^{56}Ni closed core. ^{85}Br is singly magic, $N=50$, and correspondingly has a full neutron $g_{9/2}$ orbital, as shown in Fig. 4.1b. ^{84}Br , which is just shy of magic with $N=49$, is likely to have a single neutron vacancy in the $g_{9/2}$ orbital. In the case of both nuclei, their decay is dominated by neutrons decaying from the f or p orbitals to a proton occupying the f or p proton orbitals in the daughter, $^{84,85}\text{Kr}$ respectively. Decay from a g orbital to an f or p orbital is forbidden. While decay from the $g_{9/2}$ neutron orbital to the $g_{9/2}$ proton orbital is allowed, the $g_{9/2}$ proton orbital is typically at the edge of or beyond the Q_β window.

4.2.2 β -Decay of ^{86}Br

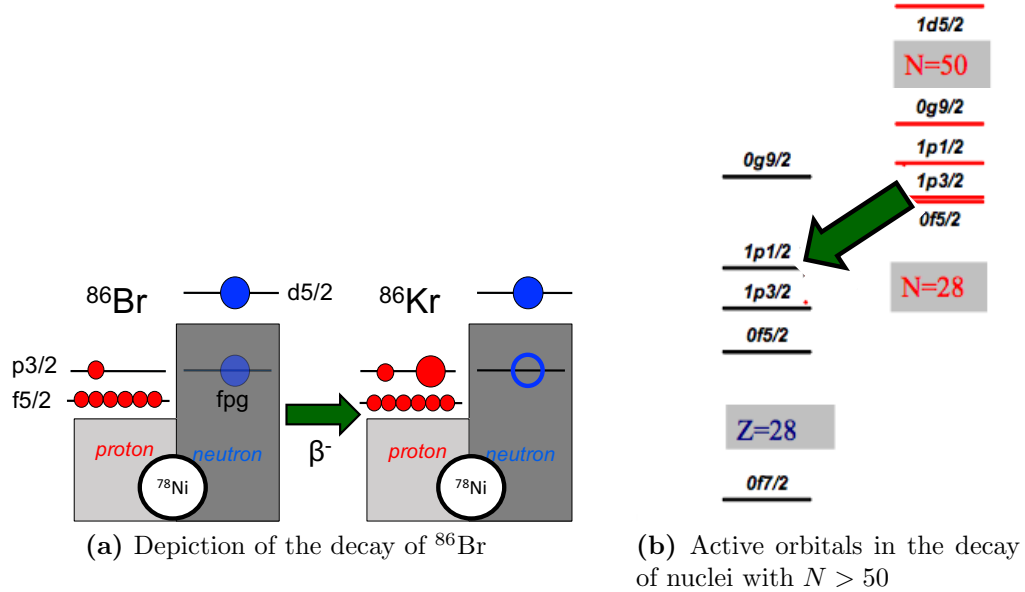


Figure 4.2: a) Representation of β decay of ^{86}Br . Illustrates that the decay occurs within a ^{78}Ni core with the $d_{5/2}$ neutron remaining in the valence space. b) A more detailed look at the shells involved in the decay of ^{86}Br .

$N=51$ isotones in the region around ^{78}Ni have been proven to have a single neutron occupying the $d_{5/2}$ valence orbital, as shown in Fig. 4.2b, while in their ground state [10, 56, 42]. As ^{86}Br is an $N=51$ nucleus, we hypothesize that it exists in a similar configuration. The Gamow-Teller decay of ^{86}Br is very likely to resemble that of $^{84,85}\text{Br}$. That is to say it is

likely to be an example of single-particle single-hole decay from within the ^{78}Ni core. This is due to the fact that transitions from the d to f , p or g orbitals necessitate a change in parity or a change of $L = 2$ angular momentum and as such are not permitted by the Gamow-Teller selection rules. Therefore the $d_{5/2}$ neutron cannot be a participant in Gamow-Teller decay and will likely act as a “spectator” to a neutron from one of the f , p or g orbitals within the $N=50$ core decaying to the f or p orbitals above the $Z=28$ core.

4.3 Decay Heat Contributions of $^{84,85,86}\text{Br}$

Table 4.1: Basic information about $^{84,85,86}\text{Br}$ including ^{235}U thermal neutron fission yields [18].

Isotope	Q_β (keV)	$T_{1/2}$	Abs. Fission Yield (1×10^{-3})
$^{84}\text{Br}_{g.s.}$	4629	31.76 m	0.19
^{85}Br	2905	2.90 m	2.35
^{86}Br	7633	55.1 s	4.59

As stated in 1.2.1, a report output by the IAEA estimates that the data currently available in the ENSDF database are missing 20% or more of the γ transitions above 1.7 MeV. This impacts the decay heat estimates produced by decay network modeling. As such they strongly outline the need for the study of fission products with the total absorption spectrometry (TAS) technique, as proposed in this work [60, 40].

As part of the 2002 report, Nichols outlined a wishlist of nuclei and associated a priority for their study. ^{86}Br was listed as a priority 1 nucleus due to the lack of TAS data, the large Q_β value and the high fission yield, shown in Table 4.1 [60, 40]. ^{85}Br , while not given a priority in the report, is also a useful addition as the Q_β value is in excess of 1.7 MeV and the fission yield is large. While ^{84}Br has a fission yield that is an order of magnitude below $^{85,86}\text{Br}$, it still has a large Q_β value and therefore is likely to be missing feeding to high energy states in the daughter.

4.4 Review of the Current Literature Describing $^{84,85,86}\text{Br}$

The sources of the data currently in ENSDF for $^{84,85,86}\text{Br}$ will be discussed here. Please note, the β decay of these nuclei, last studied in the 1970's, was examined solely using high resolution spectroscopy.

4.4.1 ^{84}Br

The β decay of ^{84}Br was last studied in 1970 by Hattula et. al [27]. Both the 6 minute and 31.8 minute isomers were studied with a high resolution Ge(Li) detector. The ^{84}Br isotopes were generated through the fission of ^{235}U and through $\text{Rb}(n,\alpha)$ reactions. A total of sixteen states in ^{84}Kr were assigned with this method.

4.4.2 ^{85}Br

The β decay of ^{85}Br was last studied in 1974 as part of a large study by Hurdus et al. of $^{84-87}\text{Se}$ and $^{85-88}\text{Br}$ [31]. Radiochemistry was used to separate Se isotopes produced by fission. The Br isotopes were then allowed to grow into the samples as Br is the β -decay daughter of Se. All nuclides were studied with a high resolution Ge(Li) detector.

The next study of the β decay of ^{85}Br occurred one year later in 1975 and was performed by Nuh et al. [41]. Once again ^{85}Br was produced through the fission of ^{235}U and Br isotopes were radiochemically separated for study. A high resolution Ge(Li) detector was used and twenty-six transitions were assigned to the decay of ^{85}Br .

4.4.3 ^{86}Br

The first β -decay study of ^{86}Br was performed in 1972 by Atcherberg et al. [8]. Here fission products of ^{235}U were separated using the Isotope Separation OnLine (ISOL) method. This is the same method used in our study of ^{86}Br and is described further in Chapter 5. A high resolution Ge(Li) detector was used and nineteen transitions were assigned to the decay of ^{86}Br . The next study of the β decay of ^{86}Br occurred in 1974 and is the same study described previously for ^{85}Br .

The latest β -decay study of ^{86}Br was accomplished in 2016 by Urban et al. using an array of HPGe detectors located in the Lohengrin fission-fragment separator at the Institut Laue-Langevin (ILL), Grenoble, FR [57]. Fission was induced in a ^{235}U target and isotopes were separated using the ISOL method. Urban et al. introduced eight new levels in ^{86}Kr populated in the β decay of ^{86}Br at 3335.0, 4359.6, 4717.6, 5653.3, 6047.4, 6094.0, 6141.4 and 6450.2 keV. They also proposed a 9% β feeding to ground state in ^{86}Kr [57].

Chapter 5

Experimental Methods

5.1 The Modular Total Absorption Spectrometer

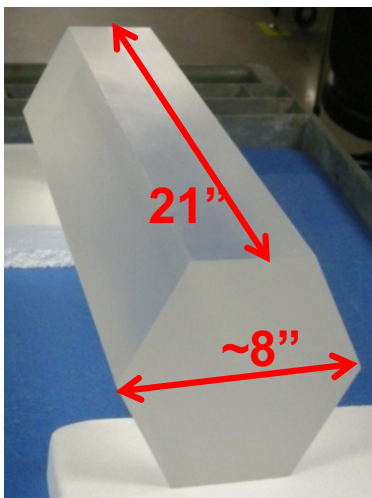


Figure 5.1: Single unwrapped MTAS crystal composed of NaI(Tl).

The Modular Total Absorption Spectrometer (MTAS) is currently the most efficient total absorption spectrometer (TAS) in the world for β -decay studies [59, 34]. MTAS has a volume that is seven times larger than the second largest TAS that operated at the Society for Heavy Ion Research (GSI) in Darmstadt, Germany for measurements of nuclei in the regions around ^{100}Sn and ^{146}Gd [33]. Other TAS detectors have been implemented at the Idaho National Laboratory (INEL) to study ground-state branching ratios in a range of nuclei [23], Jyväskylä for the study of ^{239}Pu fission products [9] and the Isotope Separator Online

Detector (ISOLDE) [44]. The Summing NaI(Tl) Detector (SuN) is currently operating at the National Superconducting Laboratory (NSCL) performing reaction measurements [50], and another TAS, the Decay Total Absorption γ -ray Spectrometer (DTAS), is undergoing commissioning at the Facility for Antiproton and Ion Research (FAIR) [53].

MTAS is the first segmented TAS detector. It is composed of nineteen NaI(Tl) crystals. Each crystal, cut in a hexagonal shape, is 21 inches long and 8 inches wide as shown in Fig. 5.1 [59]. Through the use of multiple NaI crystals, as opposed to one large crystal, the cost of the detector as a whole was vastly decreased and the ease of construction increased. Segmentation has proved to be a powerful analysis tool. It allows for the easy identification of new levels in the radioactive species along with a clear view of which γ rays de-excite a given level through the use of γ - γ matrices. This technique will be discussed in more detail in Chapter 7 and is of course limited by the resolution inherent to NaI.

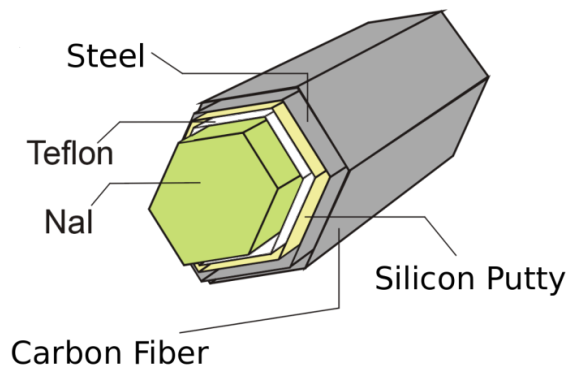


Figure 5.2: Diagram of the wrapping around each NaI crystal. Not to scale.

NaI is hygroscopic, therefore each bar must be individually wrapped both to preserve the integrity of the crystalline structure of the NaI and to make the assembly light tight. In order to maintain overall efficiency of the detector the amount of material between the individual crystals was minimized. Through the use of carbon fiber housing, much of the requisite steel was able to be replaced and the width of the material surrounding each individual crystal was decreased to ~ 2 mm [59], see Fig. 5.2.

One photomultiplier tube (PMT) is mounted on each end of a wrapped crystal to form a single module as depicted in Fig. 5.3. There is also a bundle of fiber optic cables optically coupled to each end of each module. These bundles are used for gain stabilization of the



Figure 5.3: Picture of a finished module.

PMTs in concert with a half-length reference module that sits outside of MTAS. The reference module is not included in the count of the 19 modules of MTAS for the purposes of this discussion. Gain stabilization is a contribution of this work that is discussed further in Chapter 6.

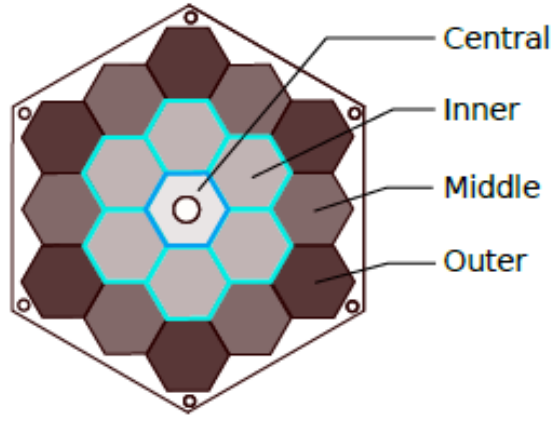


Figure 5.4: Diagram of MTAS modules displaying the configuration of the central, middle, inner and outer rings.

The nineteen modules are mounted in an aluminum frame in a honey comb pattern. There is a single unsegmented central module with a hole tapped through the center and six PMTs mounted on either end circularly around the hole. The remaining eighteen modules are mounted in two concentric rings around the central module. In order to have the same number of modules per ring and accurately reflect the distance of a given module from the center of the beam pipe, these modules are dubbed the inner, middle and outer rings. See Fig. 5.4 for clarification.

The hole tapped through the central module allows for a beam pipe to be run through the center of MTAS and the mounting of a moving tape collector (MTC) on the downstream side. The MTC reaches all the way to the other side of MTAS and is used to implant samples coming in through the beam pipe outside of MTAS on the upstream side. The samples

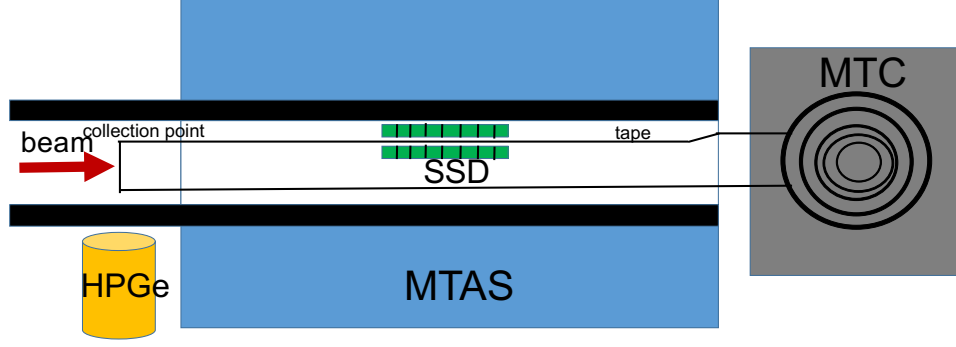
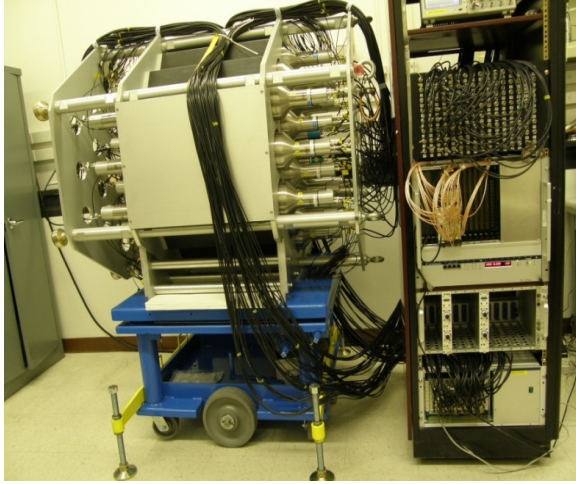


Figure 5.5: Schematic depicting the placement of the MTC, SSD and HPGe detectors relative to MTAS (not to scale) [59].

are then moved in and out of MTAS at precise intervals determined by the lifetime of the radioactive species being studied. The hole in the central module also houses two silicon strip detectors (SSD) used to detect β particles emitted as part of β decay. This reduces background through gating on β - γ coincidences. Each SSD is 1 mm thick and divided into seven segments that are each 8.5 mm wide. Segmentation allows for measuring the relative position of the implanted samples and thus aids in the centering of the radioactive sample in MTAS [59]. There is also a single HPGe detector mounted outside the beam pipe at the implantation point to record the signature γ radiation of the sample coming in to verify beam purity [59]. The relative location of the ancillary components to MTAS is shown in Fig. 5.5.

The aluminum frame holding the modules is mounted on an adjustable cart and placed inside mobile housing that holds approximately five tons of lead blankets and borated polyurethane sheets around MTAS to further reduce background γ and neutron radiation. The signals from all forty-eight PMTs are read out using a digital acquisition system (DAQ) developed by XIA with software written at the University of Tennessee [43, 59, 34]. See Fig. 5.6.

This configuration yields excellent total efficiency and full energy peak efficiency across a broad range of energies. The peak efficiency is approximately 95% around 0.5 MeV and 75% at 5 MeV. The efficiency was characterized using ^{137}Cs , ^{54}Mn and ^{65}Zn sources and compared with a GEANT4 model of MTAS as shown in Fig. 5.7.



(a) MTAS-no-shielding



(b) MTAS-at-HRIBF

Figure 5.6: a) The unshielded aluminum frame mounted on the adjustable cart. The DAQ is also shown. b) MTAS fully mounted and implemented at HRIBF with all ancillary detectors and shielding in place. The MTC is located in the immediate foreground. The HPGe detector is visible on the far side of MTAS.

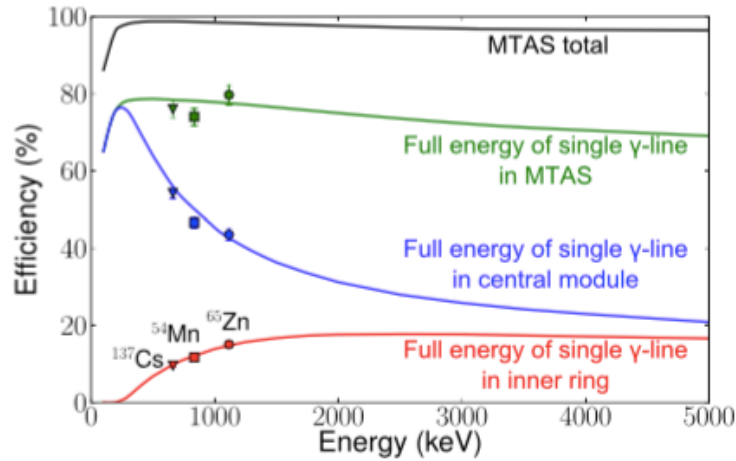


Figure 5.7: Plot of the measured efficiency of MTAS plotted with a GEANT4 model's predictions [59].

Due to MTAS's high efficiency we are able to detect transitions all the way up to the Q_β value of the nucleus of interest, as shown in Fig. 5.8. The resolution of MTAS is limited to bins of $\Delta E \approx 25$ keV. As stated in Chapter 4, the β feeding to a group of levels will be detected, MTAS however will not be able to distinguish the population of individual levels with <25 keV spacing.

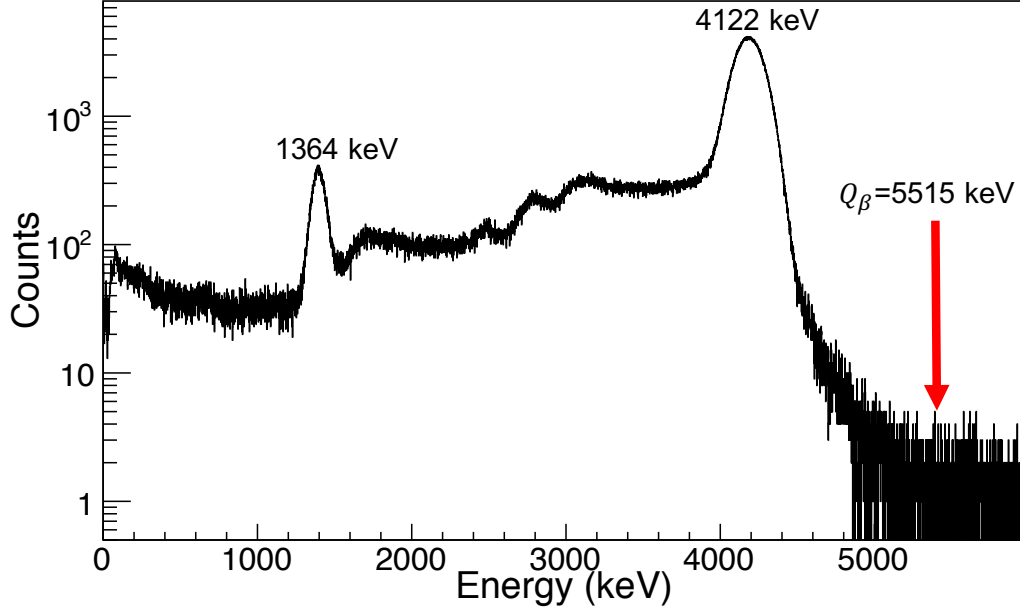
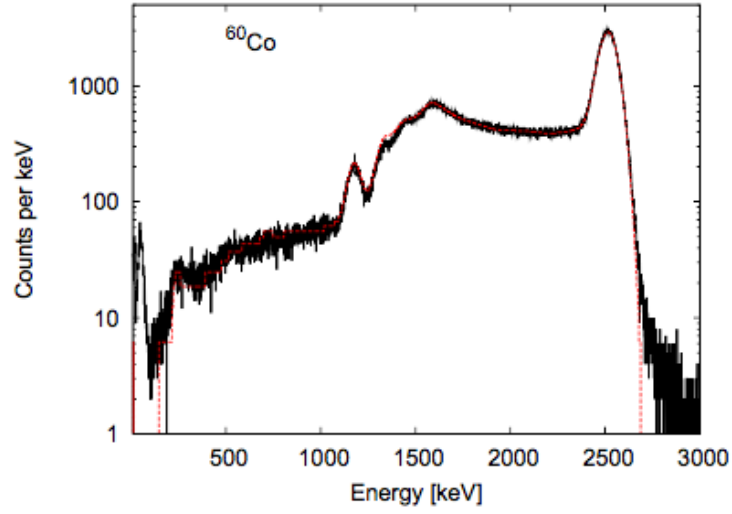


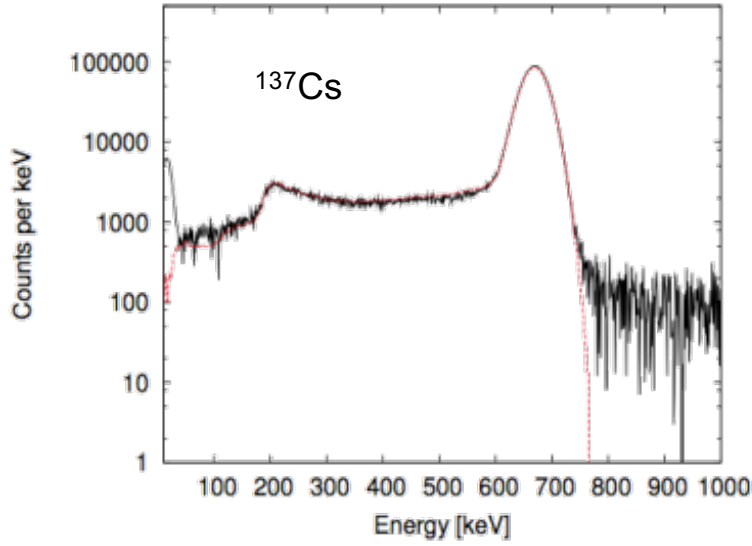
Figure 5.8: β -gated ^{24}Na spectrum. ^{24}Na was generated through the irradiation of table salt for testing the auxiliary SSD detectors. Note that MTAS detects the high energy level at 4239 keV detected before the Q_β value of 5515 keV.

5.2 Geant4 Model of MTAS

MTAS is a calorimeter capable of detecting nearly the full range of energies emitted in the electromagnetic portion of the decay of a given nuclear species. It is, however, not without imperfections. As discussed in Sec. 5.1, each individual crystal is ensconced in its own protective housing. Additionally, there are auxiliary components necessary for the operation of the detector as well as a beam pipe. All of these additions are non-active material and can absorb γ -ray energy altering the response function of the detector. In addition, there will be geometrical losses due the hole through the central module, some inevitable escapes of high energy γ rays and neutron interactions in the NaI stemming from background and β -delayed neutron production in the radioactive samples. A proper deconvolution of the spectra produced by MTAS must account for these imperfections [22]. This is accomplished through the use of a geometrically accurate GEANT4 model of MTAS that functions by generating a response based on energy deposition and the resulting light production in the NaI coupled to the resolution of the detector [22, 59, 34].



(a) MTAS (black) and GEANT4 (red) responses to ^{60}Co



(b) MTAS (black) and GEANT4 (red) responses to ^{137}Cs

Figure 5.9: MTAS data (black) plotted with Geant4 response (red) for two standard sources, ^{60}Co and ^{137}Cs . The excellent agreement between the red and black curves demonstrates the accuracy of the GEANT4 model of MTAS [22].

The GEANT4 model of MTAS has been tested with well understood sources, as shown in Fig. 5.9. There is excellent agreement between the data taken by the detector and the simulated response function. However, the Geant4 model only predicts responses up to the Q_β value of the nucleus being simulated. Therefore the data at high energies, above ~ 2600 keV and ~ 750 keV for the ^{60}Co and ^{137}Cs sources shown in Fig. 5.9 respectively represent background radiation in the detector. Discrepancies between the simulation and the data at low energies (< 200 keV) are due to threshold effects. This area is difficult to accurately model because it is very sensitive to effects such as the exact placement of the wires to the SSD.

5.3 Holifield Radioactive Beam Facility

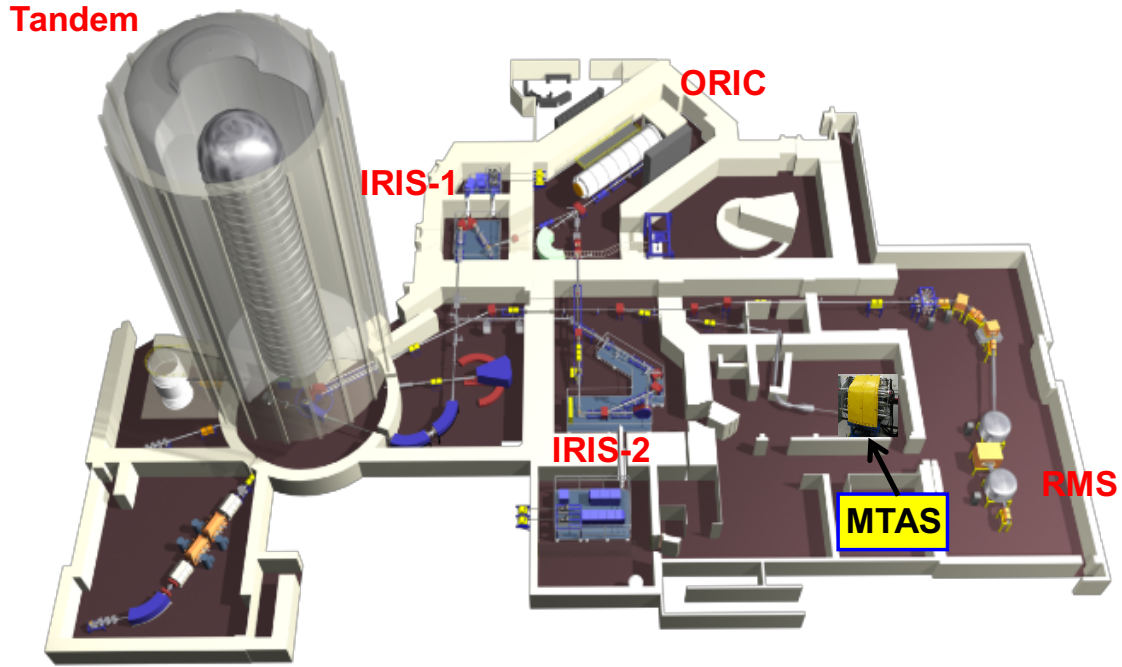


Figure 5.10: Diagram of HRIBF highlighting the location of MTAS.

The data for this project was collected at the Holifield Radioactive Ion Beam Facility (HRIBF) located within the Oak Ridge National Laboratory (ORNL). HRIBF provided radioactive beams using the isotope separation on-line (ISOL) technique. At the time of this run the original driver accelerator, the Oak Ridge Isochronous Cyclotron (ORIC), had been decommissioned. A ~ 50 pA beam of protons was accelerated in a folded geometry 25 MV tandem. The accelerated beam out of the tandem bombarded a thick uranium carbide target inducing fission within the target matrix. The fission products diffused out of the target to an ion source where they were ionized and then mass separated. Finally the beam was isobar separated and implanted on the MTC to be brought into MTAS. A full diagram of HRIBF is shown in Fig. 5.10. [51]

5.4 Data Collection with MTAS

There are two standard modes of data collection with MTAS. The first is an MTC cycle where a sample is collected on the tape in the beam pipe while simultaneously being monitored for beam purity using the HPGe detector. Once collection is complete, the sample can be paused, if desired, to wait for unwanted activity to die away. In the next phase, the MTC moves the tape with the sample into the center of MTAS with proper placement assured by the SSD. Here the sample is measured for an amount of time depending on the half-life of the nucleus of interest. Then the MTC moves the tape once again so the sample is now outside of MTAS and inside the shielded MTC box. During this phase a laser is pulsed for a period, usually 0.2 seconds, to allow for gain stabilization. Following this the cycle repeats and collection resumes. After a set number of cycles are completed, usually nine collections, a cycle with the beam off and no sample is run with the purpose of collecting background radiation. This data collection mode is most often used to measure individual, relatively short-lived nuclei.

The second collection mode of MTAS is a long collection. The procedure is similar except instead of many small collections, there is one long collection. The long collection is usually on the order of an hour and is followed by a long measurement, usually on the order of 12 hours. Background and gain stabilization are performed post measurement. Collections of this type are used for long-lived nuclei or for occasions where an extended look at the decay chain of a given mass is desired. Often times the first part of a long collection must be discarded because the large amounts of activity coming off of a large sample results in rate-driven PMT instability.

Chapter 6

Laser Gain Stabilization

6.1 Photomultiplier Tube Drift

MTAS contains forty-eight PMTs in total. Before every run all PMTs are gain matched with sources and an automatic gain matching program adjusts the voltages on the high-voltage power supplies. However, PMTs are known to exhibit gain instability resulting in mis-calibration. These instabilities can develop over time, a phenomenon known as drift, and are due to environmental factors such as temperature changes [25]. Because of the sheer number of PMTs in MTAS, certain hardware improvements were deemed necessary. The Laser Gain Stabilization (LaGS) system was developed to monitor for and correct PMT drift. LaGS generates a stabilized light pulse which shines into individual MTAS crystals generating a reference peak which can be tracked in time. The photopeak due to the laser is adjusted such that it appears well beyond the Q_β value of any nucleus, see Fig. 6.1. The location of the photopeak is determined by the parameters of the laser pulse.

LaGS has three outputs. One to the central module which allows for monitoring of all 12 central PMTs. The PMTs in the central module have proven to be very prone to rate-dependent drift. They have a large impact on the data as the central module captures the majority of the low energy γ rays and β particles. The second output goes to one of the modules in the inner ring and the third goes to the reference module beside MTAS as discussed in Chapter 1. The reference module has a ^{137}Cs source attached to it to monitor the

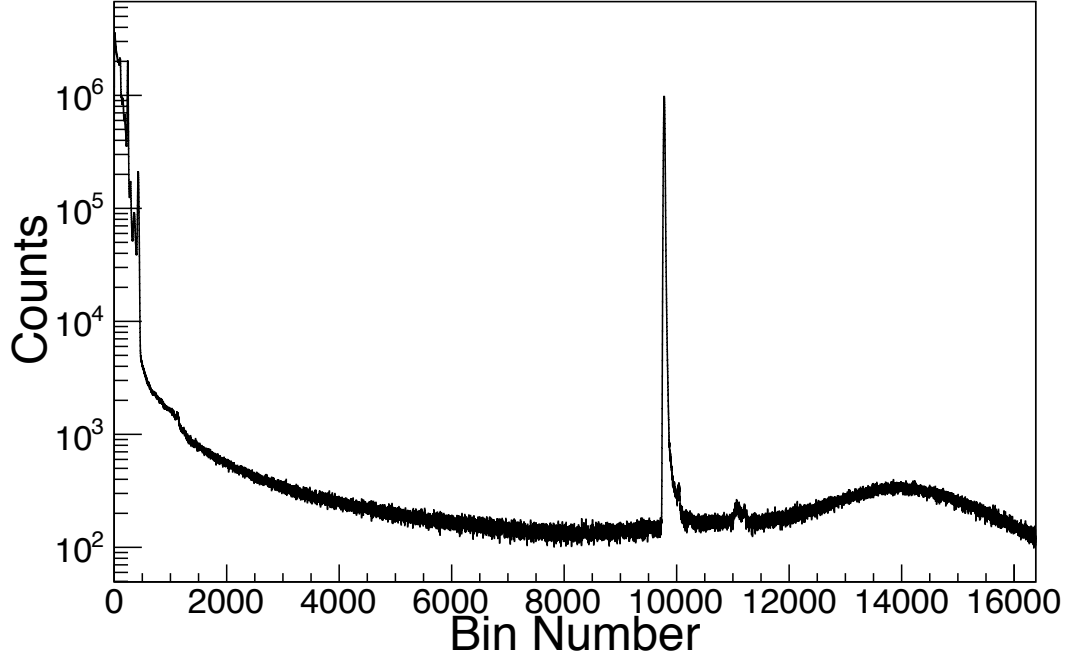


Figure 6.1: Histogram showing photopeak from laser in spectra with laboratory background. Laser photopeak located at bin ~ 10000 . The broad peak above the laser photopeak is most likely due to muon deposition in the detector.

stability of LaGS through the comparison of the relative positions of the 661 keV photopeak and the photopeak from the laser.

6.1.1 Design Considerations

There were several considerations taken into account during the design process for LaGS. The system must first and foremost be safe. LaGS contains a class IIIa laser and is thus capable of causing permanent eye damage. As such the laser must not be easily exposed. Second, light input into MTAS must be strictly controlled to avoid possible damage to the PMTs and DAQ as well as to not introduce unnecessary light into the modules of MTAS. Standardized components were desired for ease of procurement and construction. Finally, the system has to be robust so as not to falsely report PMT drift. To this end, the alignment of the optics should be stable and not easily interrupted.

Several designs were considered before settling on a final static design involving standard mounting components from Thor Labs. Some discarded designs included an integrating

sphere or the use of a translation stage in which the laser would stop and shine into each input to MTAS sequentially.

6.1.2 Laser

LaGS uses a BNC 6040 model laser pulse generator [1]. This model emits precisely timed and powered laser pulses at a wavelength of 405 nm with a maximum power of 5 mW. The pulser's timing and pulse height settings are controlled via RS-232 by a terminal computer station and is externally triggered to pulse at the appropriate time in the experimental cycle. Run settings are saved in device memory so the pulser can boot up in the correct configuration in the event of power loss.

6.1.3 Optics

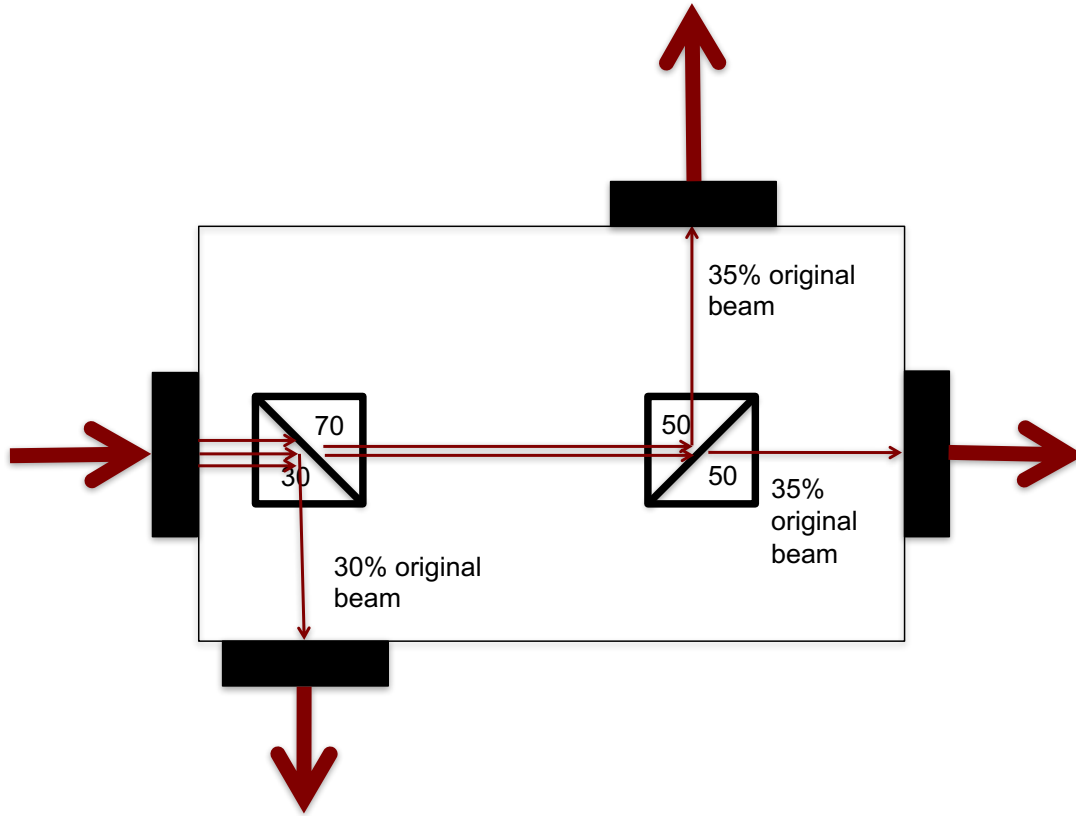


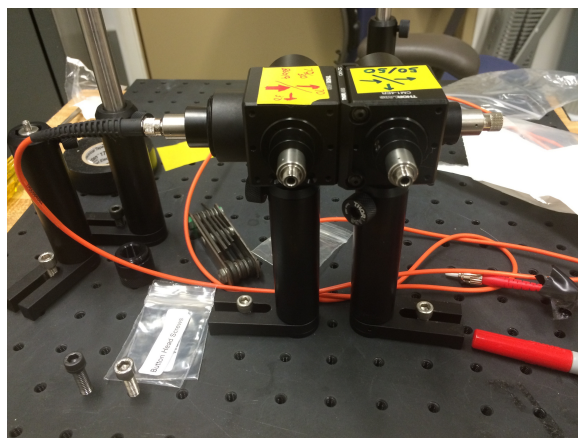
Figure 6.2: Schematic of LaGS optics. Not drawn to scale.

The light from the laser is split into three roughly equal beams using cube style beam splitters. At the input to the optics, the LaGS laser connects to a collimator lens via a fiber-optic cable. Light then passes through a 70/30 split followed by a 50/50 split. This configuration yields 30/35/35% split to each output respectively. Collimator lenses collect the light from the beam cubes and are in turn connected to one of the fiber-optic bundles that is optically coupled to one side of one module in MTAS. See Fig. 6.2 for a schematic of the optics.

Beam cube holders, mounted on posts and secured to a breadboard hold the beam splitters securely in place. The mounts for the collimator lenses couple directly to the beam cube mounts allowing for complete enclosure of the laser barring purposeful dismantling of



(a) topview



(b) sideview

Figure 6.3: Top and side views of the optics used in LaGS. The orange fiber-optic cable is the input to LaGS from the BNC 6040 laser module. Fiber-optic cables leading into MTAS are disconnected.

the system. This renders the apparatus virtually light tight although an added layer of black electrical tape was imposed as a secondary precaution. The mounts chosen are auto-aligning as by attaching the mounts the collimator lenses are automatically centered on the beam splitters. As such the optics are quickly assembled and robust enough to survive bumps and even transport. See Fig. 6.3 for a picture of the optics.

The collimator lenses are tuned to the 405 nm light from the laser by means of a reflective coating that is only permissive to wavelengths between 395 nm and 415 nm [7]. This serves to further reject ambient light and protect delicate hardware. The beam splitter cubes also have an antireflective coating on all four relevant surfaces permissive to wavelengths between 400-700 nm [6].

The only non standard parts are the terminations of the fiber-optic bundles that carry light out of LaGS to MTAS. These are SMA-style connectors that have been machined to be able to accomodate the large diameter bundle. The typical fiber termination and polishing method had to be adapted and each bundle terminated and polished by hand.

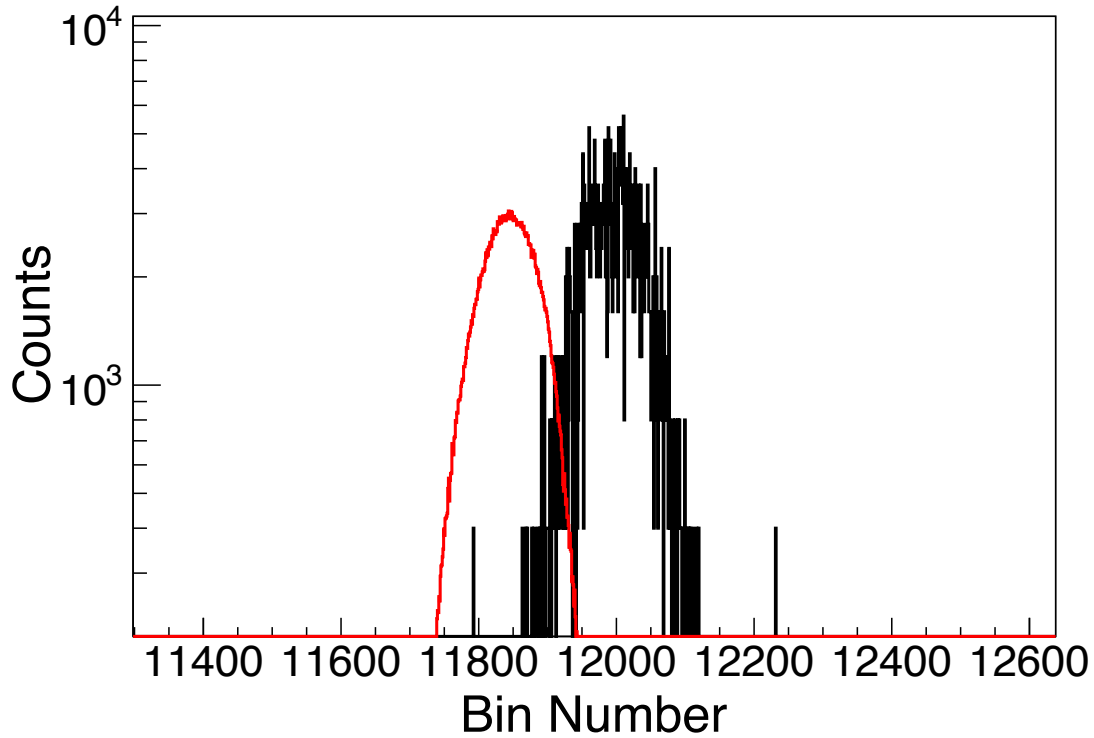


Figure 6.4: Spectra focusing on LaGS laser peak. The black spectrum was taken on January 25th, 2016 immediately after gain matching and during a run studying ^{131}Sn . The red spectrum was taken 4 days later on January 29th, 2016 during a ^{134}Sn collection. The difference in peak location is due to drift in the PMTs coupled to the central module.

6.2 Proof of Function

Gain matching the PMTs in MTAS during an experimental run is an hours-long process. It involves venting the vacuum of the beam pipe in the central module and inserting a suitable source. Then an iterative matching routine is executed to re-match the PMTs. Once the PMTs are matched, if the MTC was moved it must be restored to its proper location and the whole system must then be pumped back down to vacuum. Such a long process cannot reasonably be performed as often as necessary to completely prevent calibration shifts in the PMTs. Fortunately, LaGS has proven to be a very sensitive probe of PMT drift. LaGS has been fully tested and used in the 2015 and 2016 experimental runs at HRIBF. An example of drift observed during the MTAS January 2016 run is shown in Fig. 6.4. Over the course of four days the laser peak drifted ~ 200 channels. This does not necessarily correspond directly to a shift of 200 keV, due to the difficulties of calibration at such high energies, but

it is none the less an indicator of significant drift within the PMTs over the course of the experimental run.

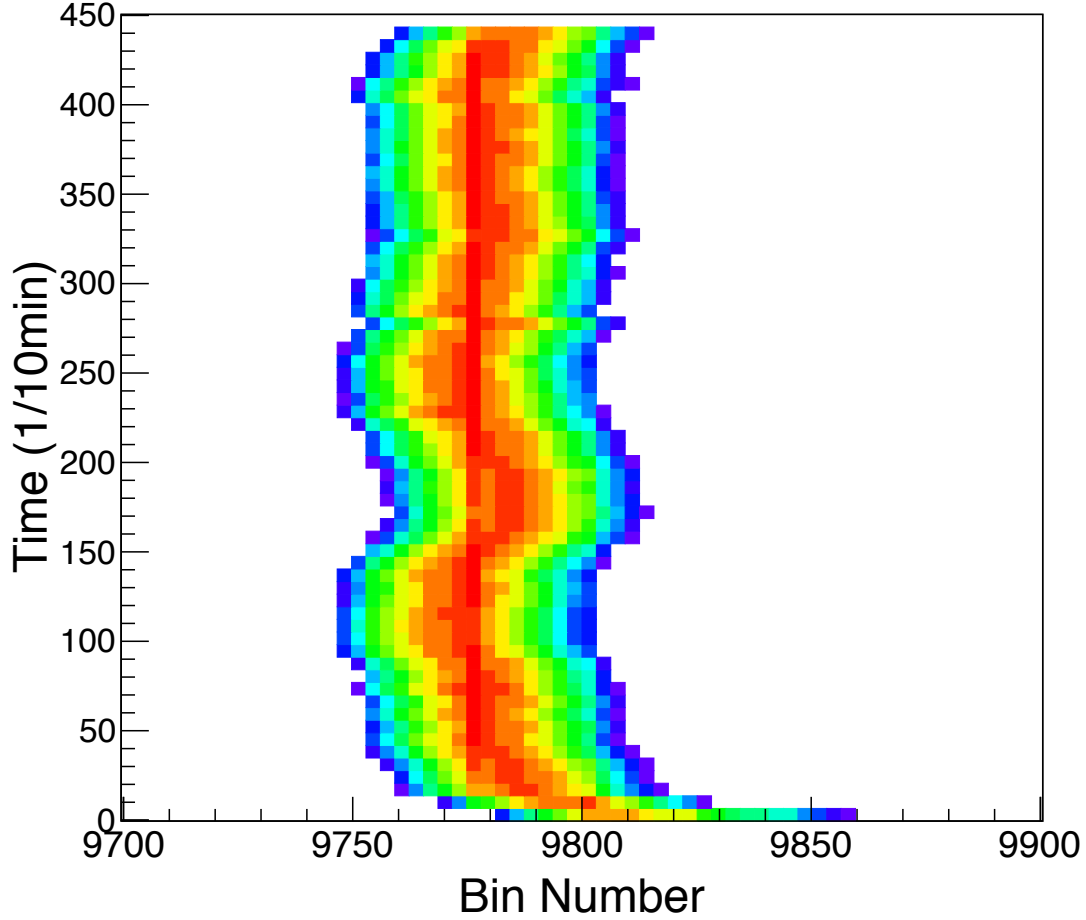


Figure 6.5: 72 hour LaGS sensitivity test. Demonstrates LaGS is sensitive to calibration shifts within 0.01%. The x axis is bin number. The y axis is time in tens of minutes, 4500 minutes = 3.1 days.

Prior to use in experiment, LaGS underwent rigorous testing both for stability and sensitivity. During one such test, LaGS was allowed to run over the course of 72 hours in August. The resulting spectrum, shown in Fig. 6.5 demonstrates the true sensitivity of LaGS to PMT drift. The drift, periodic in nature, represents the calibration shifts due to temperature in a climate controlled building over the course of day and night. A careful inspection of the spectrum reveals that one side of the function appears longer, this is due

to the longer length of the days with respect to nights in a Tennessee summer. In total, the drift observed here, measured by the amplitude between the maxima, was within 0.01%.

6.3 Recommendations for future improvements to LaGS

Currently LaGS has three outputs. A fiber-optic bundle that splits the laser light from one input into seven outputs has been procured and is awaiting testing. The laser input of LaGS is currently running under minimum power with a short pulse width (30 μ W peak, 300 ns pulse width). The laser is capable of supplying up to 5 mW of power. As such, there are two full orders of magnitude left in the supply capability. Even assuming an order of magnitude of light lost due to the lossy nature of freespace optics, LaGS could be capable of being expanded to twenty outputs, with four spares, using three of the aforementioned fiber-optic bundles. With a full twenty output system, gain stabilization could be supplied to every module in MTAS simultaneously.

LaGS could be further improved through the connection of the BNC laser module to the acquisition computer. This could be achieved through an ethernet to RS-232 or GPIB controller at which point settings on the laser could be controlled via the acquisition computer through a terminal.

Chapter 7

MTAS Data Analysis

The goal of the MTAS data analysis is to accurately extract the β -decay rates to states in the daughter nucleus. These decay rates can be converted into the decay strength distribution (S_β) from the experimental γ spectra of a given nucleus. The extracted S_β represents both allowed (Gamow-Teller) and forbidden transitions, topics introduced in Chapter 2. The Gamow-Teller strength (B_{GT}) is proportional to the transition matrix element between the initial state in the mother and a given final state in the daughter for Gamow-Teller type transitions. Taken as a distribution, it reflects the overlap between the mother's initial state and all final states in the daughter allowed by Gamow-Teller spin-parity rules. For Gamow-Teller transitions, isospin and total angular momentum can only change by ± 1 or 0 with no change in orbital angular momentum or parity.

The S_β distribution is used to validate the modified nuclear shell model discussed in Chapter 4. The extraction of S_β from MTAS experimental data will be discussed here.

A summary of the steps is as follows. During the preparatory phase, the experimental spectra must first be carefully calibrated and drift corrected. Then any contaminants (undesired activity, including background) is removed from the spectra. Once a clean experimental spectrum is obtained, β feeding to individual levels, I_β , can be extracted with the aid of GEANT4 simulations. These branching ratios representing feeding to individual states in the daughter are then converted into the decay strength distribution S_β . Errors are calculated using χ^2 analysis of I_β values.

7.1 Calibration

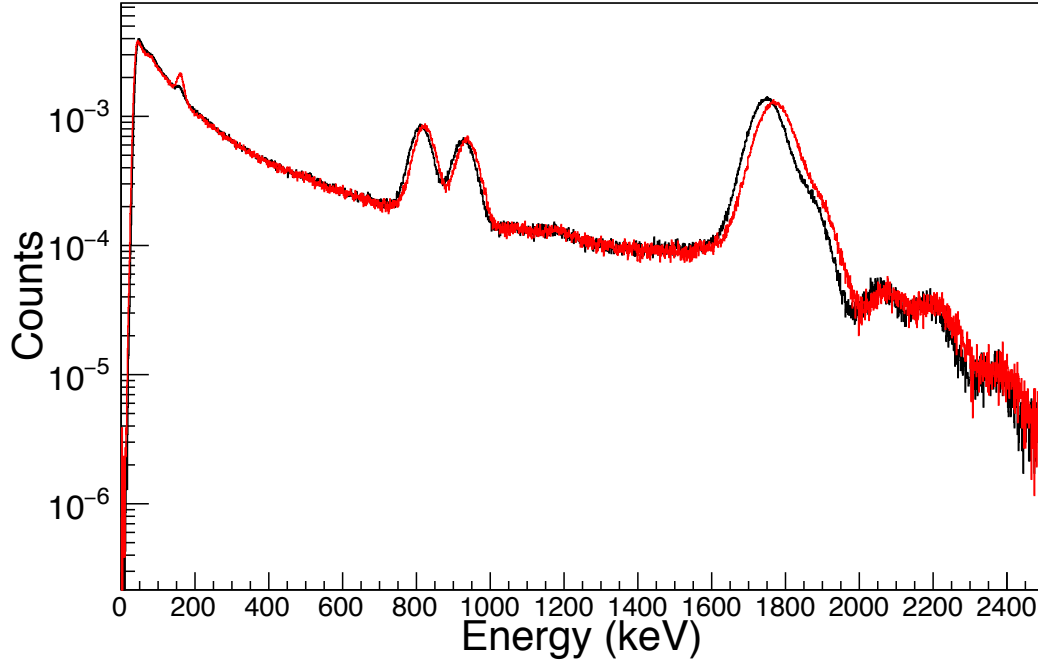


Figure 7.1: Correctly calibrated (black) and uncalibrated (red) β -gated ^{85}Br spectra. The peaks in the uncalibrated spectra are both shifted and wider when compared to the calibrated spectra due to drift in the PMTs.

The first step of the analysis was a linear calibration of all forty-eight channels in MTAS, given by $E_{\text{calibrated}} = aN_{\text{bin}} + b$ where N_{bin} is bin number. The results of the calibration are shown in Fig. 7.1. Before the MTAS experimental runs commenced, and at semi-regular intervals throughout, all of MTAS's PMTs were gain matched and calibrated on the 661 keV peak from a ^{137}Cs source as well as the 1460 keV peak from a ^{40}K source. This resulted in a rough 1 keV/channel calibration. Further discussion of the reasons for and methods of gain matching were presented in Chapter 6.

Data from eleven sources was also taken for the purposes of offline post-calibration of the data. These sources included ^{137}Cs , ^{137}Xe , ^{139}Xe , ^{22}Na , ^{54}Mn , ^{56}Co , ^{60}Co , ^{65}Zn , ^{87}Kr , ^{91}Rb and random room background for ^{40}K and the 511 keV electron-positron annihilation γ ray. Each PMT was calibrated individually using a routine written as part of this work. Following a general calibration, the central and inner modules were gain corrected to account

for PMT gain changes during collection of each dataset. The issue of gain correction was the motivation for the creation of LaGS, described in detail in Chapter 6.

7.2 Handling of Contamination

Following calibration, the data for each nucleus were checked against existing level scheme data in ENSDF. Contaminants were then identified and subtracted. Sources of contaminants include impurities in the beam, radiation from the decay of the daughter nucleus, and background radiation.

7.2.1 Removal of Contaminants in ^{85}Br

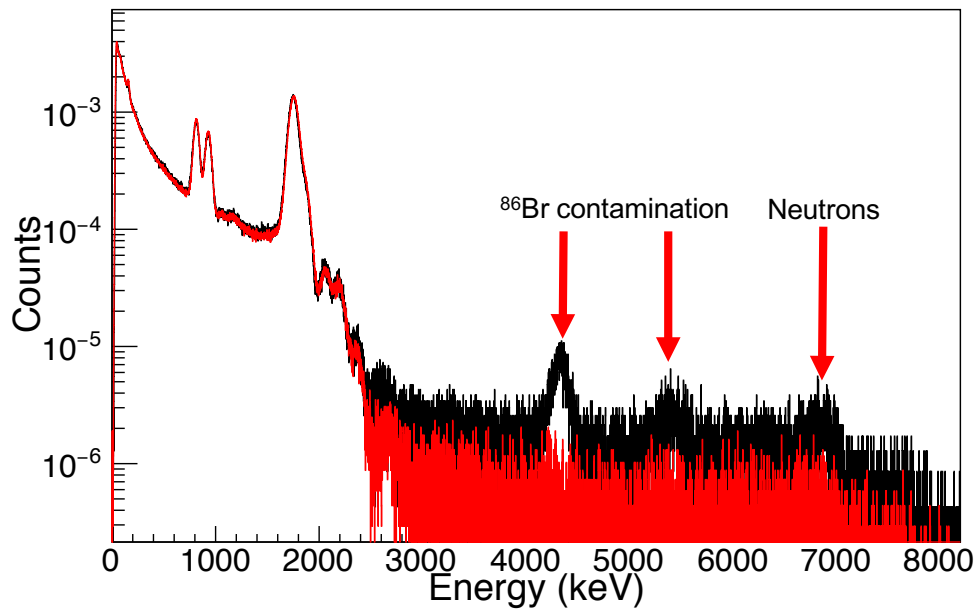


Figure 7.2: β -gated ^{85}Br spectrum with contaminants (black) and after subtraction (red). ^{86}Br was present in the beam, and the neutrons are due to ambient sources.

The sources of contamination in the ^{85}Br spectra include ^{86}Br contamination in the beam, background radiation and a small contribution of radiation from the decay of the daughter, ^{85}Kr . See Fig. 7.2. The contribution from the decay of ^{86}Br was easily subtracted as during the 2015 MTAS run a clean ^{86}Br dataset was also collected.

The β decay of ^{85}Kr has a very small Q_β window of 687 keV. This is low enough that β deposition did not significantly contribute to the ^{85}Br spectra. The first excited state in ^{85}Rb at 151 keV was visible but because it was located well below the first excited state in ^{85}Kr at 305 keV, its contribution was deemed negligible.

The majority of background radiation was eliminated from the dataset through the use of a β gate with a subsequent event window of 2 μs . Background radiation occurring during the event window was further subtracted through the use of the background cycles taken during the experiment. The background spectra were scaled for subtraction from the ^{85}Br data through making use of the neutron-capture peak in NaI(Tl) at ~ 6.8 MeV. This peak is the result of an $(n, n'\gamma)$ reaction with ^{127}I ($S_n=6.826$ MeV) within the NaI(Tl) [45]. Direct scaling of the 6.8 MeV peak in background to data was appropriate because neither the mother, daughter nor any contaminant nuclei are β -delayed neutron emitters. Therefore all neutrons present in the spectra can be assumed to be ambient and of constant rate within the window of data collection time post β gate.

7.2.2 Removal of Contaminants in ^{84}Br

The data for ^{84}Br were collected through a long collection of a single large sample over the course of an hour and was measured continuously for 7.5 hours. This differs from the normal operation of collecting smaller samples and running multiple tape cycles to collect a sufficiently large number of events as discussed in Chapter 5. As a consequence of the long collection time, the initial data rate in the central ring of MTAS of 27 kHz was high enough to cause rate-dependent drift in the PMTs. Therefore the first 1.5 hours of data was discarded in favor of a stable calibration. By discarding the first 1.5 hours of the dataset, the data from the 6^- isomer of ^{84}Br at 320 keV (6.0 minutes) was, unfortunately, eliminated from the spectra as fifteen half-lives of the given isomer had passed. Therefore, only the decay of the 2^- ground-state isomer (31.76 minutes) will be discussed in this dissertation.

The daughter of ^{84}Br , ^{84}Kr , is stable and there were no contaminants in the beam. Therefore the only outside contribution to the ^{84}Br spectra was background. Background subtraction was handled in the same manner as described above for ^{85}Br .

7.2.3 Removal of Contaminants in ^{86}Br

The removal of contaminants from ^{86}Br was the easiest of all three datasets. There were no contaminants present in the beam and the daughter of ^{86}Br , ^{86}Kr , is stable and therefore did not contribute any radiation. Therefore after calibration, ^{86}Br was background subtracted leaving a clean dataset.

7.3 Identification of New Levels

The segmentation of MTAS allows for identification of new levels in the radioactive species along with the path through which a given level de-excites through the use of γ - γ matrices. This technique, while limited by the native resolution of NaI and the efficiency of the detector, is beyond the capabilities of other TAS detectors. The geometry of MTAS allows for the separation of the inner portion of the detector, that is likely to see individual γ rays, from the remainder of the detector, which behaves as a traditional summing TAS detecting level energy.

A γ - γ matrix is defined here as a three-dimensional plot of one module of MTAS plotted against the another module or sum of modules. An example is shown in Fig. 7.3 where three previously undetected high-energy levels in ^{85}Kr are highlighted. The resulting plot, when taken topographically shows a level energy on the y axis and γ energy on the x axis. Illustration of this point is shown in Fig. 7.4.

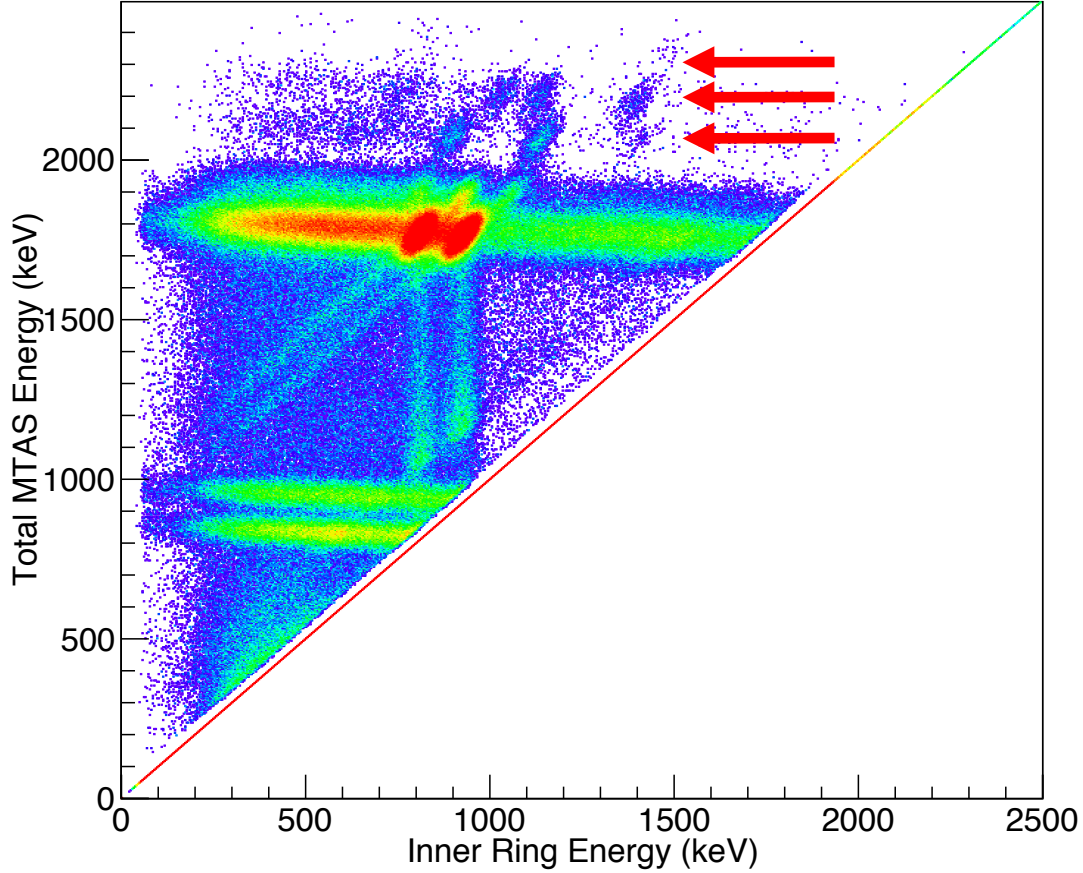
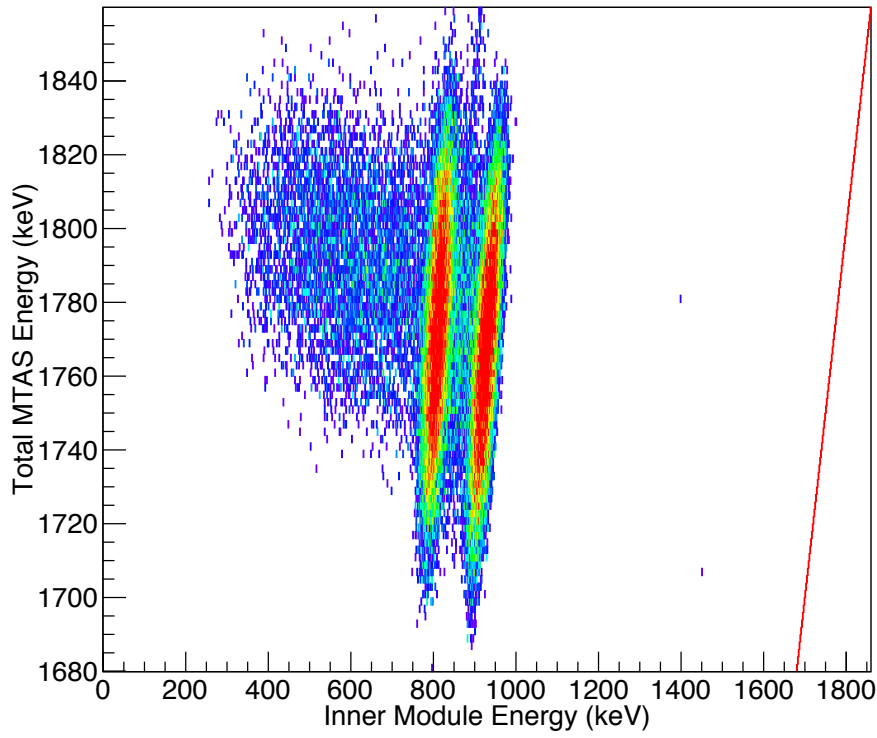
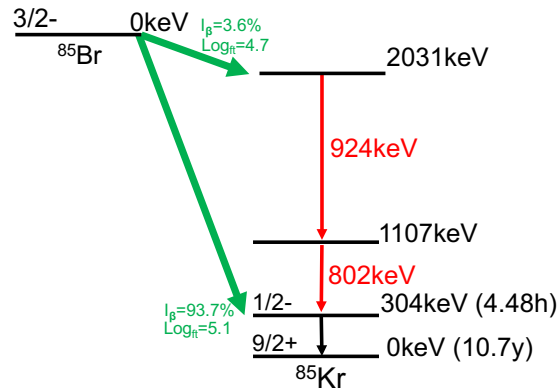


Figure 7.3: ^{85}Br γ - γ matrix. Dots represent correlated events. Summed MTAS energy is on the y axis and inner module energy is on the x axis. Taking a look at the broader picture, the loci represent γ -ray energy. The plot should be interpreted as the energy of individual γ rays on the x axis and the energy of the level that the γ ray de-excites on the y axis. The red diagonal line represents summed energy and is useful for identifying level energy. With this method levels can be identified as well as the path through which they de-excite. To obtain the excitation energy of a given level in ^{85}Kr , the energy of the isomeric state, 305 keV, must be added to the observed energy. This is due to the fact that the isomeric state's decay to the ground state was not detected in this experiment as the half-life is 4.48 hours. Therefore the isomeric state is effectively the ground state as seen by MTAS. Three newly detected levels at 2137 keV, 2329 keV and 2649 keV are highlighted. These newly detected levels will be discussed in detail in Chapter 8.



(a)



(b)

Figure 7.4: a) γ - γ matrix for the decay of ^{85}Br zoomed in on the level at 2031 keV. MTAS views this level at ~ 1726 keV due to the long lifetime of the 305 keV isomeric state. The two strongest γ rays from this level are shown. b) ^{85}Br decay scheme for the level at 2031 keV.

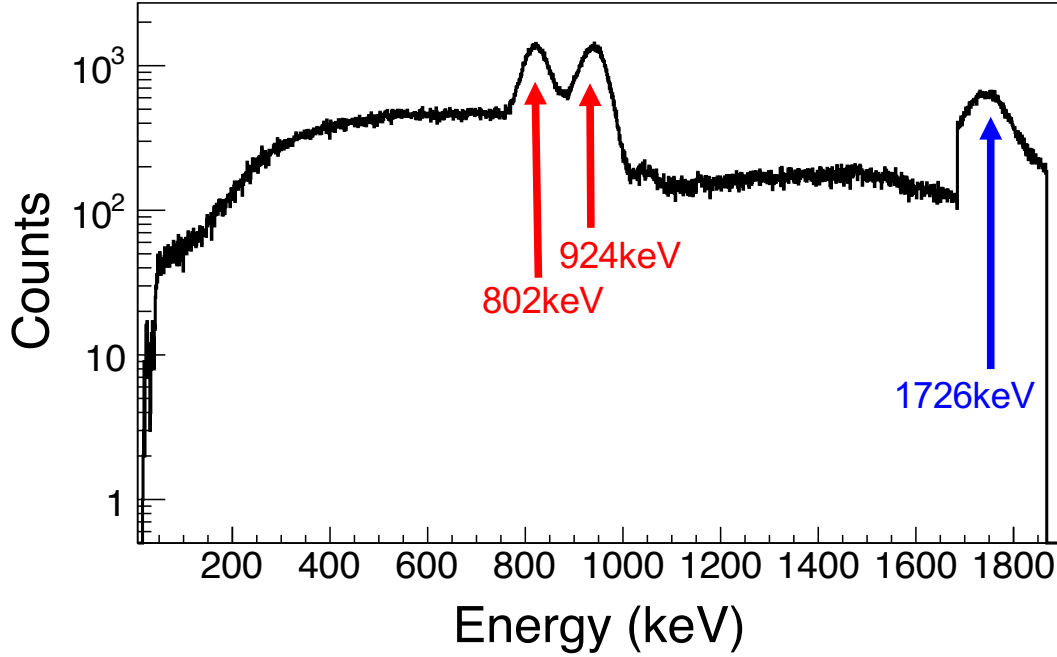


Figure 7.5: Projection taken around level at 2031 keV in ^{85}Kr γ - γ matrix. The peaks due to 802 keV and 924 keV γ rays are highlighted in red and the peak due to sum, equal to level energy, is highlighted in blue. The offset before the 1726 keV peak is due to the fact that the peak is located on the summed line showing energy deposited in all of MTAS, visible as the mostly red diagonal line in Fig. 7.3. Please note that because the 2031 keV level decays to the long lived (4.48 hour) 305 keV isomeric state, it appears shifted down by 305 keV.

For each newly detected level, projections were taken encompassing that level for both the inner ring versus total MTAS and central ring versus total MTAS, example shown in Fig. 7.5. Then gaussian fits including background contributions were performed for all γ rays observed. The area of the fits were scaled with a well known γ ray in the level scheme through taking a projection around a strongly β -fed level. Then γ -ray intensity was estimated by convolving the extracted and scaled fit area with the efficiency of the detector using Equation 7.1. β feeding to a given level was calculated by summing up all the γ -ray energy in the cascade in the form of the area under the peaks.

$$\varepsilon = \varepsilon_{Total}(E_{Level}) \cdot \varepsilon_{Ring}(E_{\gamma}) \quad (7.1)$$

Decay paths were assigned using the knowledge of γ energy, level energy and the existing level scheme in ENSDF. With these three known quantities, it is only a matter of finding where the γ rays fit within the decay scheme in order to make the assignments.

7.4 Limitations of γ - γ Analysis

The γ - γ analysis described here is a powerful tool but is not without limitations. It is best applied for nuclei near closed shells, and therefore whose spectra have well separated levels. Nuclei that decay to highly excited states with high level densities and other nuclei with more complicated configurations, likely to be observed in mid-shell nuclei, would be more difficult to analyze due to the limited resolution of a NaI(Tl) detector of this type. In cases such as these, it is best to employ an approach involving the placement of groups of pseudo-levels with separations of ~ 20 keV that decay via E1, E2 or M1 transitions to known levels [54, 55, 34, 22].

7.5 Discussion of the Role of γ - γ Matrices in the Disqualification of ^{85}Se as a Valid Dataset

Originally this work was meant to include data from the decay of ^{85}Se as the primary physics case. That data, obtained during the 2011 commissioning run of MTAS at HRIBF, proved to be far too contaminated and thus were discarded. In spite of this fact the case of ^{85}Se is useful as a demonstration of the power of γ - γ matrices in the identification and elimination of contaminants in a dataset.

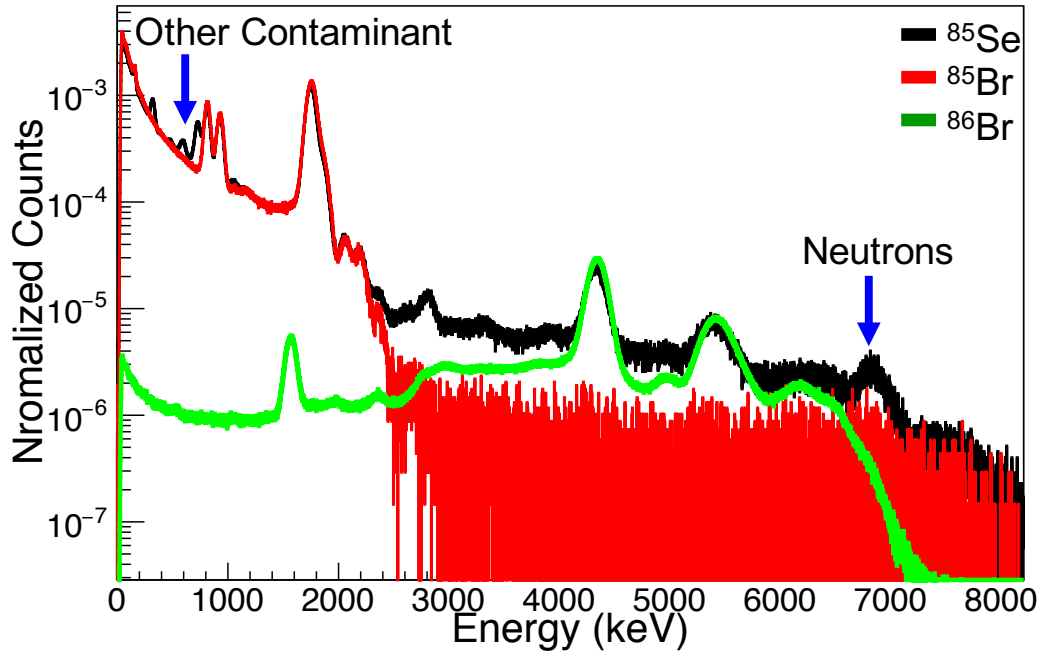


Figure 7.6: ^{85}Se dataset (black) plotted with ^{85}Br (red) and ^{86}Br (green). Background radiation has not been subtracted, thus the neutron peak is still visible. The neutron peak and other contaminant highlighted with blue arrows.

As one would expect, the decay of the daughter of ^{85}Se , ^{85}Br , is present in the dataset as shown in Fig. 7.6. Therefore the first step in isolating ^{85}Se was to remove ^{85}Br . This was achieved through a time gate making use of the different half-lives of ^{85}Se and ^{85}Br , 32.9 seconds and 2.90 minutes respectively. Given that the longest data collection for the ^{85}Se run was 300 seconds, clean ^{85}Br data were obtained by isolating data taken between MTC cycle second 160 and 300 and was subtracted from second 35 to 160. The purpose here being

that by taking the data present after more than four half-lives of ^{85}Se , it could be safely assumed that the decay of ^{85}Br was the main contributor at that point in the tape cycle. This subtraction was repeated later, with better statistics after ^{85}Br data were taken during the 2015 MTAS run. This was thought to yield a clean ^{85}Se dataset and work on identifying any new levels was begun.

However, it later became apparent that the high-energy peaks around 4-6 MeV, first assumed to belong to ^{85}Se as they are well beyond the Q_β value of ^{85}Br at 2.9 MeV, were in fact due to ^{86}Br contamination in the beam. Because ^{86}Br data were also taken during the 2015 run of MTAS, this contribution too could be subtracted from the dataset leaving what was then assumed to be a “clean” ^{85}Se spectrum.

Difficulties persisted however. The peak located at 321 keV, highlighted in Fig. 7.6 was first thought to be the first excited state in ^{85}Br , located at 345 keV, shifted due to error present in the calibration. After a thorough re-calibration and drift correction, the peak still did not align with 345 keV. At this time, the γ - γ matrix for the decay of ^{85}Se , as shown in Fig. 7.7, was examined and an unexpected level and associated cascade were immediately obvious around ~ 730 keV. Taking a projection, shown in Fig. 7.8 between 690 and 760 keV revealed a clear cascade with a β -fed level at 728 keV decaying via a 408 keV γ ray to an also β -fed level at 320 keV which then decays to the ground state. ^{85}Br does not have any levels at 728 or 320 keV so it was decided that this contribution was, in fact, due to another in-beam contaminant and that very little, if any ^{85}Se decay was present in the supposed ^{85}Se dataset. Sources of molecular contaminants consisting of highly-bound sulphide or fluoride compounds with mass $A=85$ that can survive extraction from the uranium carbide target were explored. However, no obvious candidates matched the signature of the contaminant. Additionally, after a triple background subtraction the statistics of the dataset were very poor so the analysis was subsequently abandoned.

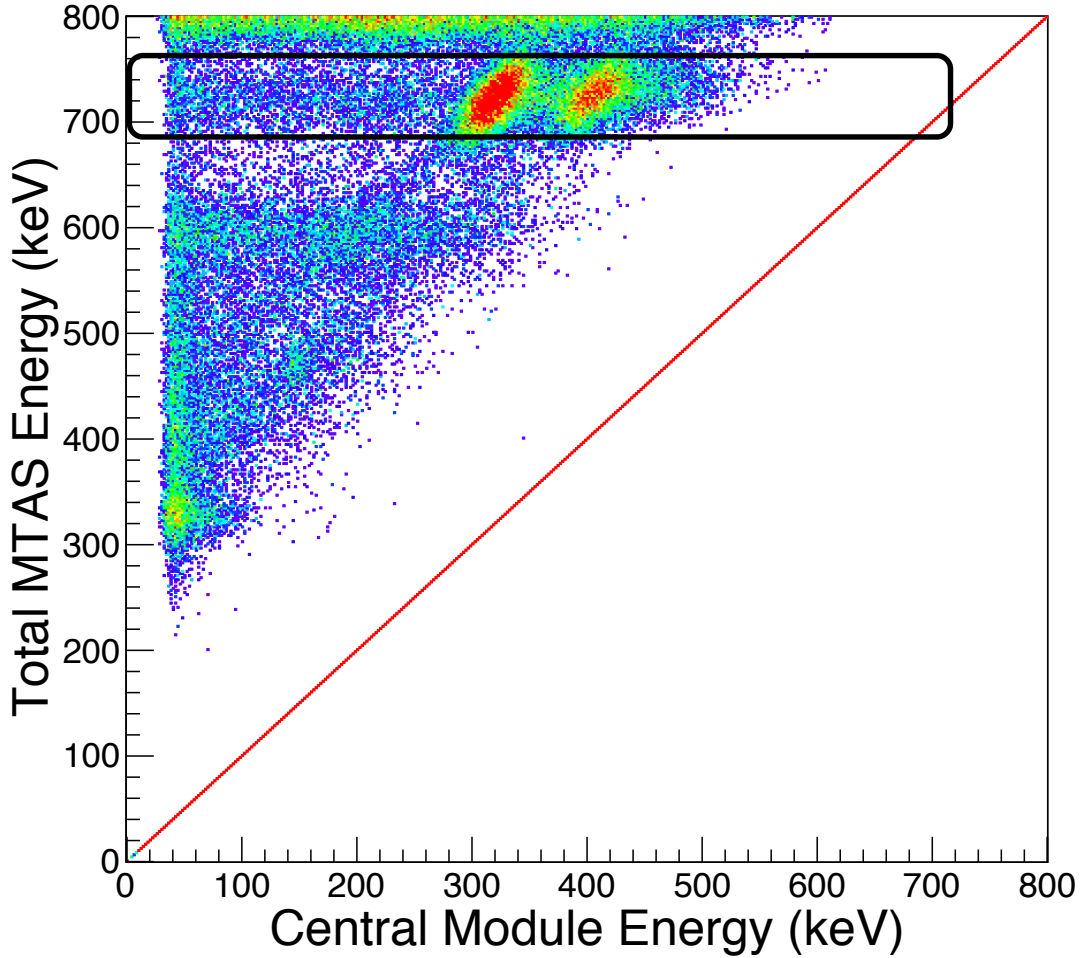


Figure 7.7: γ - γ matrix for the decay of ^{85}Se , showing γ emission in ^{85}Br . 728 keV level and associated decay due to contaminant inside black box.

7.6 Adjustments to Decay Scheme

Once any new levels and their resulting decay paths were identified and the corresponding β and γ feedings estimated, the results were combined with decay data from ENSDF and formatted as an ENSDF style data file. These data were then run through the Geant4 model of MTAS as discussed in Chapter 5.

In the first pass, β feedings were iteratively adjusted until good agreement between the simulations and data for the total summed spectra of MTAS was reached. Once agreement was close, a fitting routine using the maximum entropy method [54] was employed. Because

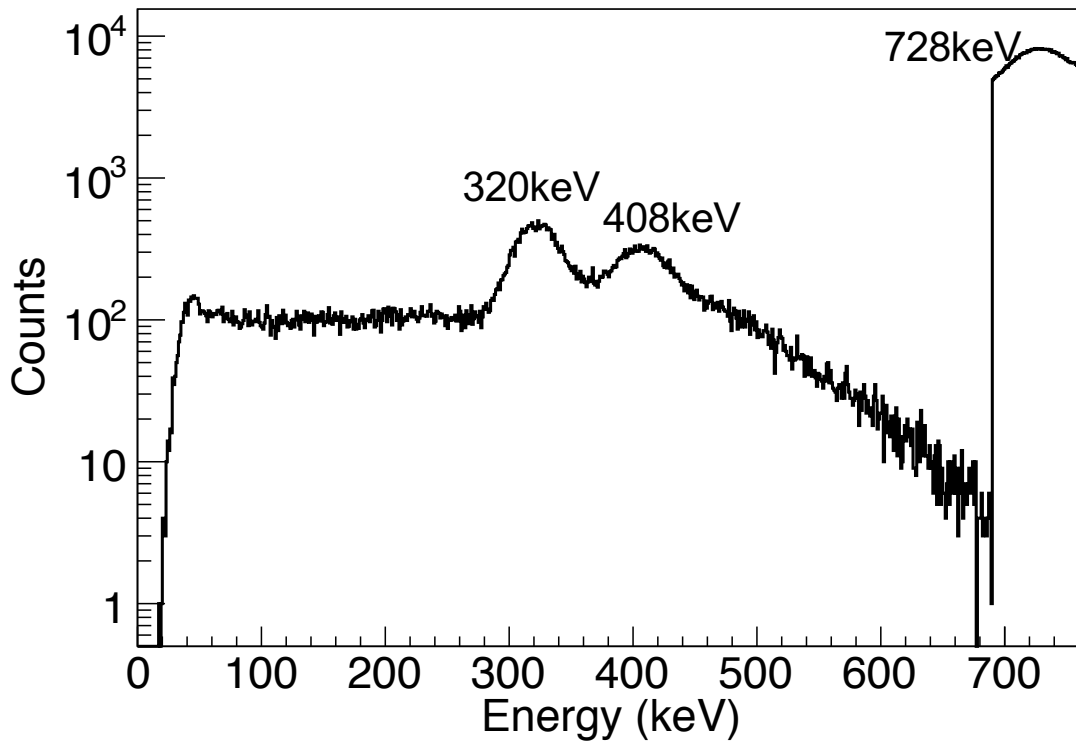


Figure 7.8: Projection of γ - γ matrix around 728 keV contaminant level in ^{85}Se dataset. 320 keV and 428 keV γ -rays highlighted as well as summed level at 728 keV.

peaks corresponding to individual γ rays are visible when just looking at the central and inner modules of MTAS, see Fig. 7.9, the next step involved iterative adjustments to γ feedings for those modules. Then a final readjustment of β feeding was performed for the total summed spectra. Adjustments to γ feedings proved significant as differences in extracted strengths, described in the the next section, of up to 20% were noticed on some well β -fed levels post γ correction. Some of the weakly β -fed levels had strengths altered by up to 50%. This indicates that knowledge of the path through which a level de-excites is an important factor in understanding the structure of a given nucleus.

The case of ^{84}Br , shown in Fig. 7.10, is used here as an example to demonstrate the completed feeding adjustments.

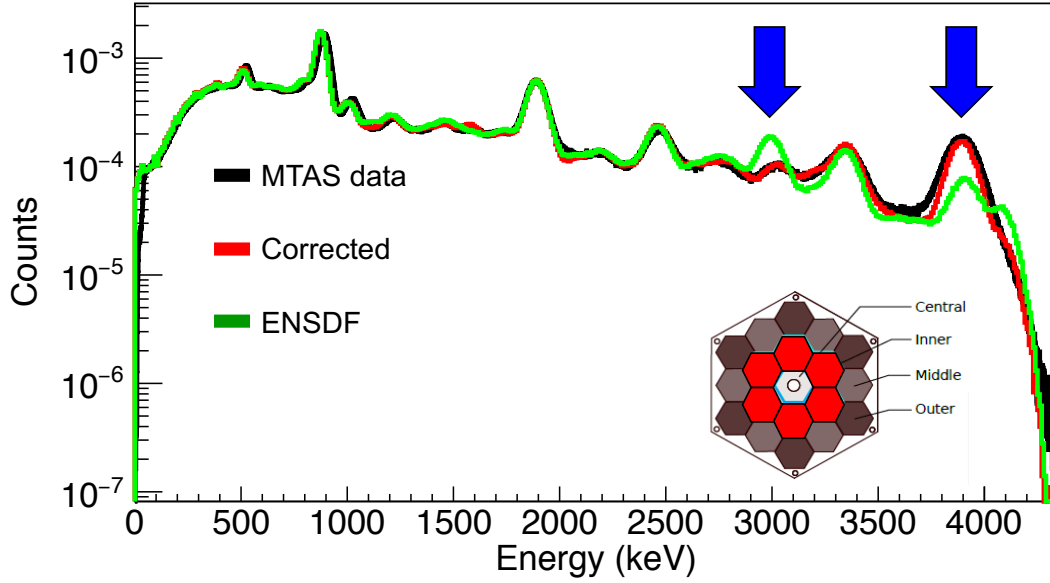


Figure 7.9: Demonstration of γ rays (highlighted with blue arrows) in ^{84}Br central module spectra. MTAS data are in black, the simulation of the corrected spectra is in red and the simulation of the data currently in ENSDF is in green. The central module of MTAS is highlighted in red on bottom right.

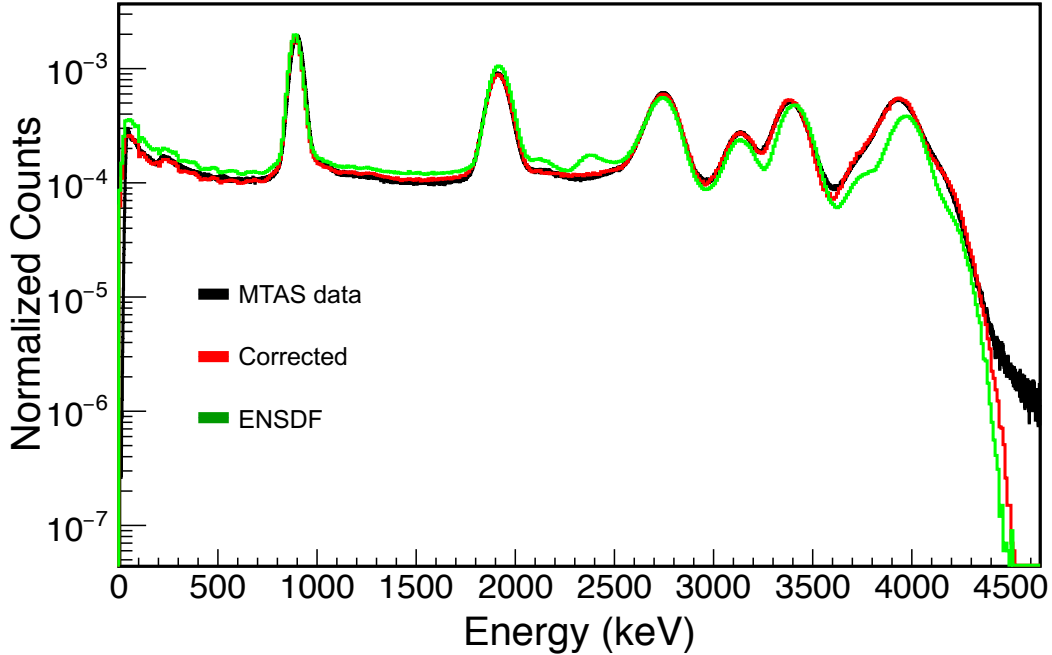


Figure 7.10: Comparison of ^{84}Br data (black), Geant4 simulation of ^{84}Br using ENSDF data (green) and Geant4 simulation with corrected β and γ feedings (red).

7.7 Ground State Feeding

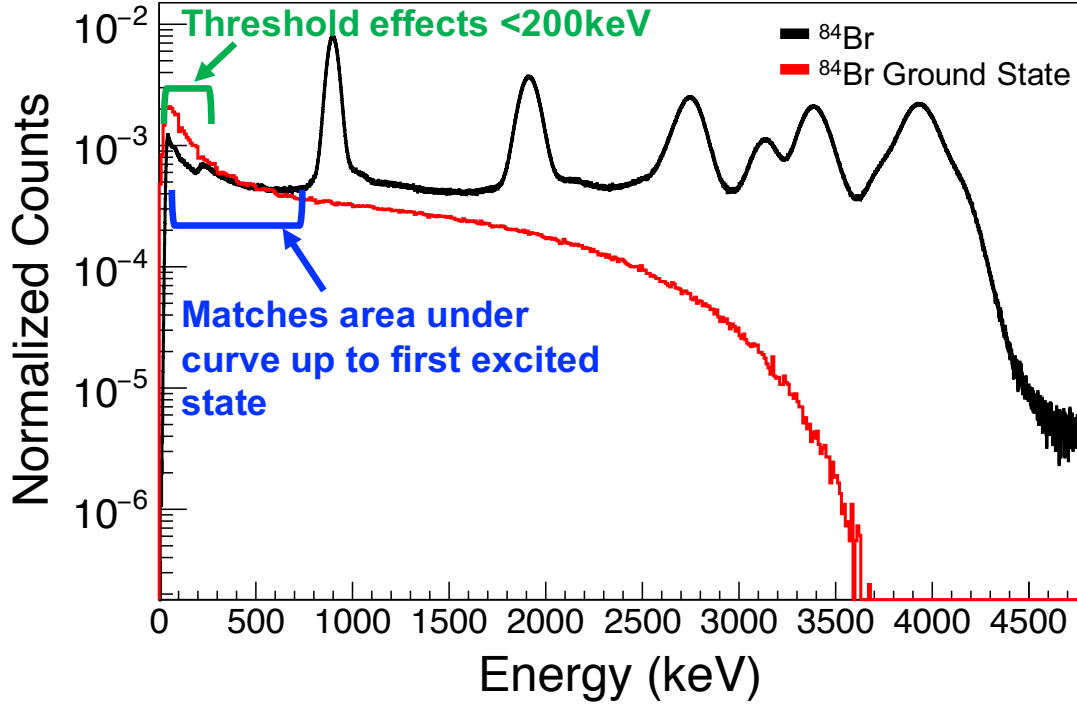


Figure 7.11: Demonstration of how β feeding to the ground state in the daughter is determined. The MTAS data for ^{84}Br data are in black and a GEANT4 simulation for just the ground state contribution in ^{84}Br is shown in red. The first ~ 200 keV are very sensitive to threshold effects and are therefore disregarded.

The β feeding to most levels is determined through relative peak height in the experimental spectra. The β feeding to the ground state of the daughter nucleus cannot be seen in the form of a discrete peak, however, because the ground state does not emit any γ radiation. For nuclei with large Q_β values, the relatively high energy electrons emitted when the ground state is fed are capable of passing through both the beam pipe and material wrapping the modules to be deposited in the NaI. Because the emitted β radiation does deposit energy in active detector material it must be part of the deconvolution of the spectra. This deposited energy is apparent in the form of a distribution of events underneath the peaks in the spectra, as shown in Fig. 7.11. Adjustments to the simulated ground state feeding in the daughter are made accordingly with specific focus given to matching the areas under the curves of the experimental and simulated spectrum up to the first excited state. The first

~ 200 bins in the simulated spectra are very sensitive to what is termed threshold effects. The spectra in this area is highly responsive to, for example, the exact placement of the wires leading to the SSD and is therefore difficult to accurately simulate. Consequently, the first ~ 200 keV is disregarded in comparisons between simulation and data.

7.8 Extraction of Decay Transition Strengths

After adjustments to β and γ feedings are complete, $\log(ft)$ values are calculated using the LOGFT utility from ENSDF [2]. The B_{GT} can then be extracted using Equation 7.2.

$$ft = \frac{D}{B_F + (\frac{g_a}{g_v})^2 B_{GT}} \quad (7.2)$$

Where $D = \frac{\ln(2)\bar{K}^{-1}}{g_v^2} = 6144.2(13)$ seconds, $\frac{g_a}{g_v} = -1.2695(29)$, and B_F is defined as the Fermi matrix elements and therefore $B_F = 0$ [49].

7.9 χ^2 Error Analysis

Errors were calculated with a χ^2 analysis which evaluates the variance between the data being evaluated and the model being used to describe the data with respect to the error distribution of the samples. χ^2 is given by Equation 7.3

$$\chi^2 = \sum \left\{ \frac{1}{\sigma_i^2} [y_i - y(x_i)]^2 \right\} \quad (7.3)$$

[12] where for each bin $\sigma_i = \sqrt{N_{counts}}$. In this case the model describing the data is the same maximum entropy fitting routine described above. The fitting routine was used iteratively, changing the β -feeding intensity, I_β , to a given level in steps of 0.1% and repeating the fit with alterations to the feeding up to $\pm 10\%$ of the original I_β . This yielded a set of raw χ^2 values versus I_β . However, the degrees of freedom, $\nu \gg 1$ in this case so the raw χ^2 value alone was not a good approximation of the error. Therefore the reduced χ^2 , χ_ν^2 , was necessary. χ_ν^2 is given by Equation 7.4

$$\chi_\nu^2 = \frac{\chi^2}{\nu} \quad (7.4)$$

where $\nu = N_{bins} - 2N_{levels}$ with N_{levels} being the number of levels. The factor of 2 is derived from the fact that we fit level energy and the β -feeding intensity to each level when calculating the raw χ^2 .

The function χ_ν^2 versus I_β , was then fit with a second order polynomial $y = ax^2 + bx + c$, example shown in Fig. 7.12. Error was calculated using the extracted fit parameters a , b , and

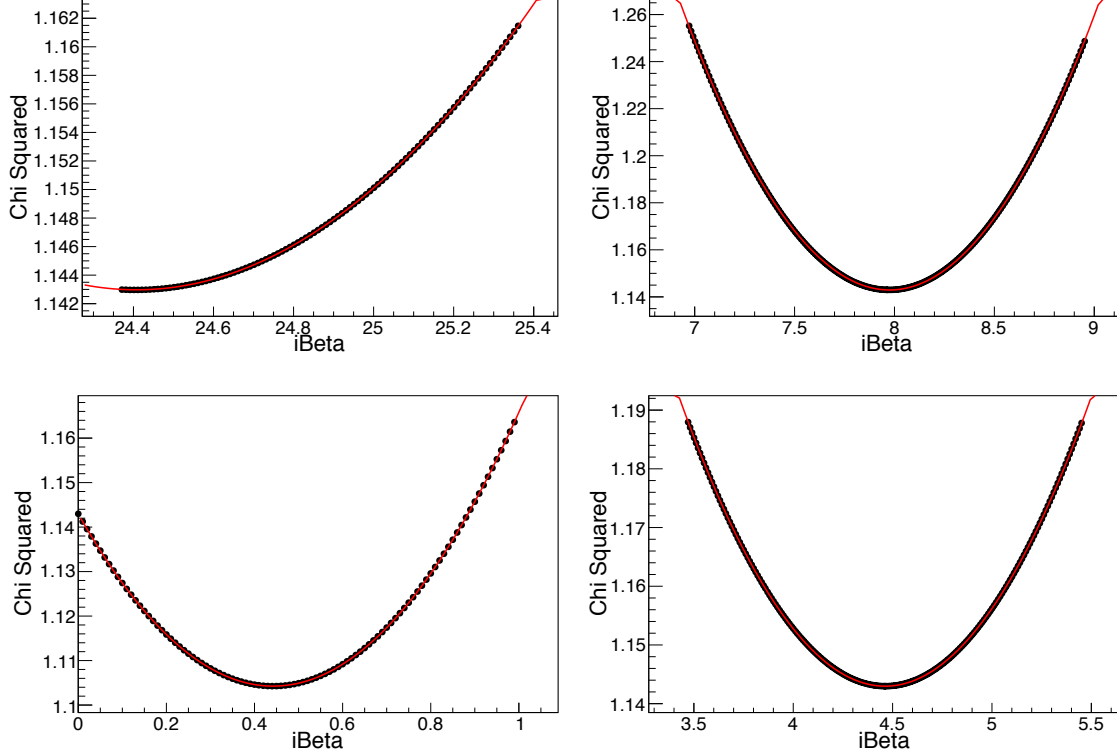


Figure 7.12: Four examples showing χ_ν^2 versus I_β fitted with a second order polynomial for levels in the decay of ^{84}Br . The entire range of $\pm 10\%$ of I_β was not always covered due to a bug in the iterative fitting program generating the raw χ^2 values. The resulting fits to χ_ν^2 were, however, not impaired.

c. Minimum and maximum error, $E_{\min, \max}$, is the solution to the second order polynomial given by Equation 7.5.

$$E_{\min, \max} = \frac{-b \pm \sqrt{b^2 - 4a(c - \chi_{\min} - \sigma_{\text{var}})}}{2a} \quad (7.5)$$

where $\chi_{\min}$ is the value of χ_ν^2 at the minimum of the parabola and is given by $\chi_{\min} = -\frac{b^2}{4a} + c$. σ_{var} is the variance away from $\chi_{\min}$ to chosen to be $\sim 1\sigma$ from the minimum value and is dependent on the degrees of freedom ν . In this case $\sigma_{\text{var}} = 0.02\chi_{\min}$. This value was chosen with a reference table [48]. This method was used to calculate error for each level in the decays of $^{84,85,86}\text{Br}$.

7.10 Treatment of γ rays in TAS Analysis

While MTAS is obviously capable of seeing some γ rays, as evidenced by the efficacy of γ - γ matrices, it is important to remember that MTAS is still a summing detector and therefore is not tuned to γ -singles measurements. It is for this reason that the γ -ray cascades seen through γ - γ matrices are used as a starting point in the analysis and the fine-tuning is achieved with the use of the Geant4 model discussed above. The effect of the difficulty of detecting individual γ rays with this setup is that γ rays are treated as if they are virtual. That is to say that while their energies are reported their individual strengths and associated errors are not. In order to accurately report on the properties of individual γ rays, high resolution spectroscopy measurements would have to be included in tandem with the TAS measurements listed here. Unfortunately that is beyond the scope of this particular experiment.

7.11 Calculations of $\langle E_\gamma \rangle$, $\langle E_\beta \rangle$ and Anti-neutrino interactions with matter

The final step of the analysis is to calculate the average γ energy, $\langle E_\gamma \rangle$, average β energy, $\langle E_\beta \rangle$, and the expected number of anti-neutrino interactions with matter resulting from the β decay of $^{84,85,86}\text{Br}$. These three calculations are critical for understanding the implications the results of this dissertation have for practical applications, such as decay heat production in nuclear reactors.

7.11.1 Calculating $\langle E_\gamma \rangle$

The $\langle E_\gamma \rangle$ is given by the sum over all levels in the decay scheme of the β -feeding branching ratio for each level, I_β , multiplied by the energy of a given level, E_L , as shown in Equation 7.6.

$$\langle E_\gamma \rangle = \sum^{levels} I_\beta E_L \quad (7.6)$$

7.11.2 Calculating $\langle E_\beta \rangle$

In order to calculate the $\langle E_\beta \rangle$ of the decay of a given nucleus, the distribution of emitted β radiation, $N(E_\beta)$, with the assumption that the decay is **allowed**, must first be calculated for each individual level. $N(E_\beta)$ is given by Equation 7.7

$$N(E_\beta) = \sqrt{E_\beta^2 + 2E_\beta + m_e c^2} (Q_\beta - E_\beta)^2 (E_\beta + m_e c^2) f(Z, E_\beta) \quad (7.7)$$

where E_β is the energy of the β particle, m_e is the mass of the electron, c is the speed of light, Q_β is the energy available in the β decay of the given nucleus and $f(Z, E_\beta)$ is the Fermi function [36]. Then $\langle E_\beta \rangle$ for a single level may be given by summing the average β energy for a given level times the branching ratio of that level. The $\langle E_\beta \rangle$ of the nucleus is then given by summing over all levels in the decay scheme, the full equation is shown in Equation 7.8.

$$\langle E_\beta \rangle = \sum^{levels} I_\beta \left(\sum^{bins} N(E_\beta) E_\beta \right) \quad (7.8)$$

7.11.3 Calculating the Expected Number of Anti-neutrino Interactions with Matter

The distribution of the emitted anti-neutrinos for a given level, $N(E_{\bar{\nu}_e})$, is calculated virtually identically to $N(E_\beta)$. Because anti-neutrino energy $E_{\bar{\nu}_e} = Q_\beta - E_\beta$, a simple substitution is made to Equation 7.7 such that $N(E_{\bar{\nu}_e}) = N(Q_\beta - E_\beta)$.

The cross section for anti-neutrino interaction with matter is given by $\sigma_\nu(E_{\bar{\nu}_e}) = aE_{\bar{\nu}_e}^2 + bE_{\bar{\nu}_e} + c$. The coefficient values, calculated by Strumia et al., are $a = 0.00871253 \times 10^{-41} \text{ cm}^2/\text{MeV}^2$, $b = -0.0196754 \times 10^{-41} \text{ cm}^2/\text{MeV}$ and $c = 0.00722737 \times 10^{-41} \text{ cm}^2$ [52].

Finally, the number of anti-neutrinos emitted in the β decay of a given nucleus that are expected to interact with matter is given by Equation 7.9.

$$N_\nu = \sum^{levels} \int_0^{Q_\beta} \sigma_\nu(E_{\bar{\nu}_e}) N(E_{\bar{\nu}_e}) dE_{\bar{\nu}_e} \quad (7.9)$$

It is necessary to sum over each level because, as mentioned above, $N(E_{\bar{\nu}_e})$ provides the distribution of emitted anti-neutrinos for a single level.

Chapter 8

Results of $^{84,85,86}\text{Br}$ Analysis

The results of the analysis for each nucleus will be discussed here. Please see Appendix [A](#) for a full list of β feedings and extracted S_β for each level in each nucleus with accompanying error. Newly detected levels are highlighted there in red.

8.1 Results from the Analysis of the β decay of ^{84}Br

The analysis of the decay of the 2^- ground-state isomer (31.8 minutes) of ^{84}Br yielded no newly detected levels. The only addition to the decay scheme was a 3878 keV γ ray decaying from the level at 3878 keV to the ground state. A significant amount of decay strength was shifted up to high energies, as illustrated in Fig. [8.1](#). Specifically, the corrected β feedings show a 7.7% increase in feeding to levels above 1.7 MeV relative to the data currently in ENSDF. There was also a decrease in feeding to the ground state of 8.6% relative to ENSDF. The corrected β feeding and extracted S_β for ^{84}Br with error bars are shown in Figures [8.2](#) and [8.3](#) respectively.

The decay scheme for ^{84}Br is shown in Fig. [8.4](#). It is important to note that for this, and all other decay schemes shown in this document, that the γ intensity, I_γ , represent not the number of γ rays per 100 decays but rather the amount of intensity, in the form of a percentage, that they carry away from the level they are directly de-exiting. This is due to the fact that, as mentioned in Chapter [7](#), γ rays are being treated as virtual. The decay

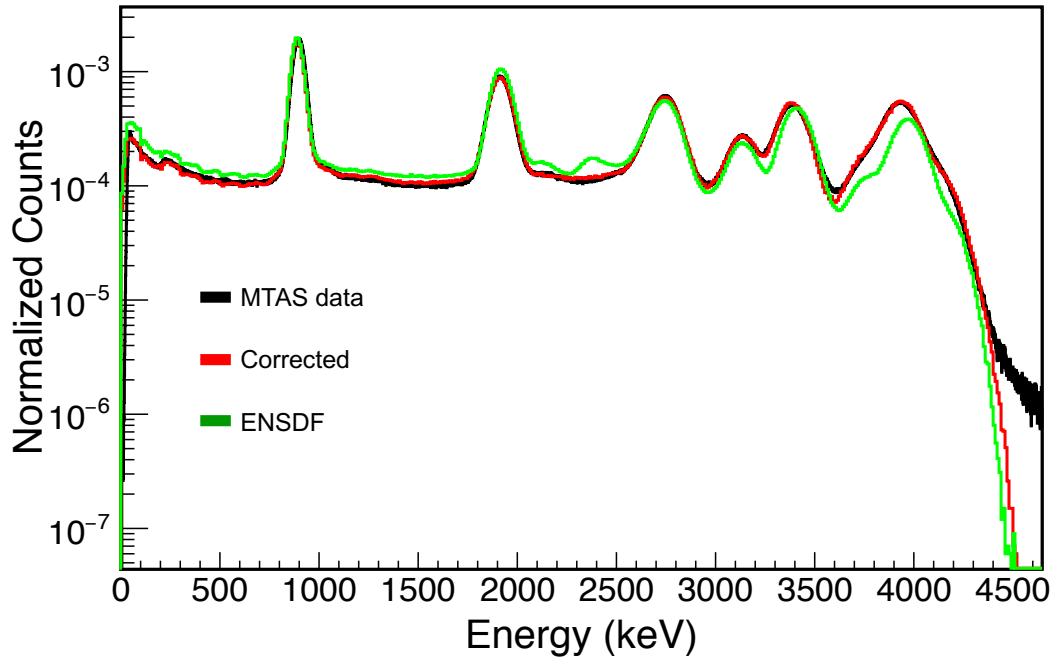


Figure 8.1: Comparison of ^{84}Br data (black), Geant4 simulation of ^{84}Br using ENSDF data (green) and Geant4 simulation with corrected β and γ feedings (red).

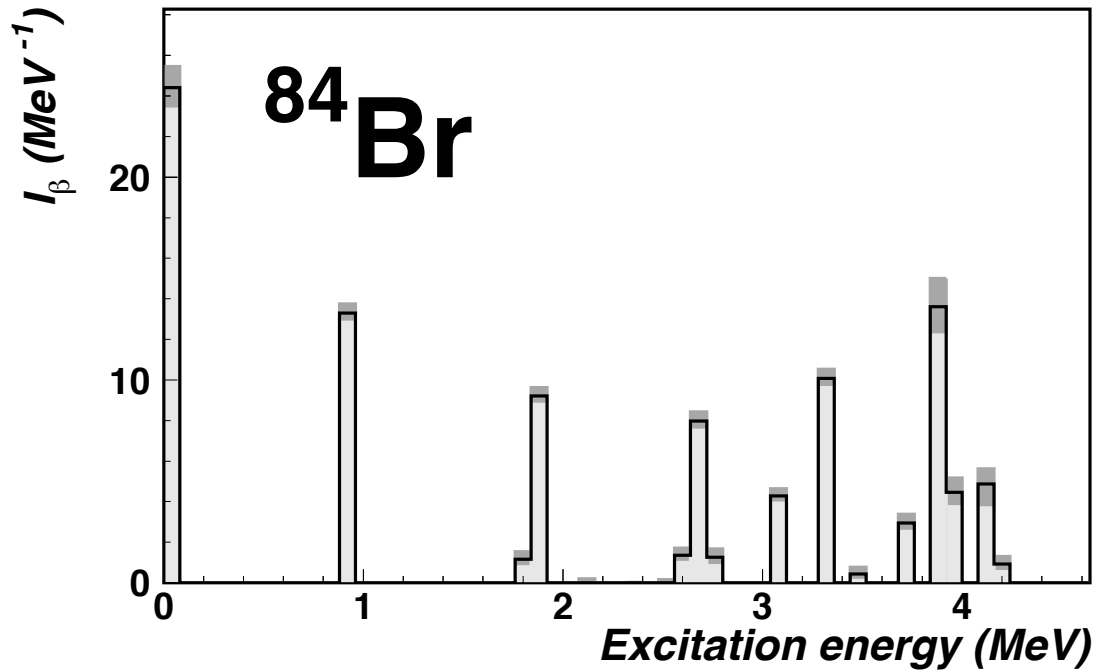


Figure 8.2: Corrected ^{84}Br I_β feedings with error bars.

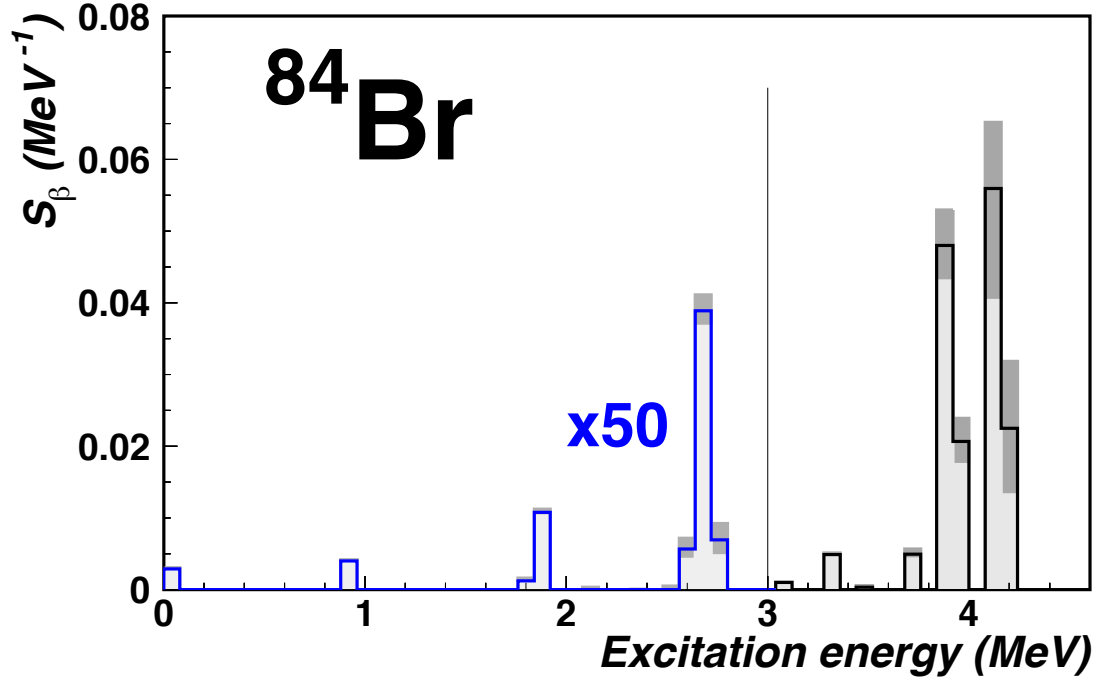


Figure 8.3: Extracted S_β from corrected ^{84}Br β feedings with error bars. Please note that the low energy portion up to 3 MeV is enhanced by a factor of 50 in order to display transitions to states at low excitation energies in ^{84}Kr . This section is highlighted in blue.

Table 8.1: Results from the calculations of $\langle E_\gamma \rangle$, $\langle E_\beta \rangle$ and N_ν for the decay of ^{84}Br compared to the data currently in ENSDF. $\Delta = \text{Data} - \text{ENSDF}$.

	Analysis	ENSDF	Δ
$\langle E_\gamma \rangle$ (keV)	2123(65)	1764.49	+358.51
$\langle E_\beta \rangle$ (keV)	1062(26)	1228.33	-166.2
N_ν ($\times 10^{-43}\text{cm}^2$)	0.716(0.025)	0.91	-0.19

schemes are being included to provide information about the pathways through which the daughters of $^{84,85,86}\text{Br}$ de-excite when they are left in an excited state pursuant to β decay.

The results from the calculations of average γ and β energies as well as the number of expected anti-neutrino interactions with matter from the decay of ^{84}Br are shown in Table 8.1. They are compared with the same calculations performed using the data currently in ENSDF.

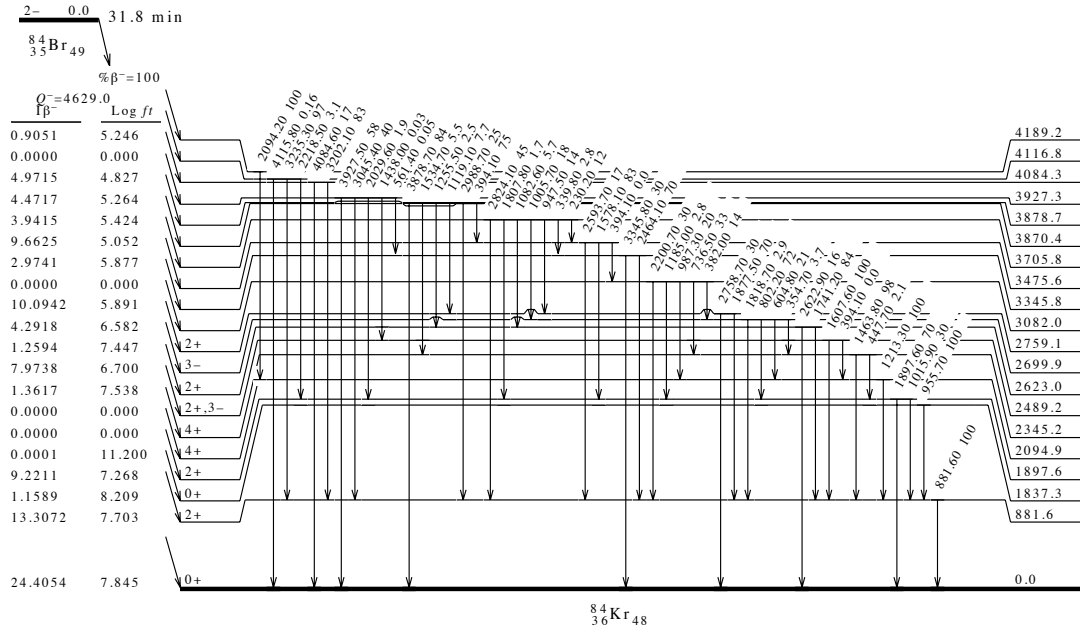


Figure 8.4: ^{84}Br decay scheme. Please note that the γ intensities, I_γ are reported such that for each level all I_γ s of γ rays directly de-exciting that level are scaled to 100% of the total energy coming directly from that level. This is due to the fact that, as stated in Chapter 7, γ rays are being treated as virtual.

8.2 Results from the Analysis of the β decay of ^{85}Br

Four new levels and associated γ cascades were detected in ^{85}Br . There were three new levels at high energy at 2330, 2470 and 2650 keV. The fourth level, at 1720 keV, was assigned as part of the cascade from the level at 2330 keV.

The new level at 2330 keV is of particular interest. Mathematically, it would be possible for this level to be the level at 2031 keV decaying to the ground state via a level at 1416 keV. Indeed, ENSDF reports that there is a weakly β -fed level (0.066%) at 1416 keV decaying to the ground state of ^{85}Kr , making it the only level in ^{85}Kr outside of the isomeric state at 305 keV that decays directly to the ground state. However, this analysis found that the 1416 keV γ ray was in fact misplaced and is part of the cascade from the newly detected level at 2330 keV. This argument is supported by the fact that the level at 2330 keV is β -fed strongly enough to be seen clearly both in the summed MTAS spectra and the γ - γ matrices. Due to the fact that the spin-parity of the ground state of the mother, ^{85}Br , is $\frac{3}{2}^-$ and the ground

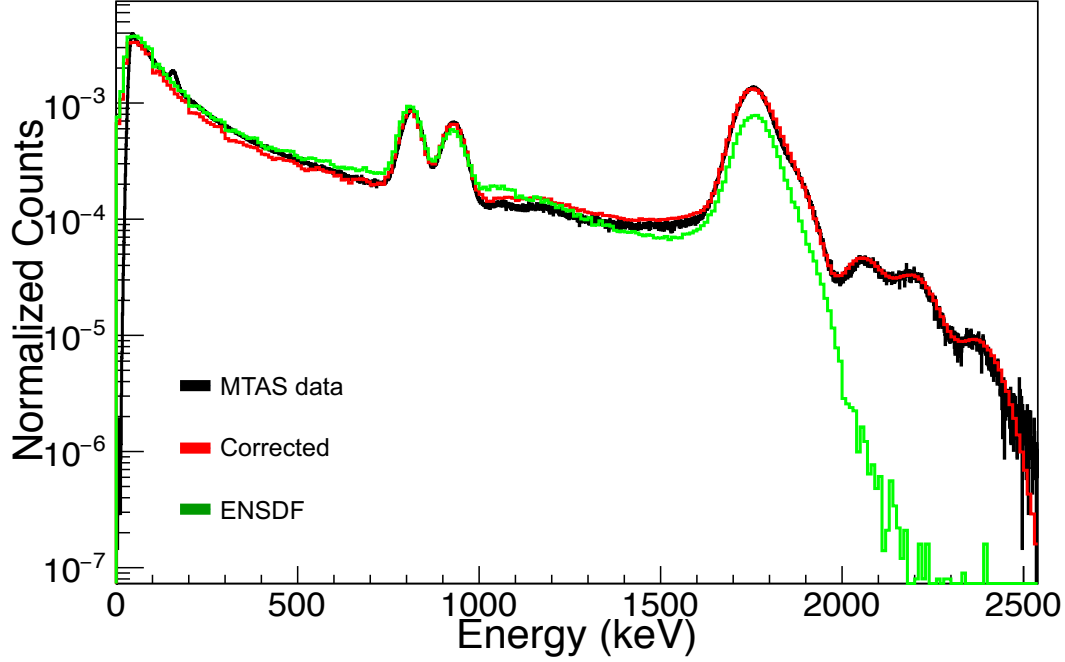


Figure 8.5: Comparison of ^{85}Br data (black), Geant4 simulation of ^{85}Br using ENSDF data (green) and Geant4 simulation with corrected β and γ feedings (red).

state of the daughter, ^{85}Kr , has a spin-parity of $\frac{9}{2}^+$, γ transitions linking these two states would be to states of spin larger than $\frac{5}{2}$, and thus forbidden. Alternatively, the isomeric state at 304.88 keV has a spin-parity of $\frac{1}{2}^-$ which provides for allowed transitions. This is consistent with the strong presence of the level at 2330 keV in ^{85}Kr . Due to the allowed nature of transitions to the level at 2330 keV in ^{85}Kr , it was concluded that this level is in fact a new level and the 1416 keV γ ray was reassigned to a level at 1720 keV that decays to the isomeric state. A similar argument was used to justify the assignment of the decay of the other two high-energy levels at 2470 and 2650 keV to the isomeric state instead of the ground state.

The completed β feedings and extracted S_β for ^{85}Br with associated error bars are shown in Figures 8.7 and 8.8.

As is expected in this region, and is clearly visible in Fig. 8.5, a significant amount of transition intensity to levels at high excitation energies in the daughter has gone undetected. In the case of the decay of ^{85}Br , there was an increase of 2.2% in β feeding to levels above 1.7 MeV with respect to the data in ENSDF. Feeding to the isomeric state at 304.88 keV

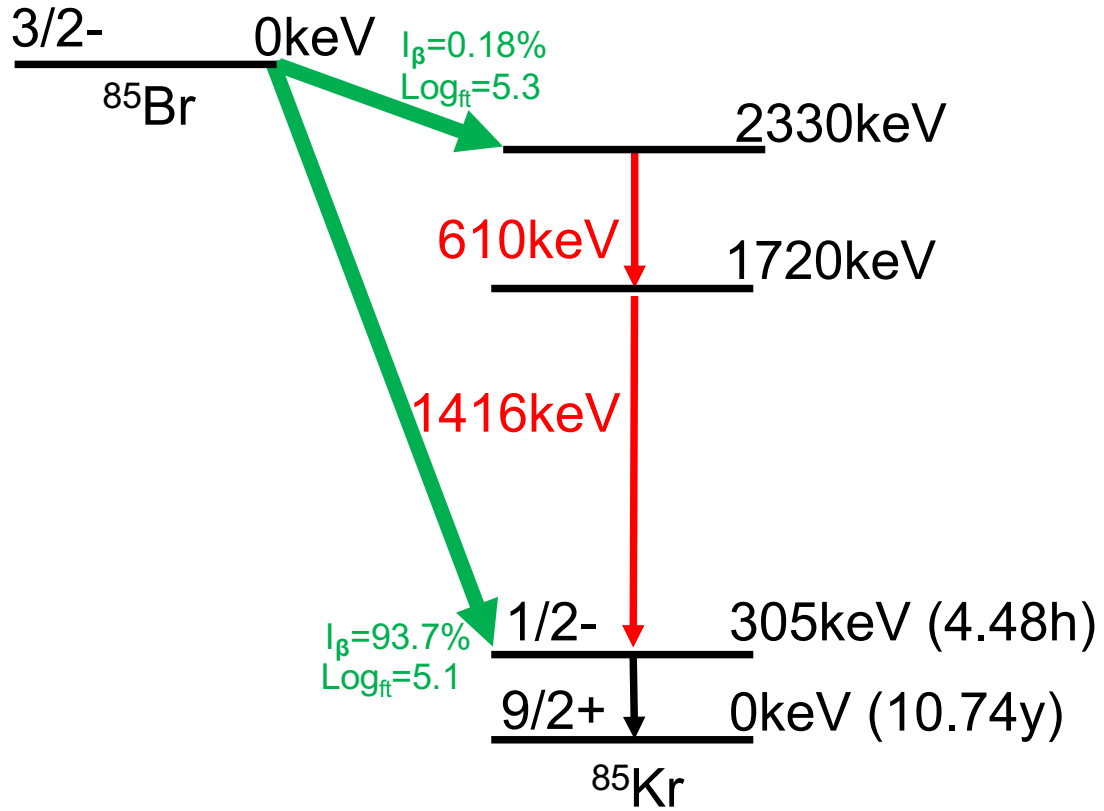


Figure 8.6: Decay scheme highlighting the decay to the level at 2330 keV in ^{85}Kr and concomitant cascade. The β feeding is denoted in green, observed γ rays are in red and levels are in black.

decreased by 2.3% with respect to ENSDF and the ground state remains non β -fed. The decay scheme for ^{85}Br is shown in Fig. 8.9.

Table 8.1 presents the results from the calculations of average γ and β energies as well as the number of expected anti-neutrino interactions with matter from the decay of ^{85}Br performed with data from this analysis and the data currently in ENSDF.

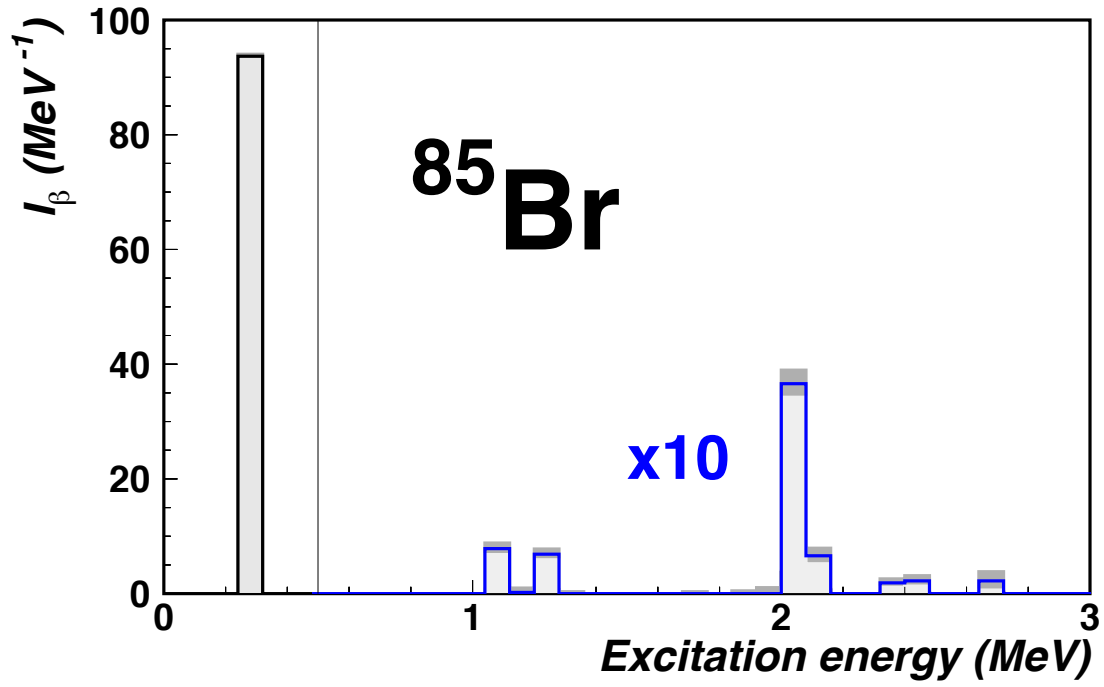


Figure 8.7: Corrected ^{85}Br I_β feedings with error bars. Please note that the area in blue is magnified by a factor of ten to make the transitions visible.

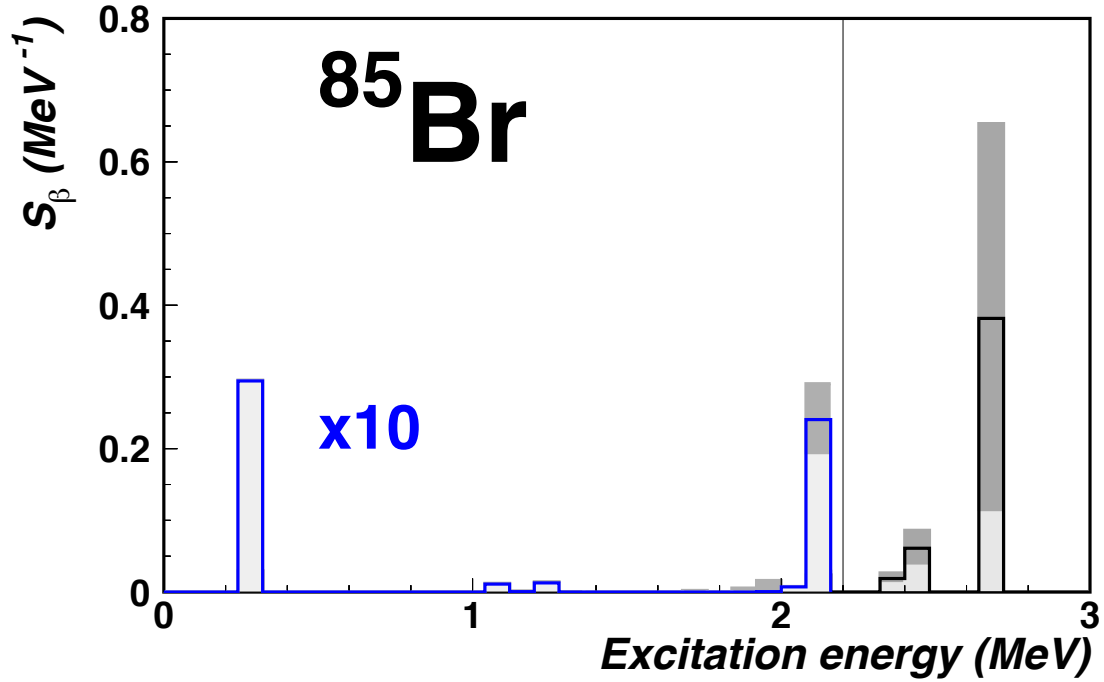


Figure 8.8: Extracted S_β from corrected ^{85}Br β feedings with error bars. Please note that the area in blue is magnified by a factor of ten to make the transitions visible.

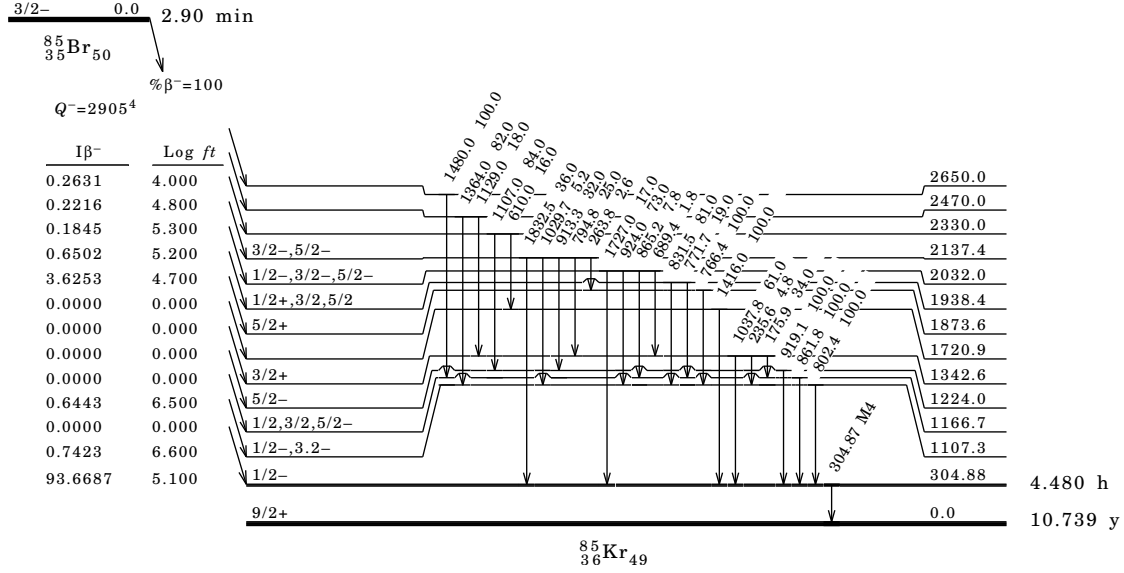


Figure 8.9: ^{85}Br decay scheme. Please note that the γ intensities, I_γ are reported such that for each level all I_γ s directly de-exciting that level are scaled to 100% of the total energy coming directly from that level. This is due to the fact that, as stated in Chapter 7, γ rays are being treated as virtual.

Table 8.2: Results from the calculations of $\langle E_\gamma \rangle$, $\langle E_\beta \rangle$ and N_ν for the decay of ^{85}Br compared to the data currently in ENSDF. $\Delta = \text{Data} - \text{ENSDF}$.

	Analysis	ENSDF	Δ
$\langle E_\gamma \rangle$ (keV)	405.9(8.2)	365.62	+40.37
$\langle E_\beta \rangle$ (keV)	1040.7(4.2)	1058.65	-17.96
N_ν ($\times 10^{-43}\text{cm}^2$)	0.16195(0.00074)	0.1656	-0.0037

8.3 Results from the Analysis of the β decay of ^{86}Br

The β -feeding intensities and branching ratios for ^{86}Br were not, in fact, part of this work and were provided by A. Fijalkowska and collaborators [Fijalkowska et al.] to be used as a test of the nuclear shell model, as described in Chapter 4. This was done because A. Fijalkowska et al. explored the ramifications that the updated ^{86}Br decay data had for decay heat production in nuclear reactors but the implications from a nuclear structure perspective had yet to be explored. The error bars included in Figures 8.11 and 8.12 are an original part of this work.

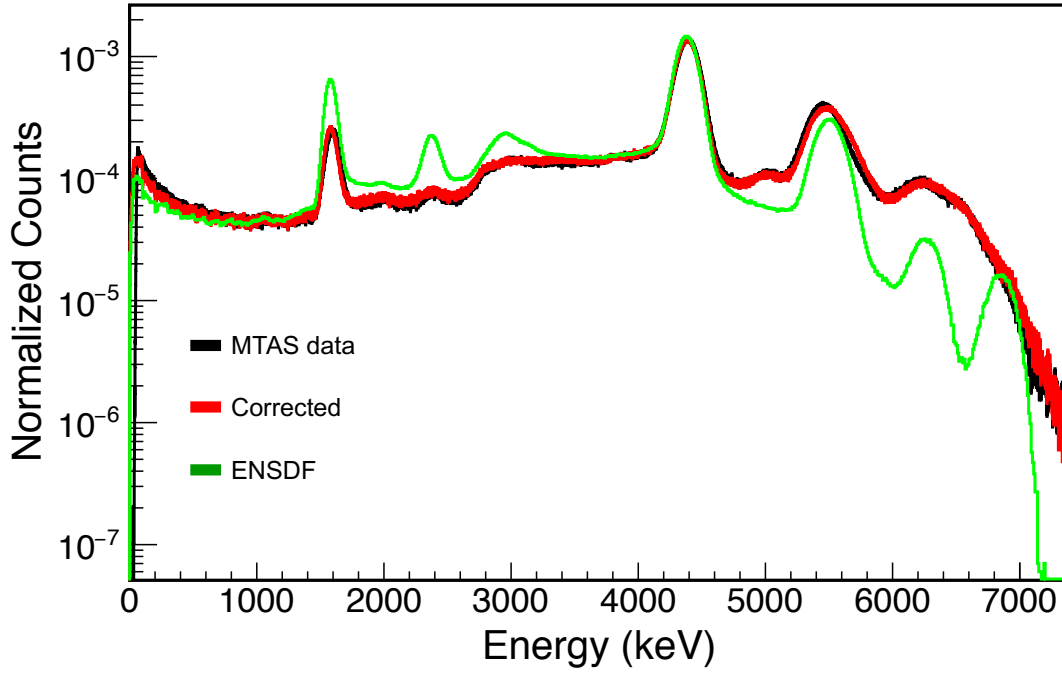


Figure 8.10: Comparison of ^{86}Br data (black), Geant4 simulation of ^{86}Br using ENSDF data (green) and Geant4 simulation with corrected β and γ feedings (red).

Because the data for ^{86}Br were analyzed by another person, the methods of the analysis differ from those described in detail in this work. Instead of making use of γ - γ matrices, a process developed for this dissertation after the ^{86}Br analysis was completed, A. Fijalkowska used the pseudo-level approach in the analysis of this data set. The idea behind an analysis of this type is what is important is the β -feeding strength. It is based on the assumption that levels may be treated as virtual and the γ cascade from a given level is of negligible importance. This is supported by the idea that total absorption spectrometers are summing detectors and the data should be treated as if it comes from a calorimeter. An approach of this type is most often employed when level densities are high enough as to be indistinguishable with the resolution of a NaI(Tl) detector. The pseudo-level method places pseudo-levels at regular intervals with the intent of reproducing the transition strength missing in the spectra relative to that reported in ENSDF. In this case, pseudo-levels were placed at 100 keV intervals between 4800 and 7800 keV to yield the result shown in Fig. 8.10. The β feeding and extracted S_β for ^{86}Br , both with error bars are shown in Figures 8.11 and 8.12 respectively.

The results of the analysis of the ^{86}Br spectra show that there is a 2.2% increase in β feeding to states above 1.7 MeV and a 5.7% increase in β feeding to the ground state, both relative to data currently in ENSDF. The decay scheme for ^{86}Br is shown in six parts in Figures 8.13-8.18. This decay scheme is unique compared to the other two for $^{84,85}\text{Br}$ because ^{86}Br was analyzed by A. Fijalkowska using the pseudo-level method as mentioned above. Therefore all cascades coming from the pseudo-levels represent E1, E2 and M1 transitions to known levels.

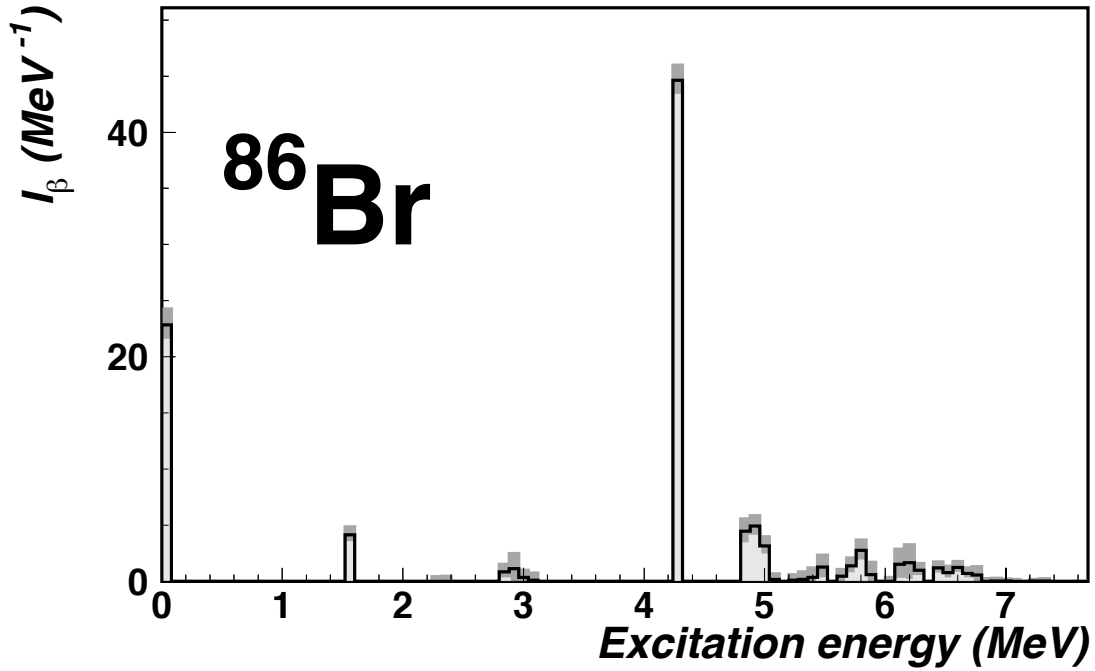


Figure 8.11: Corrected ^{86}Br I_β feedings with error bars.

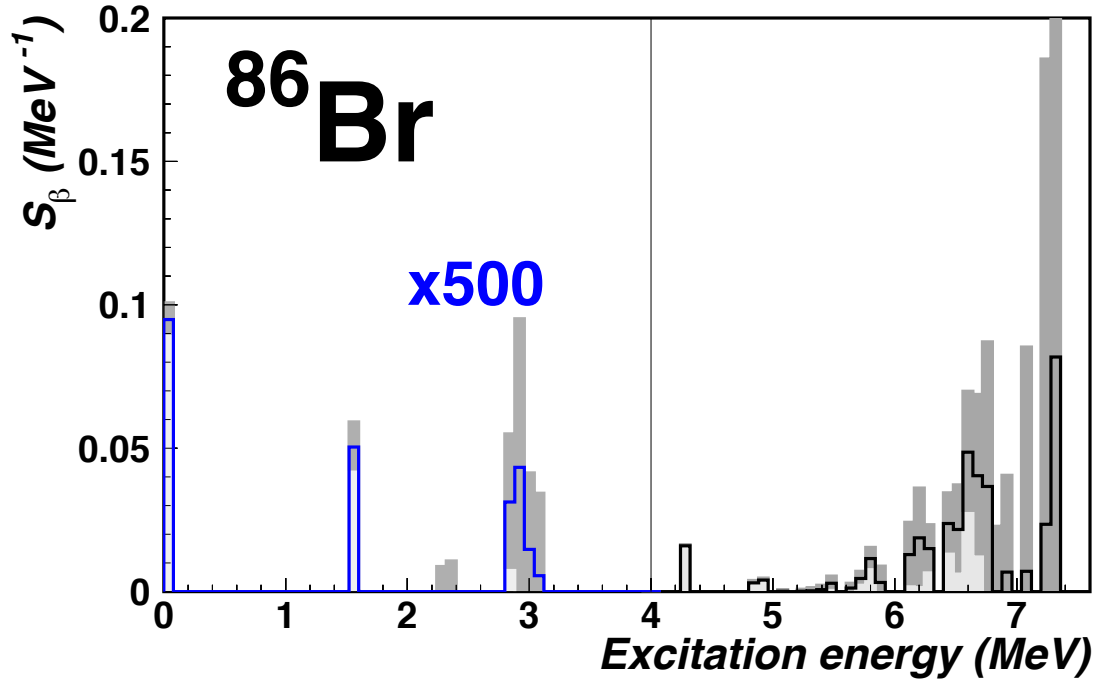


Figure 8.12: Extracted S_β from corrected ^{86}Br β feedings with error bars. Please note that the blue portion of the plot indicates that it has been magnified 500 times.

Table 8.3: Results from the calculations of $\langle E_\gamma \rangle$, $\langle E_\beta \rangle$ and N_ν for the decay of ^{86}Br compared to the data currently in ENSDF. $\Delta = \text{Data} - \text{ENSDF}$.

	Analysis	ENSDF	Δ
$\langle E_\gamma \rangle$ (keV)	3667(207)	3341.62	+326
$\langle E_\beta \rangle$ (keV)	1862.5(72.1)	1903.25	-40.8
N_ν ($\times 10^{-43}\text{cm}^2$)	2.73(0.14)	2.62	-0.11

The results from the calculations of average γ and β energies as well as the number of expected anti-neutrino interactions with matter from the decay of ^{86}Br are shown in Table 8.3. They are compared with the same calculations performed using the data currently in ENSDF.

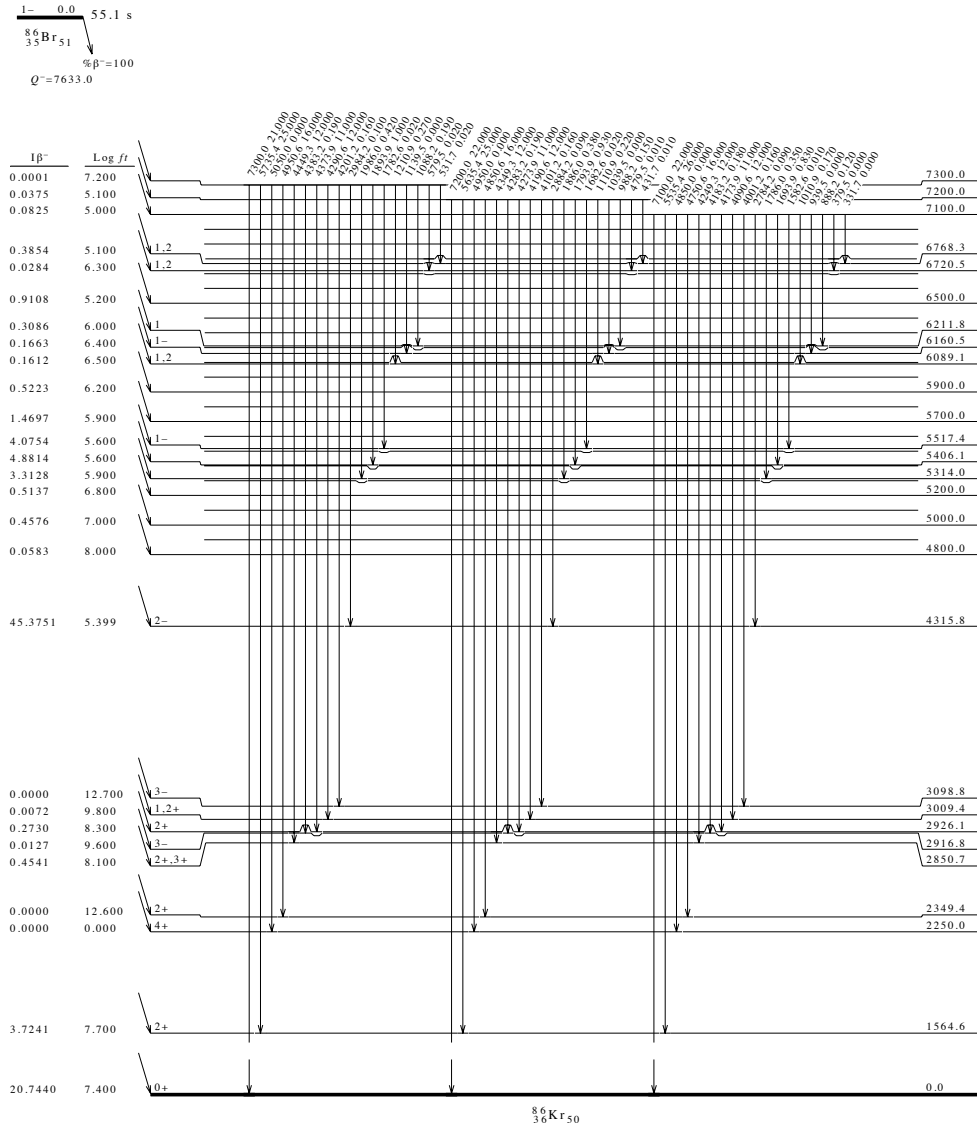


Figure 8.13: The first part of the ^{86}Br decay scheme. Please note that the γ intensities, I_γ are reported such that for each level all I_γ s directly de-exciting that level are scaled to 100% of the total energy coming directly from that level. This is due to the fact that, as stated in Chapter 7, γ rays are being treated as virtual.

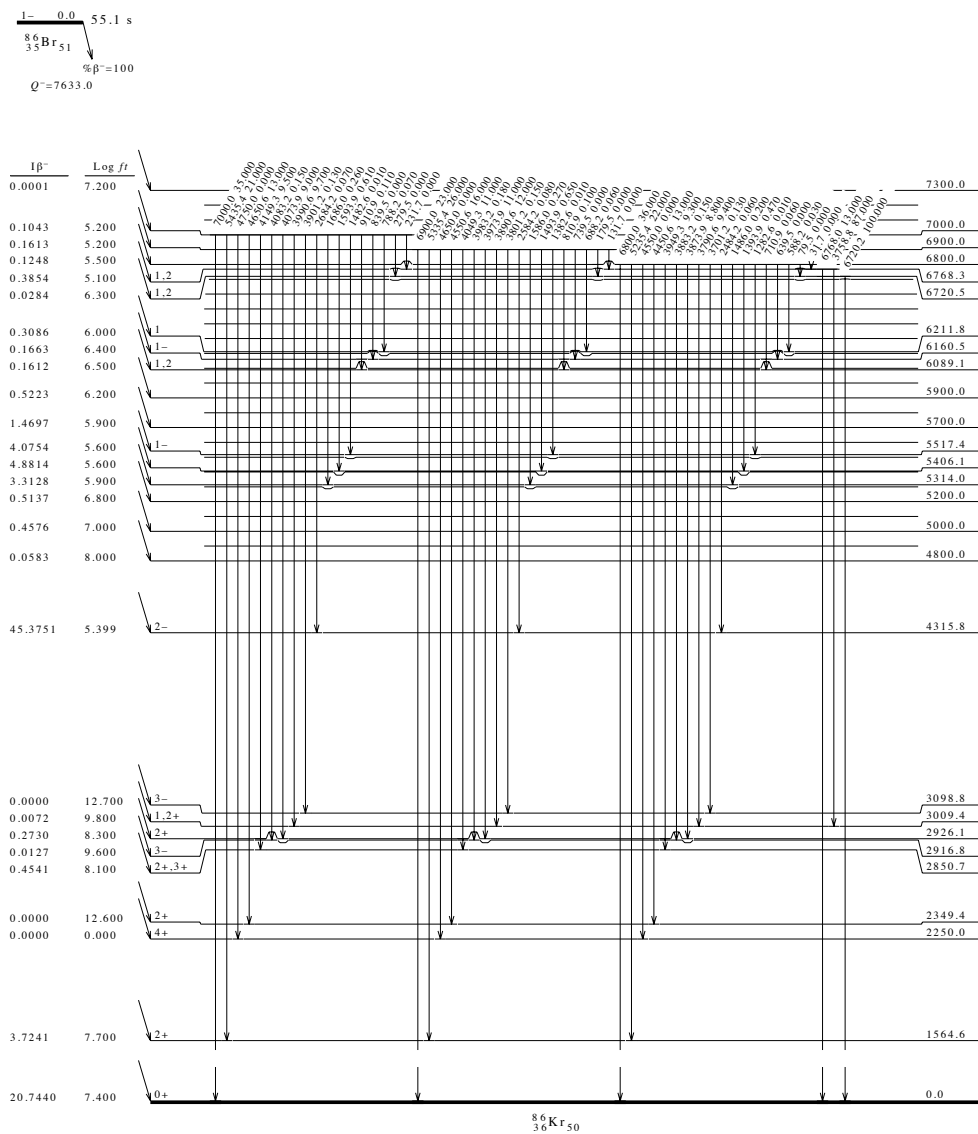


Figure 8.14: The second part of the ^{86}Br decay scheme.

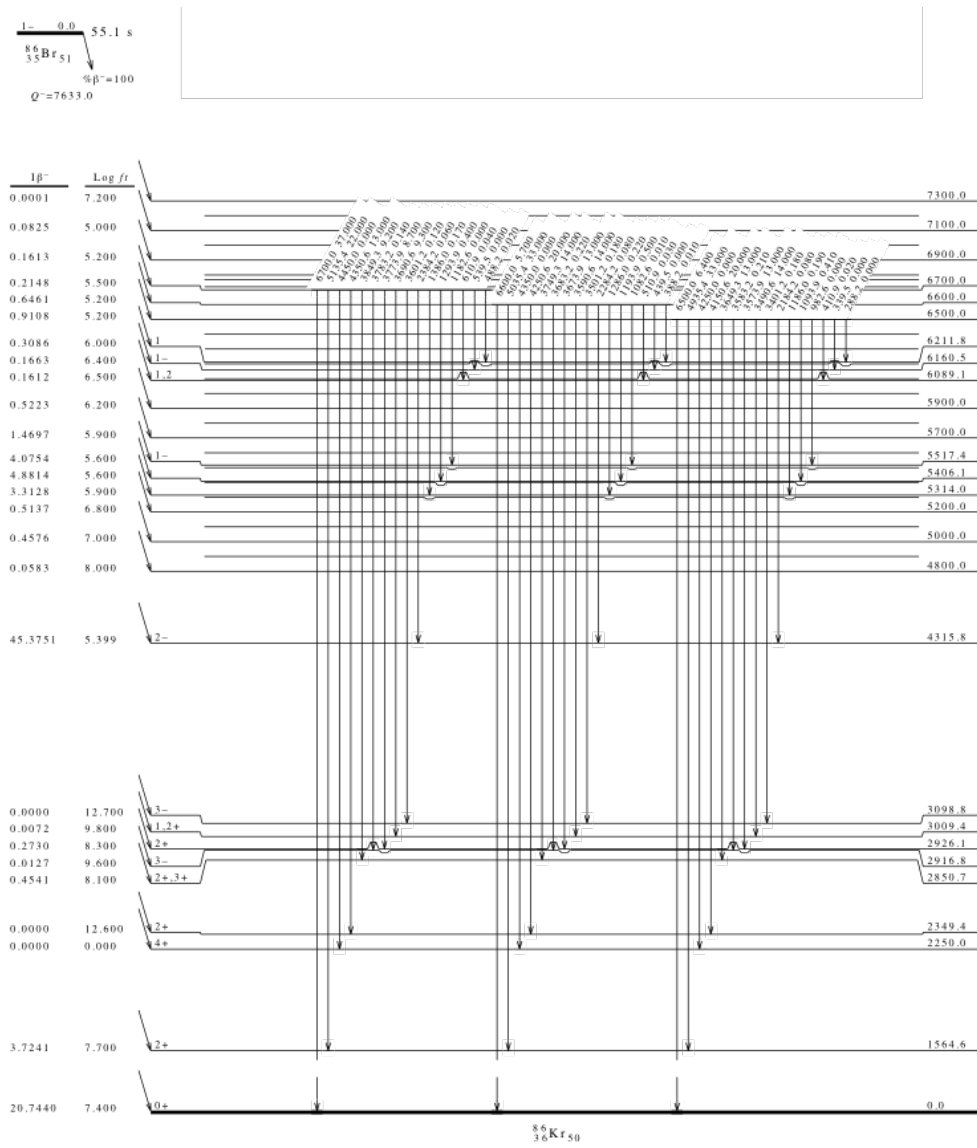


Figure 8.15: The third part of the ^{86}Br decay scheme.

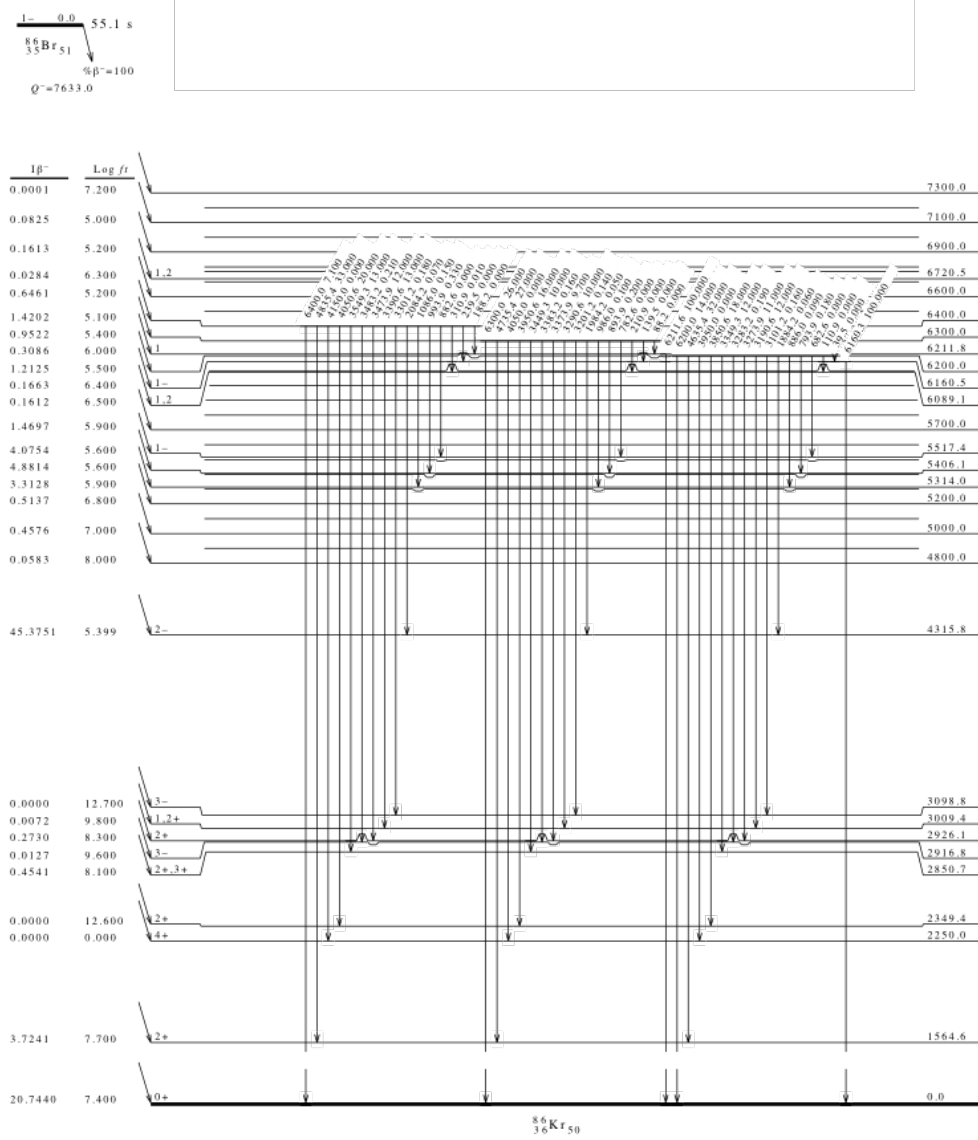


Figure 8.16: The fourth part of the ^{86}Br decay scheme.

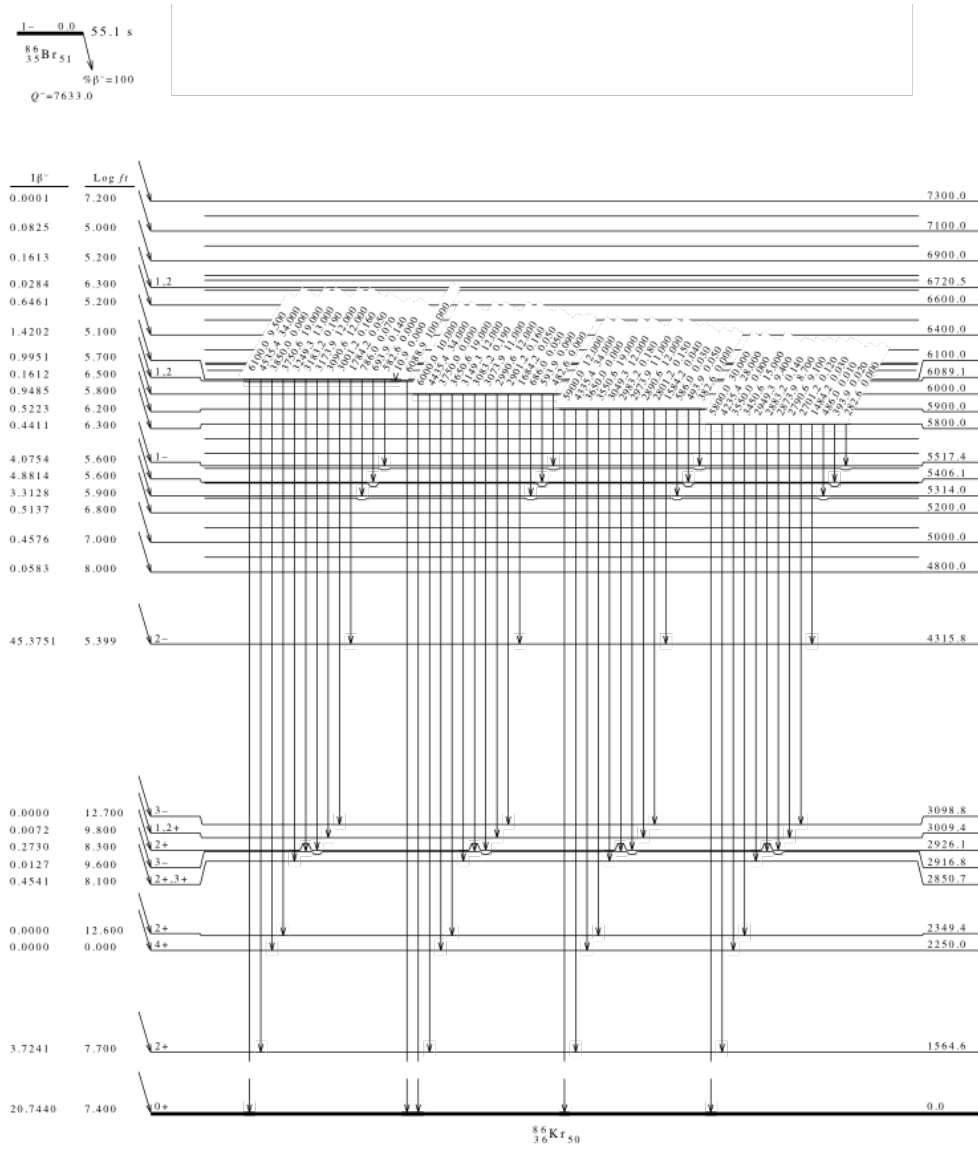


Figure 8.17: The fifth part of the ^{86}Br decay scheme.

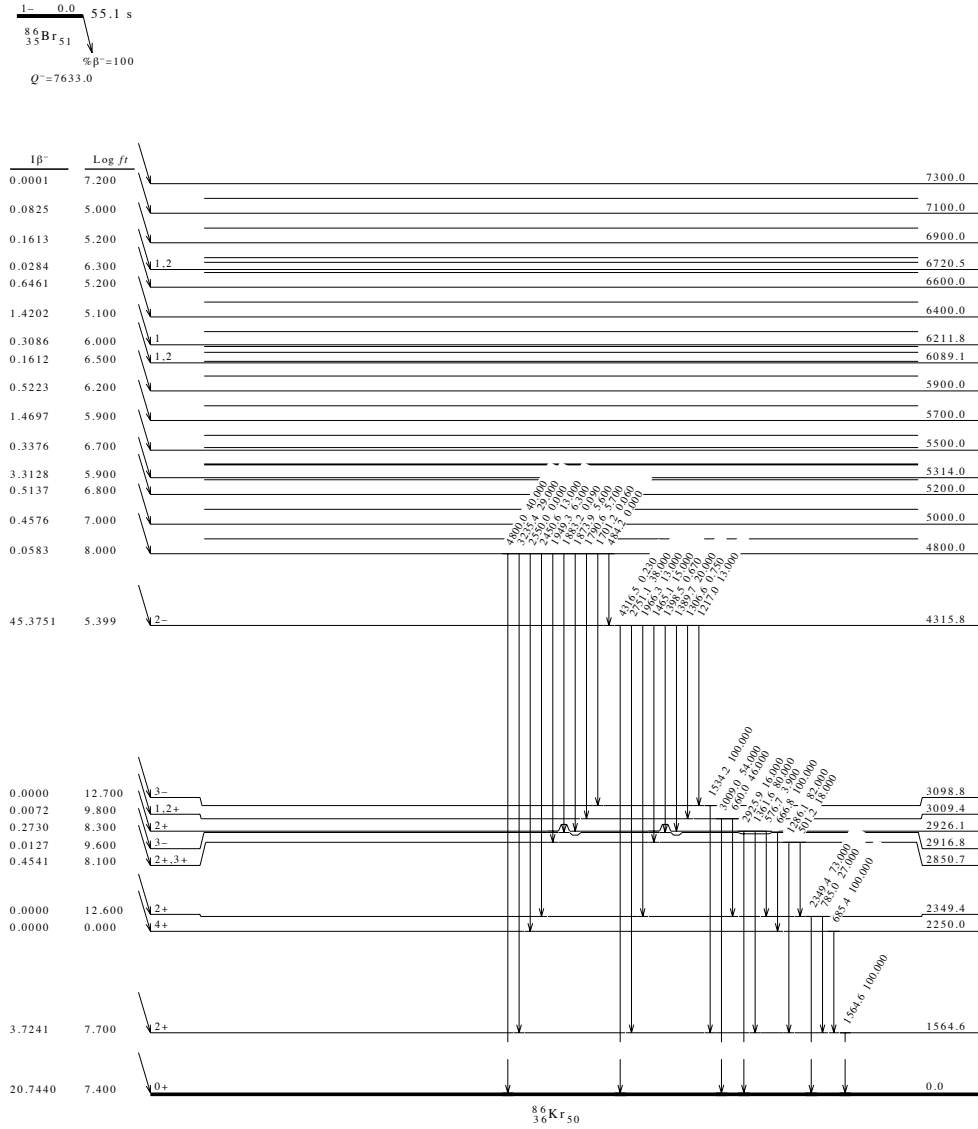


Figure 8.18: The sixth and final part of the ^{86}Br decay scheme.

Chapter 9

Discussion

9.1 Results and the Effect on Decay Heat Calculations

The results of the analysis of all three nuclei studied in this thesis yield an increased percentage of β feeding above 1.7 MeV, shown in Table 9.1.

Additionally, the average γ energy emitted in the β decay of $^{84,85,86}\text{Br}$ universally increased with respect to what is known and the average emitted β energy and number of anti-neutrino interactions with matter decreased. These results are shown in Tables 8.1, 8.2 and 8.3 in Chapter 8. The implication is that the respective expected contributions of $^{84,85,86}\text{Br}$ to decay heat production in nuclear reactors will increase with respect to what is currently known. This is an important consideration because all three of these nuclei are strongly produced by fission. The increase in the contribution to decay heat production is a result of the fact that a larger portion of energy is being released in a form that will be likely to interact with the material of a nuclear reactor. Specifically, when compared to the data that are currently in

Table 9.1: The percentage of β feeding to states above 1.7 MeV from the experimentally extracted I_β and the data currently in ENSDF in the first two columns for $^{84,85,86}\text{Br}$. The third column, $\Delta = \text{Experiment} - \text{ENSDF}$.

	Experiment (%)	ENSDF (%)	Δ (%)
^{84}Br	62.29	54.55	+7.74
^{85}Br	4.95	2.76	+2.19
^{86}Br	75.53	73.34	+2.19

ENSDF, more energy is released in the form of γ rays than previously known. Anti-neutrinos in particular are practically non-interactive.

9.2 Results and the Effect on the Reactor Anti-neutrino Anomaly

The reactor anti-neutrino anomaly is rooted in the fact that when the anti-neutrino spectra from a nuclear reactor is measured, only 0.943(22) of expected anti-neutrinos are detected [39, 11]. There is also a 10% excess of high-energy anti-neutrinos, specifically anti-neutrinos with energies between 5-7 MeV, when compared to what is predicted using global nuclear models [39, 30, 29]. This is termed the “shoulder” [29].

There are two possible causes of these observations. The first is that the deficit is caused by missing nuclear data. More specifically, an underestimation of the amount feeding to states at high excitation energies in the daughter and a corresponding underreporting of the γ radiation being emitted. Unobserved feeding to states at high excitation energies in the daughter often results in an overestimation of feeding to the ground state. This effect serves to shift the anti-neutrino energy spectra from high energy to low energy. A second possible cause of the anomaly has been proffered in the form of an as yet unknown particle called the sterile anti-neutrino [39, 30]. The sterile anti-neutrino is dubbed such because it would be expected to be even less interactive than normal neutrinos. However, in order to confirm or deny the existence of this hypothetical particle, the first step must be to ensure that the anomaly is not a result of missing nuclear data in the form of overly large ground state to ground state feeding and missing feeding to levels at high excitation energies in the daughter.

A recent paper published by Rasco et al. used MTAS data to study three of the top contributors to the high energy anti-neutrino flux in nuclear reactors, ^{92}Rb , $^{96\text{gs}}\text{Y}$ and ^{142}Cs [46]. The results of the analysis were used to update the current simulations for the expected anti-neutrino spectrum. All three of these nuclei showed missing feeding to states at high excitation energies in the daughter. However, although the results for $^{96\text{gs}}\text{Y}$ confirmed the data currently in ENSDF with a ground state to ground state feeding of 95.5(20)% and the

Table 9.2: The ground state feedings for the experimentally extracted I_β and the data currently in ENSDF in the first two columns for $^{84,85,86}\text{Br}$. The third column, $\Delta = \text{Experiment} - \text{ENSDF}$.

	Experiment (%)	ENSDF (%)	Δ (%)
^{84}Br	24.4	33	-8.6
^{85}Br	93.7	96	-2.3
^{86}Br	20.7	15	+5.7

Table 9.3: Number of expected anti-neutrino interactions with matter, N_ν ($\times 10^{-43}\text{cm}^2$), calculated for $^{84,85,86}\text{Br}$ for both the data taken for this disseration and the data currently in ENSDF. The third column is the ratio of N_ν values from the experimental data to ENSDF.

	Experiment	ENSDF	$\frac{\text{Experiment}}{\text{ENSDF}}$
^{84}Br	0.72	0.91	0.79
^{85}Br	0.16	0.17	0.98
^{86}Br	2.45	2.62	0.94

ground state to ground state feeding of ^{142}Cs decreased from 56% in ENSDF to 44(2)%, the measured ^{92}Rb ground state to ground state feeding increased from 51(8)% to 95.2(7)% [46]. This served to increase the shoulder between 5-7 MeV from 10% to 12%. This result highlights the need to examine nuclei that upon further study are revealed to not only to have missed transition strength to high excitation energies in the daughter but also demonstrate a drop in ground state feeding from what is currently known.

The previous section highlighted the fact that all three nuclei, $^{84,85,86}\text{Br}$, have more transitions to states at high excitation energies in their respective daughters, and emit more γ radiation than is currently stated by ENSDF. The ground state feedings for $^{84,85}\text{Br}$, shown in Table 9.2, follow the pattern of overestimated ground state feeding and therefore are of interest to further studies of the reactor anti-neutrino anomaly.

Additionally, as shown in Table 9.3, the number of emitted anti-neutrinos is decreased with respect to what is currently known for all three nuclei.

Despite the fact that the intensity of forbidden transitions is smaller than the strength of allowed transitions it is predicted that forbidden transitions might have an outsized role in the reactor anti-neutrino anomaly [28]. This is due to the fact that forbidden transitions are estimated to make up approximately 30% of the transitions in the β decay of nuclei pertinent

to the reactor anti-neutrino flux [28]. Due to the difficulty in realistically calculating forbidden transition strengths for nuclei in this region, they contribute an outsized amount of uncertainty when modeling anti-neutrino flux coming from nuclear reactors. The answer to this is, of course, more exhaustive direct measurements of nuclei.

Fortunately, the decay strength, S_β , extracted in this analysis includes both allowed and forbidden transition strengths. Experimentally, using the TAS technique, the entire decay strength is accessible, thus giving a complete picture of the decay properties. A priori, we cannot say which transitions in the S_β distribution are allowed or forbidden. We can however make assumptions based on the systematics of the $\log(ft)$ values as well as with our shell model predictions.

9.3 Recent Study of ^{86}Br at IGISOL

Another publication on a total absorption spectroscopy measurement of ^{86}Br will, as of May 2017, soon be published [47]. This experiment was performed at IGISOL in Jyvaskyla, Finland using a BaF_2 detector called Rocinante [58]. Beams were produced through proton-induced fission of uranium followed by electro-magnetic separation and further purification by making use of a Penning Trap [47]. Rocinante is segmented, but not in the same manner as MTAS is segmented. Instead of being a series of long hexagonal detectors forming rings it is segmented with twelve crystals forming a single ring [58]. This setup does not allow for the same method of γ - γ analysis discussed in this dissertation due to the fact that it cannot plot the inner material of the detector, where individual γ rays are more likely to be visible, against the entirety of the detector material where level sums will be seen. A. Fijalkowska et al. have already published the updated β feedings for ^{86}Br [22]. Nevertheless, it is important to note that this experiment achieved identical, within error bars, results as those shown here. Their analysis showed a ground state feeding of 15.01% or 20.23%, the second value agrees within error to our value of 20.7% $\pm$ 4.5% [47]. They also agree with our assertion that no feeding was observed to levels at 2250 and 2350 keV.

9.4 Shell Model Calculations for $^{84,85,86}\text{Br}$

9.4.1 Description of Model

As discussed in Chapter 4, bromine nuclei are $Z=35$ nuclei and therefore have seven protons occupying the $0f_{5/2}1p_{1/2,3/2}$ shells outside of a ^{56}Ni closed core. $N=49$ ^{84}Br is likely to have a single neutron vacancy in the $g_{9/2}$ orbital and $N=50$ ^{85}Br will have a full $g_{9/2}$ orbital in its ground state. $N=51$ ^{86}Br is likely to have a full $g_{9/2}$ orbital and a single neutron in the $d_{5/2}$ orbital while in its ground state. The Gamow-Teller transformation of this $d_{5/2}$ neutron, is, however, not energetically possible in the β decay of ^{86}Br . Additionally, the $g_{9/2}$ proton orbital is typically at or above the Q_β value and thus is energetically unavailable. Decay from a g orbital to a f or p orbital is forbidden per Gamow-Teller selection rules. Therefore the decay for all three nuclei is likely to be dominated by allowed decays of neutrons decaying from the f or p neutron orbitals to a proton occupying the f or p proton orbitals in their respective daughters.

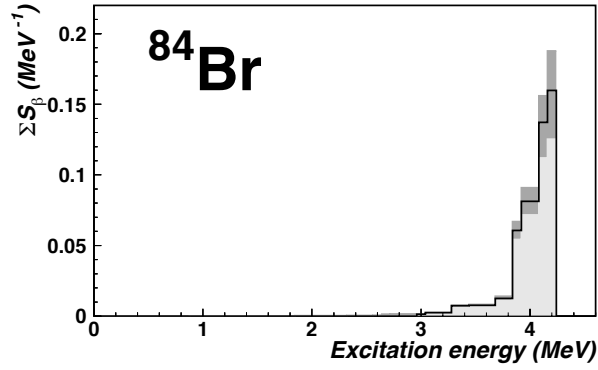
Shell model calculations were performed to investigate the role of nuclear structure in the decay of $^{84,85,86}\text{Br}$. The calculations were done with NuShellX with jj44bnp interactions [5, 15]. Single-particle energies for the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$ and $g_{9/2}$ states were derived from experimental systematics of nuclei in the region of ^{57}Ni - ^{78}Ni , see Tables 9.4 and 9.5 [37, 19, 10]. Results were binned to 100keV.

Table 9.4: Binding energies for protons and neutrons used in shell model calculations for $^{84,85}\text{Br}$ [19].

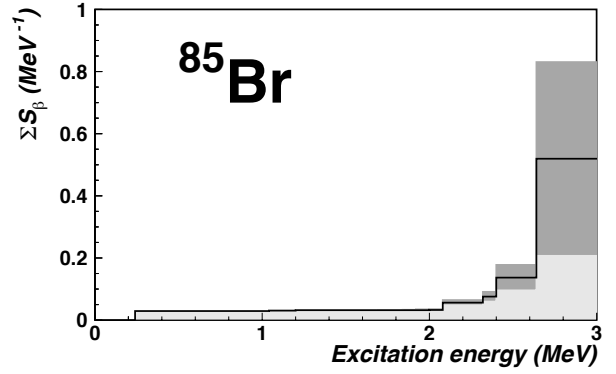
Orbital	Binding Energy (MeV)
$g_{9/2}$	-5.894
$p_{1/2}$	-8.269
$f_{5/2}$	-9.286
$p_{3/2}$	-9.657

9.4.2 Quenching of Shell-Model Gamow-Teller Strength

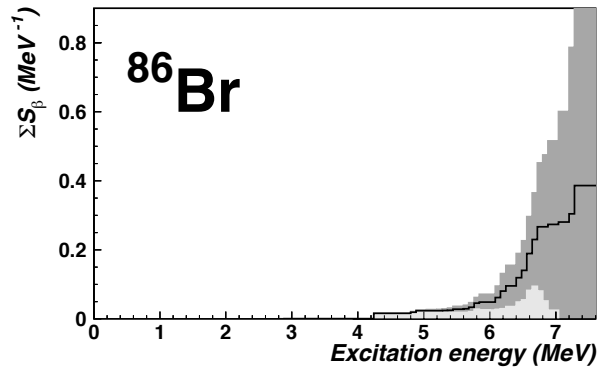
For shell model calculations, it is necessary to “quench” the resulting decay matrix elements in order to achieve agreement with experimental values [17]. The need for quenching arises



(a) ^{84}Br with quenching



(b) ^{85}Br with quenching



(c) ^{86}Br with quenching

Figure 9.1: The sum of extracted S_β (black) plotted with nuclear shell model B_{GT} for $^{84,85,86}\text{Br}$. The ratio of the total sums at Q_β was used to calculate quenching factors for each respective shell model calculation. The calculations (red) are shown shown post quenching.

Table 9.5: Binding energies for protons and neutrons used in shell model calculations for ^{86}Br [37]. — indicates the orbital is not energetically available.

Orbital	Proton Binding Energy (MeV)	Neutron Binding Energy (MeV).
$d_{5/2}$	—	-1.98
$g_{9/2}$	-8.91	-5.86
$p_{1/2}$	-12.04	-7.21
$f_{5/2}$	-14.94	-8.39
$p_{3/2}$	-13.44	-8.54

from the fact that nuclear shell model calculations are performed using a limited valence space, discussed in Chapter 2. While the use of a constrained valence space is inherent to the shell model approach, it necessarily results in states that cannot possibly have correct absolute normalizations as they lack coupling to the wave functions outside the valence space [17]. That is to say, a sufficiently large valence space will result in an accurate reproduction of decay matrix elements with correct relative strengths and position in energy. However, those matrix elements, though correct relative to one another and in the correct position energy-wise will, when compared to data, need to be scaled. This scaling factor, called quenching, was calculated through a comparison of the sum of the experimental extracted S_β and the sum of the B_{GT} located within the Q_β window as shown in Fig. 9.1. Quenching was calculated as 0.4 (or 60%) for ^{84}Br and 0.2 (80%) for $^{85,86}\text{Br}$.

9.4.3 Shell Model Calculations for $^{84,85}\text{Br}$

The calculations for $^{84,85}\text{Br}$ used a ^{56}Ni core and jj44bnp interactions, derived from experimental data for nuclei with $Z=28-30$ and $N=48-50$. See footnote in Cheal et al. [19]. This configuration space allows for unimpeded scattering of protons and neutrons in their respective fpg shells [10].

The results of the shell model calculations for both $^{84,85}\text{Br}$ predict that the $\nu p_{1/2} \mapsto \pi p_{3/2}$ transition, highlighted in Fig. 9.2, will dominate. The data agree with the shell model predictions. There is agreement in both transition energy and relative strengths between the experimental S_β and calculated B_{GT} , as shown in Figures 9.3 and 9.4. Therefore using this

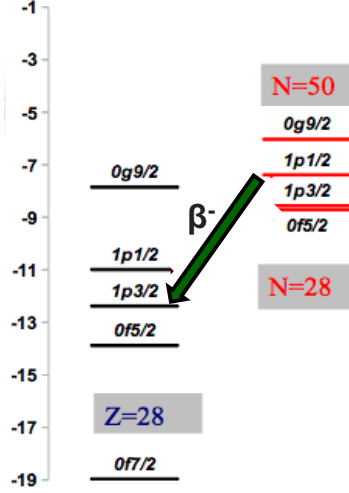


Figure 9.2: Level diagram of approximate relationships between neutron orbitals in $^{84,85}\text{Br}$ and proton orbitals in $^{84,85}\text{Kr}$. The green arrow represents the β^- -decay transition from $\nu p_{1/2}$ to $\pi p_{3/2}$ that our calculations predict to be the dominant transition in the β decay of $^{84,85}\text{Br}$.

model we are able to reasonably predict the Gamow-Teller strength distribution or B_{GT} for $^{84,85}\text{Br}$.

Despite the fact that the general mechanics of the decay of $^{84,85}\text{Br}$ are the same, they have strikingly different decay patterns. In the case of ^{84}Br , shown in Fig. 9.3, the majority of the B_{GT} goes to highly excited states. This is due to the fact that the ground state of the mother is 2^- and the ground state of the daughter is 0^+ which makes the ground state to ground state transition forbidden. Allowed-type transitions to states at low excitation energies in ^{84}Kr are unlikely to occur because the neutron fp to proton fp Gamow-Teller transition creates a particle-hole excitation. The resulting transition cannot be allowed because by including negative parity fp proton and neutron orbitals, a positive parity state is produced. Thus the transition is forbidden as it would necessarily be between the negative parity ground state in ^{84}Br to a hypothetical positive parity state. Participation of the $g_{9/2}$ orbital would allow for negative parity states but because of its high energy will produce states at high excitation energies in the daughter. The end result is that there are not many options for transitions to allowed spin states at low excitation energies in ^{84}Kr .

The same structure drives a very different pattern in the decay of ^{85}Br , shown in Fig. 9.4. The majority of the strength goes to the $\frac{1}{2}^-$ isomeric state at 305 keV. In this case there

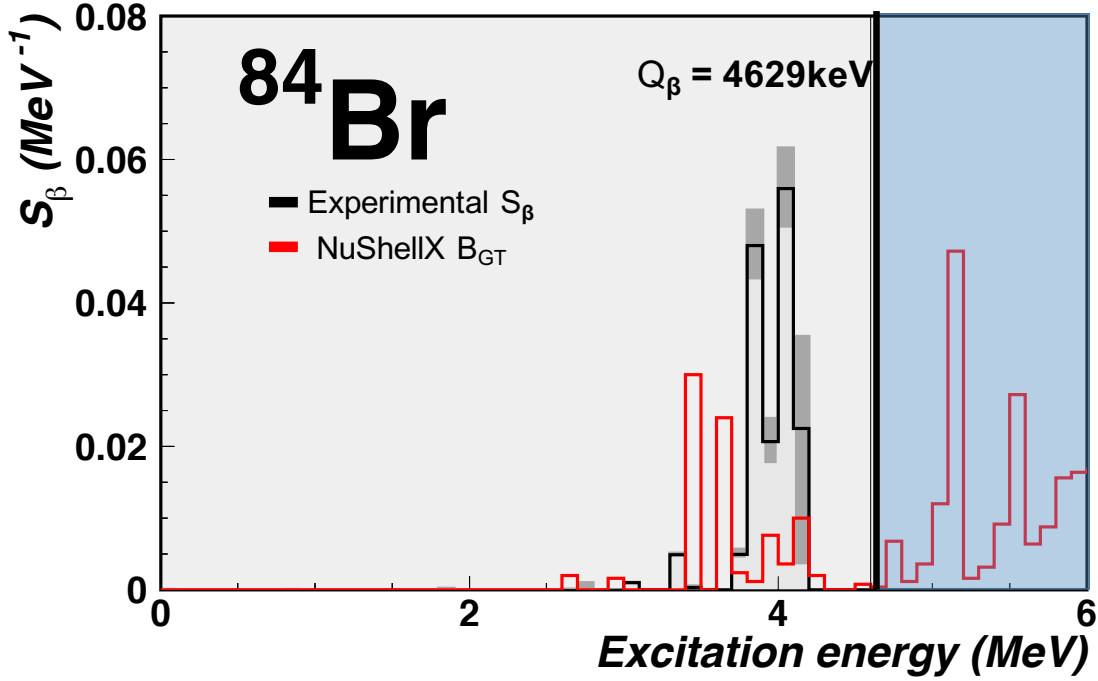


Figure 9.3: Extracted S_β from MTAS spectrum (black) and B_{GT} from shell model calculations (red) for ^{84}Br . Note that S_β includes both allowed and forbidden transitions. The shaded blue area represents the area outside the Q_β window that is not energetically available for the decay.

are states with the right spin to be fed through Gamow-Teller decay but they are either only lightly populated or not populated at all. This decay would not be properly described using a statistical model as such a model would populate these allowed states, something that is clearly contradicted by the experimental S_β .

The result here is that neither the decay of ^{84}Br nor the decay of ^{85}Br would be accurately described with a statistical model. The observed decay of these nuclei is shown here to be dominated by shell structure effects as is expected so close to a closed shell.

9.4.4 Shell Model Calculations for ^{86}Br

Shell model calculations for ^{86}Br , shown in Fig. 9.5 were performed with a model space similar to that used for $^{84,85}\text{Br}$ with the addition of a neutron in the $d_{5/2}$ orbital above an $N=50$ shell gap of 3.9 MeV and different single-particle energies [37]. While the natural core for ^{86}Br might appear to be ^{78}Ni , in which the $d_{5/2}$ neutron decays and the remainder

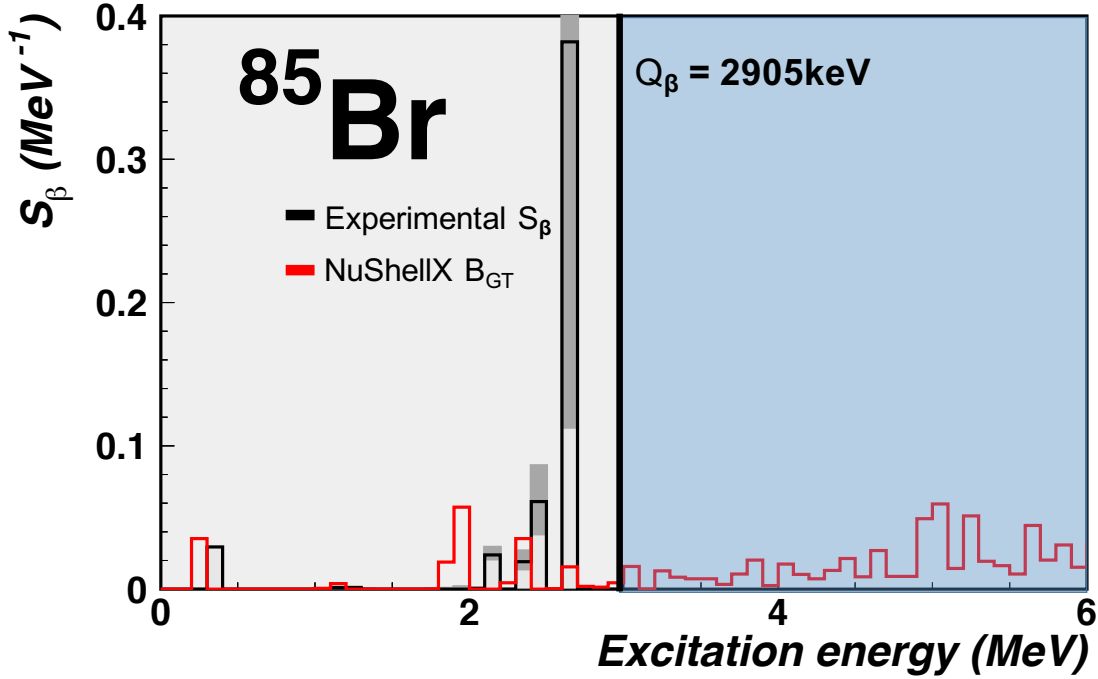


Figure 9.4: Extracted S_β from MTAS spectrum (black) and B_{GT} from shell model calculations (red) for ^{85}Br . Note that S_β includes both allowed and forbidden transitions. The shaded blue area represents the area outside the Q_β window that is not energetically available for the decay.

is treated as an inert core, this configuration cannot accurately capture the experimentally observed decay strengths. This phenomenon is discussed further in Chapter 4. Because the $d_{5/2}$ neutron cannot have an energetically available spin-orbit partner, it is not a participant in the Gamow-Teller decay of ^{86}Br . The occupancy of the $d_{5/2}$ neutron orbital was blocked to two neutrons because by allowing cross-shell excitations, the increase in the number of possible configurations made the calculation computationally intractable [10]. The predictions of the shell model calculations for ^{86}Br are identical as those for $^{84,85}\text{Br}$ as they suggest the $\nu p_{1/2} \mapsto \pi p_{3/2}$ transition will dominate.

When the daughter of ^{86}Br , ^{86}Kr , is populated in an excited state via the Gamow-Teller decay of a fp orbital, neutrons are necessarily in a particle-hole configuration across the $N=50$ shell gap. Their excitation energy is expected to start around the shell gap energy of 3.9 MeV. Therefore ^{86}Br can be viewed as a “threshold” nucleus whose B_{GT} is pushed up relative to $^{84,85}\text{Br}$ by a threshold equal to the energy of the shell gap. This effect is confirmed by the experimental observation of decay strength feeding levels with excitation

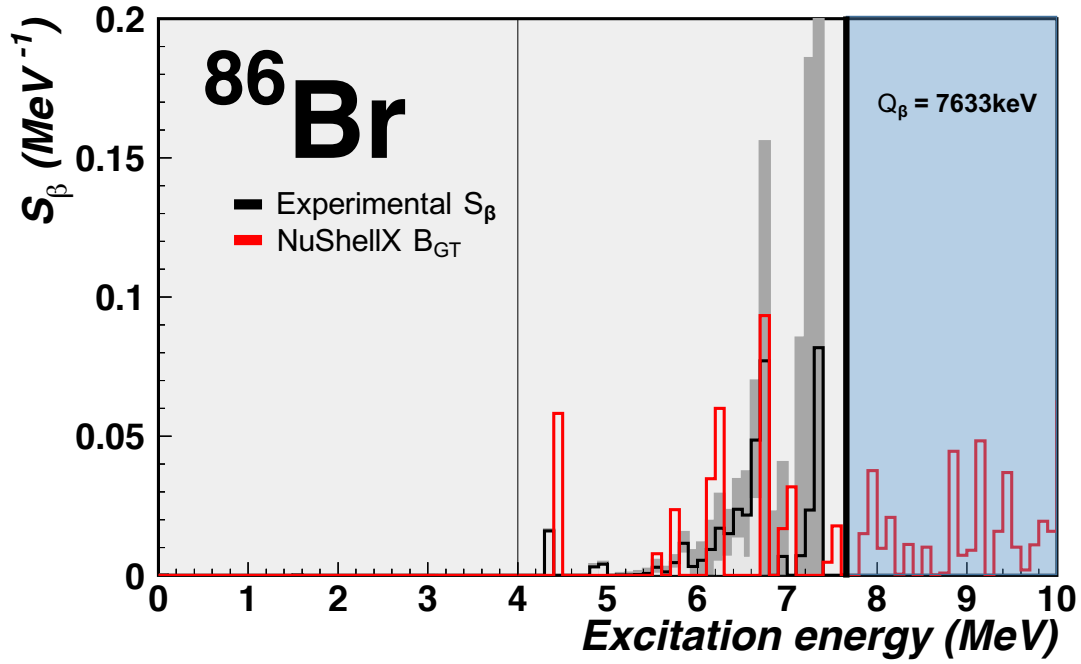


Figure 9.5: Extracted S_β from MTAS spectrum (black) and B_{GT} from shell model calculations (red) for ^{86}Br . Note that S_β includes both allowed and forbidden transitions. The shaded blue area represents the area outside the Q_β window that is not energetically available for the decay.

energies above 3.9 MeV. The single strong transition at ~ 4 MeV is likely to be the same $\nu p_{1/2} \mapsto \pi p_{3/2}$ transition observed in the decays of $^{84,85}\text{Br}$. There remains the problem that the quenching is unusually large. Quenching values are expected to be $\sim 30\%$, here the quenching is 80%. Such a large quenching factor suggests that the model is incomplete. We suspect that the inconsistency is due to Pauli blocking of the $p_{3/2}$ proton orbital but further development of the theory describing this region will be left for more advanced calculations.

9.5 Comparison of Shell Model Calculations for ^{86}Br to Interpretation in Urban et al. Paper

The recent publication on high resolution spectroscopy measurements of the β decay of ^{86}Br performed by Urban et al. [57] conclude that the $\nu g_{7/2} \mapsto \pi g_{9/2}$ transition dominates and forbidden decay of the $d_{5/2}$ neutron accounts for the small-magnitude transitions to states at low excitation energies in ^{86}Kr . They however do not show any calculated B_{GT} .

Additionally, the shell model calculations performed here disagree with that interpretation. Our calculations show that only a very small percentage of the $g_{7/2}$ neutron orbital contributes to the ground-state wave function of ^{86}Kr . Such a small contribution would not compete with Gamow-Teller core decay.

Chapter 10

Conclusions

In conclusion, we are able to reasonably predict the experimental decay strength matrix elements, S_β , with shell model calculations making use of a ^{56}Ni closed shell for $^{84,85,86}\text{Br}$. Using the nuclear shell model we can predict both excitation energies and, with the inclusion of a quenching factor, the strengths of the individual matrix elements. The decay of $^{84,85}\text{Br}$ are both heavily structural and not well reproduced by statistical models. Furthermore, ^{86}Br behaves as a threshold nucleus due to the fact that the particle-hole coupling of the fpg shell to the $d_{5/2}$ neutron orbital shifts the B_{GT} up by the shell gap relative to the B_{GT} distributions of $^{84,85}\text{Br}$.

Despite the fact that we can describe the B_{GT} with a sufficiently complex nuclear shell model, even in situations when we have to cross $N=50$ the shell and we can capture the complexity of the decay without invoking statistical arguments, the accuracy of the model is not yet sufficient to replace the data. The model described here does provide us with a picture of the physics driving the structure of this region. This picture is best used to aid in the planning of future experiments.

Chapter 11

My Contributions to the Project

- Participated in extended total absorption spectroscopy experimental campaigns in January 2012, March 2015 and October 2015 to February 2016 at the Holifield Radioactive Ion Beam Facility (HRIBF) in the Oak Ridge National Laboratory during which the β -decay of over 70 fission products of ^{238}U were measured using the Modular Total Absorption Spectrometer
 - Aided in setup including gain matching photomultiplier tubes and calibrating detectors
 - Altered run-time code to include new detector types
 - Led shifts and beam tuning efforts
 - Created auto-updating software-based beam monitor, audible tape transport break alarm and visible laser activity indicator
- Developed novel γ - γ matrix method of analyzing TAS data capable of reporting both level feedings and the path through which the level de-excites
- Generated PMT by PMT calibrations and cleaned $^{84,85,86}\text{Br}$ datasets
- Analysis of $^{84,85}\text{Br}$ data using C++, Geant4 and Root from March 2015 experimental run. Identified newly detected high-energy levels, concomitant γ cascades and updated strength distributions

- Ran shell model calculations in NushellX for $^{84,85,86}\text{Br}$
- Developed, constructed, tested and fully characterized 3-channel laser gain stabilization system (LaGS) for 14 of the 48 photomultiplier tubes in the Modular Total Absorption Spectrometer. Utilized system in 2015 and 2016 data runs. Design for a 19-channel system covering all 48 photomultiplier tubes is complete and undergoing testing

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Appendices

Appendix A

Tables of extracted I_β and S_β for $^{84,85,86}\text{Br}$

Table A.1: ^{84}Br results and associated error for I_β and S_β .

Level Energy (keV)	I_β (%)	I_β Error _{min} (%)	I_β Error _{max} (%)	$\text{Log}(ft)$	S_β	S_β Error _{min}	S_β Error _{max}
0	24.4	-1	+1	7.8	6e-05	-1e-05	0
881.6	13.3	-0.4	+0.4	7.7	8e-05	0	0
1837.3	1.2	-0.4	+0.4	8.2	2.4e-05	-9e-06	+6e-06
1897.6	9.2	-0.4	+0.4	7.3	0.0002	0	+5e-05
2094.9	<0.2	-0.2	0	>8.1	<6e-06	-6e-06	0
2345.2	<0.02	-0.02	0	>9.6	<8e-07	-8e-07	0
2489.2	<0.2	-0.2	0	>8.3	<1e-05	-1e-05	0
2623	1.4	-0.4	+0.4	7.5	0.00012	-4e-05	+3e-05
2699.9	8	-0.4	+0.4	6.7	0.0008	0	0
2759.1	1.3	-0.4	+0.4	7.4	0.00015	-6e-05	+4e-05
3082	4.3	-0.4	+0.4	6.6	0.001	0	+0.0002
3345.8	10.1	-0.5	+0.5	5.9	0.005	0	0
3475.6	0.4	-0.3	+0.3	7.1	0.0003	-0.0002	+0.0003
3705.8	3	-0.4	+0.4	5.9	0.005	0	+0.001
3870.4	9.7	-0.7	+0.7	5.1	0.03	0	+0.008
3878.7	3.9	-0.7	+0.7	5.4	0.02	-0.003	0
3927.3	4.5	-0.7	+0.7	5.3	0.02	0	+0.005
4084.3	4.9	-0.5	+0.5	4.8	0.06	-0.01	0
4116.8	<0.2	-0.2	0	>5.6	<0.004	-0.004	0
4189.2	0.9	-0.4	+0.4	5.2	0.024	-0.01	+0.006

Table A.2: ^{85}Br results and associated error for I_β and S_β . New levels are highlighted in red. The ground state was not detected in this case as the isomeric state at 304.87keV has a half-life of 4.48 hours and therefore has no error as measured in this experiment.

Level Energy (keV)	I_β (%)	I_β Error _{min} (%)	I_β Error _{max} (%)	$\text{Log}(ft)$	S_β	S_β Error _{min}	S_β Error _{max}
0	0	0	0	0	0	0	0
304.9	93.7	-0.3	+0.3	5.1	0.03	0	0
1107.3	0.78	-0.1	+0.1	6.5	0.001	-0.0002	0
1166.7	<0.07	-0.07	0	>8	<0.0001	-0.0001	0
1224	0.69	-0.1	+0.1	6.5	0.001	0	+0.0003
1342.6	<0.04	-0.04	0	>9.6	>0.0001	-0.0001	0
1720.9	<0.03	-0.03	0	>8.3	<0.0002	-0.0002	0
1873.6	<0.05	-0.05	0	0	<0.0006	-0.0006	0
1938.4	<0.1	-0.1	0	>7.9	<0.001	-0.001	0
2032	3.7	-0.2	+0.2	4.7	0.08	0	+0.02
2137.4	0.66	-0.1	+0.1	5.2	0.024	-0.005	+0.006
2330	0.19	-0.07	+0.07	5.3	0.019	-0.007	+0.005
2470	0.22	-0.09	+0.09	4.8	0.06	-0.02	+0.02
2650	<0.4	-0.4	0	>4	0.4	-0.3	+0.2

Table A.3: ^{86}Br results and associated error for I_β and S_β part one of three. Pseudo-levels are highlighted in blue.

Level Energy (keV)	I_β (%)	I_β Error _{min} (%)	I_β Error _{max} (%)	$\text{Log}(ft)$	S_β	S_β Error _{min}	S_β Error _{max}
0	22.9	-1	+1	7.3	0.0002	0	0
1564.6	4.2	-0.7	+0.7	7.6	0.0001	-2e-05	+2e-05
2250	<0.4	-0.4	0	0	<2e-05	-2e-05	0
2349.4	<0.5	-0.5	0	>10	<2e-05	-2e-05	0
2850.7	0.9	-0.7	+0.7	7.8	6e-05	-5e-05	+4e-05
2916.8	<0.7	-0.7	0	>8.1	<5e-05	-5e-05	0
2926.1	0.7	-0.7	+0.7	7.9	5e-05	-4e-05	+5e-05
3009.4	<1	-1	0	>8.1	<5e-05	-5e-05	0
3098.8	<0.6	-0.6	0	>8.6	<5e-05	-5e-05	0
4315.8	44.6	-1	+1	5.4	0.02	0	0
4800	4.5	-1	+1	6.1	0.003	-0.0006	+0.0008
4900	4.9	-0.9	+0.9	6	0.0038	-0.0008	+0.001
5000	3.2	-0.8	+0.8	6.1	0.003	-0.001	+0.0008
5100	<0.5	-0.5	0	>7.3	<0.0006	-0.0006	0
5200	<0.5	-0.5	0	>7.4	<0.0006	-0.0006	0
5300	<0.5	-0.5	0	>7.1	0.0007	-0.0007	0
5314	<0.2	0	+0.2	0	<0.0003	0	+0.0003
5400	<0.3	-0.2	+0.3	7	0.0004	-0.0004	+0.0006
5406.1	<0.7	-0.2	+0.5	>7.1	<0.0014	-0.0003	+0.0009
5500	0.7	-0.5	+0.5	6.4	0.0015	-0.001	+0.002
5517.4	0.6	-0.5	+0.5	6.5	0.0012	-0.001	+0.001
5600	0.5	-0.5	+0.6	6.5	0.0012	-0.001	+0.002
5700	1.4	-0.7	+0.7	5.9	0.005	-0.002	+0.003
5800	2.8	-0.9	+0.9	5.5	0.012	-0.004	+0.003
5900	0.6	-0.6	+1	6.1	0.003	-0.003	+0.007
6000	<0.4	-0.4	0	>5.8	<0.002	-0.002	0
6089.1	0.7	-0.7	+0.7	5.9	0.005	-0.005	+0.007
6100	0.9	-0.6	+0.6	5.7	0.008	-0.005	+0.004
6160.5	0.2	-0.2	+0.5	6.3	0.002	-0.002	+0.006
6200	0.5	-0.5	+0.5	5.9	0.005	-0.005	+0.007
6211.8	1	-0.6	+0.6	5.5	0.012	-0.007	+0.007
6300	1	-0.6	+0.6	5.4	0.015	-0.009	+0.009
6400	1.2	-0.5	+0.5	5.2	0.024	-0.01	+0.01
6500	0.8	-0.6	+0.6	5.2	0.024	-0.02	+0.01
6600	1.2	-0.5	+0.5	4.9	0.05	-0.02	+0.03
6700	0.7	-0.5	+0.5	5	0.04	-0.03	+0.04
6720.5	0.5	-0.4	+0.4	5.1	0.03	-0.02	+0.03
6768.3	0.04	-0.04	+0.3	6.1	0.003	-0.003	+0.03
6800	<0.3	-0.3	0	>5.5	<0.02	-0.02	0
6900	<0.07	-0.07	0	>5.8	<0.03	-0.03	0
7000	<0.06	-0.06	0	>5.6	<0.04	-0.04	0
7100	<0.04	-0.04	0	>5.7	<0.07	-0.07	0
7200	<0.05	-0.05	0	>5.2	<0.2	-0.2	0
7300	<0.06	-0.06	0	>4.7	<0.5	-0.5	0

Vita

Kathleen (known to most as Callie) was born in Nashville, TN in 1987. She was the fourth generation in her family to attend the Harpeth Hall School for girls. While there, a few stellar teachers ignited her love for science. With their help, she obtained a job as a lab assistant at Vanderbilt University in the Geo-chemistry Department. In college Callie pursued a dual degree. She studied Physics at Middlebury College and Electrical Engineering at Dartmouth. She spent a semester before college and her school breaks interning at the Oak Ridge National Laboratory's Spallation Neutron Source where she worked on imaging-based beam profile monitors. She got certified as an Emergency Medical Technician so that during the school year she could work nights and weekends with her squad at Dartmouth and as a medic for sports teams. After college Callie moved down to Peru and volunteered in the emergency room of a small but very busy medical post in Cusco, Peru. During this time she met some local physics professors and together they founded Callie's first non-profit, Q'omer Q'aya. Q'omer Q'aya (meaning "Green Tomorrow" in Quechua) worked to both educate university students about green energy production and to aid local villages that did not have access to electricity or running water. They taught seminars at the Universidad del Altiplano in Puno, Peru on sustainable energy production and then with the class built projects such as solar hot-water heaters and windmill water pumps for villages in need. Callie then attended graduate school in the interdisciplinary Energy Science and Engineering program, the topic of which is discussed at length here in this dissertation. During this time she co-founded another non-profit called Ask a Scientist. The main mission of Ask a Scientist is science outreach and Callie is currently serving as Chief Operations Officer. Callie has been very fortunate to have both strong support from family and friends and a string of stellar mentors in her life. For this fact she is eternally grateful.