

THE SIMULTANEOUS EXTRACTION OF THE ISOVECTOR GIANT MONOPOLE
RESONANCE AND THE ISOVECTOR SPIN GIANT MONOPOLE RESONANCE IN
 ^{90}Y VIA THE $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B})^{90}\text{Y}$ CHARGE EXCHANGE REACTION AT 100 MEV/U

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ABSTRACT

The isovector giant monopole resonance (IVGMR) is a collective excitation in which the proton and neutron fluids oscillate radially out-of phase with each other. Studies of the IVGMR, along with its spin partner, the isovector spin giant monopole resonance (IVSGMR), provide important information about the bulk properties of nuclear matter and improve our understanding of isovector matter. However, studies of these resonances have been historically challenging, as a probe system with spin selectivity is necessary to isolate the resonances from each other. Further, significant uncertainties arise when comparing the results of different experiments measuring the resonances separately. By utilizing the ($^{10}\text{Be}, ^{10}\text{B} + \gamma$) charge exchange reaction, spin filters that are selective to the $\Delta T = 1, \Delta S = 0$ response and the $\Delta T = 1, \Delta S = 1$ response are obtained, allowing for the simultaneous extraction and study of the IVGMR and the IVSGMR in a single experiment. The identification of the $\Delta T = 1, \Delta S = 0$ channel is achieved by gating on the superallowed Fermi transition $^{10}\text{Be}(0^+, g.s.) \rightarrow ^{10}\text{B}(0^+, 1.74 \text{ MeV})$, which is detected by measuring the 1022 keV γ -ray emitted by the ^{10}B ejectile. Similarly, the identification of the $\Delta T = 1, \Delta S = 1$ channel is achieved by gating on the Gamow Teller ($\Delta S = 1$) transition $^{10}\text{Be}(0^+, g.s.) \rightarrow ^{10}\text{B}(1^+, 0.718 \text{ MeV})$ by detecting the 718 keV γ -ray emitted by the ^{10}B ejectile. In this work, the IVGMR and IVSGMR in ^{90}Y are measured using the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B} + \gamma)$ reaction at 100 AMeV at the Facility for Rare Isotope Beams (FRIB). In addition, previous data on ^{12}C are used to demonstrate the isolation of the $\Delta S = 0$ and $\Delta S = 1$ response in a single measurement. The exhaustion of the non-energy weighted sum rule (NEWSR) in ^{90}Y for the IVGMR was $199 \pm 81(\text{stat}) \pm 80(\text{syst}) \%$, and for the IVSGMR it was $121 \pm 47(\text{stat}) \pm 48(\text{syst}) \%$. The extracted IVGMR and IVSGMR distributions are also compared to the results from calculations in the proton-neutron relativistic quaiparticle

time blocking approximation showing reasonable consistency.

I dedicate this work to my wife, Krystal, and my daughters, Kinsley and Ember. You push me to be better every day and I couldn't have done this without you.

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Chapter 1. Introduction

Giant resonances are highly energetic, collective excitations of nuclear matter that involve many, if not all, of the nucleons in a nucleus. The study of giant resonances provides valuable information on the bulk properties of matter and the nuclear response at high excitation energies [1]. They are categorized by isospin (ΔT), multipolarity (ΔL), and spin (ΔS), and the strength of each resonance depends on the number of participating nucleons and is limited by a sum rule for the resonance. The sum rule refers to the total transition strength associated with a specific operator and quantum numbers [1]. The resonance is considered "giant" when it exhausts at least 50% of the respective sum rule.

The first evidence of collective nuclear excitations was observed by Bothe and Gentner in 1937 [21], when they observed a higher photo-absorption cross section at high excitation energies. This resonance was later identified as the isovector giant dipole resonance (IVGDR). The first theoretical description of the IVGDR was introduced by Migdal in 1944 [22], and was rediscovered by Baldwin and Klaier in 1947 [23]. The results of Baldwin and Klaier were subsequently interpreted by Goldhaber and Teller [24] and Steinwedel and Jensen [25] as dipole oscillations of protons versus neutrons. In the following decades, the IVGDR was systematically investigated [26, 27] and theoretical frameworks were developed to describe these resonances ([28] and sources within). In the 1970s the isoscalar quadrupole resonance was discovered, showing giant resonances could also be isoscalar in nature [29–31], followed by the discovery of the isoscalar monopole resonance in the mid-to-late 70s [32, 33]. Inspired by the successful studies of the isoscalar monopole resonance, which has been valuable to the study of the incompressibility of nuclear matter, significant effort has been invested into studying its isovector partners, the isovector giant monopole resonance (IVGMR) and the

isovector spin giant monopole resonance (IVSGMR).

The IVGMR and the IVSGMR are excitations over two major nuclear oscillator shells, referred to as $2\hbar\omega$ excitations. These monopole ($L = 0$) resonances are wide ($\Gamma > 10$ MeV) and lie in the continuum region of the excitation-energy spectrum. The resonances are described as out-of-phase oscillations of proton and neutron matter ($T=1$), while the IVSGMR is also mediated by transfer of spin ($S=1$), which causes oscillations of spin up (down) protons and neutrons out of phase with spin down (up) protons and neutrons. The study of these resonances provides valuable information about the bulk properties of nuclear matter and the isovector response at high energies and can improve our understanding of asymmetric nuclear matter [34–37]. Further, systematic studies of the excitation energies and collectivity of the resonances can be used to constrain the nuclear Equation of State of nuclear matter by reducing the ambiguities in the isovector component of nucleon-nucleon interactions, such as in Skyrme interactions [38]. Due to the $2\hbar\omega$ nature of the excitation, studies of the monopole resonances can provide information about the continuum, and experimental data serves as a fertile testing ground for modern density functional theories at high energies. Because the non-energy weighted sum rule (NEWSR) is sensitive to the difference in radii between the proton and neutron distributions [39], measurements of the strengths of the isovector giant monopole resonance can provide a complimentary way to measure the neutron skin thickness. Finally, information on the spin-isospin response at high energies also has an impact on astrophysics, such as modeling and nucleon-neutrino cross sections [40, 41]. Unfortunately, these resonances have been historically difficult to study, primarily due to a lack of clean probes to isolate the resonances. In this thesis, the ($^{10}\text{Be}, ^{10}\text{B}$) charge-exchange reaction is used to study the isovector giant monopole resonances in ^{90}Y . As described below, this probe is unique in the way it can be used to isolate isovector monopole strength in the excitation

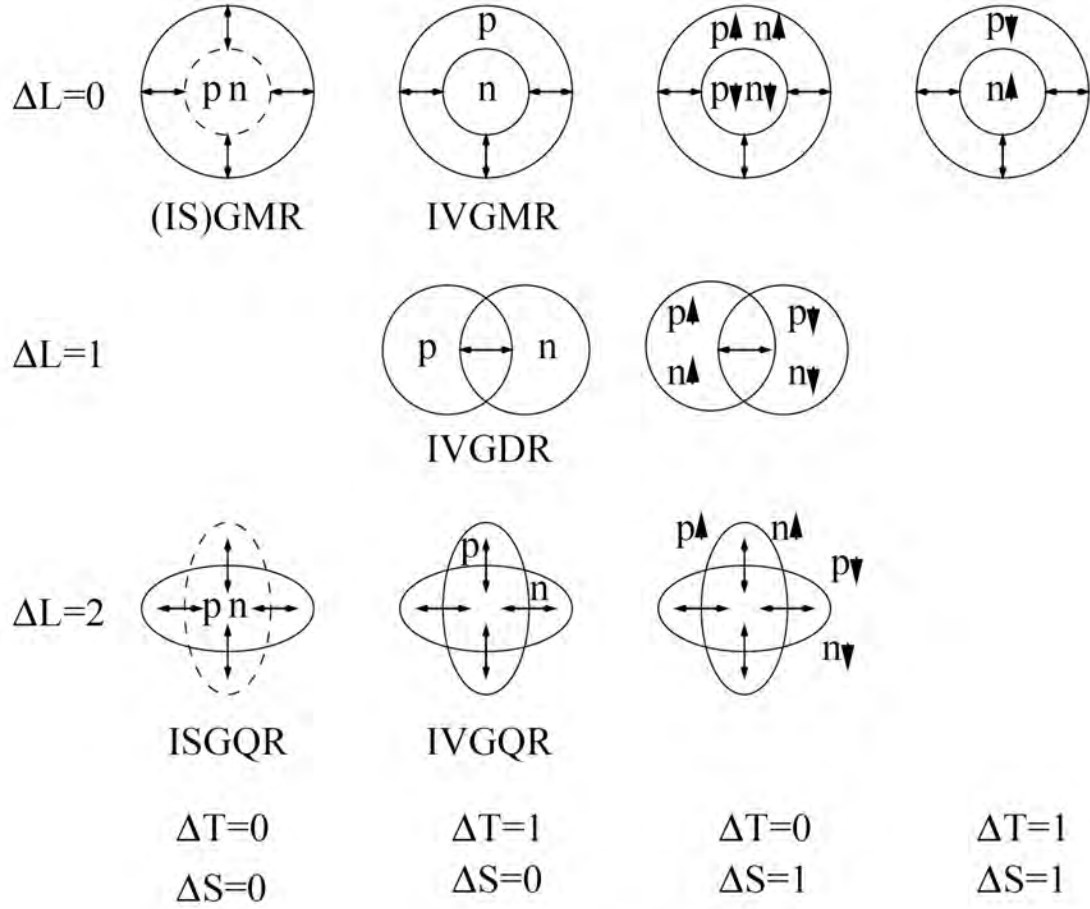


Figure 1.1: Macroscopic depiction of giant monopole resonances within the hydrodynamic model from [1].

energy spectrum.

1.1 Theoretical Description

Giant resonances are described macroscopically using a hydrodynamical model, where the resonances are described as small-amplitude oscillations of incompressible proton and neutron fluids that move in-phase (isoscalar) or out-of-phase (isovector) with each other. These oscillations are described as surface-vibrations, compressional vibrations, or a superposition of both modes. The theoretical descriptions of surface-vibrations and compressional vibra-

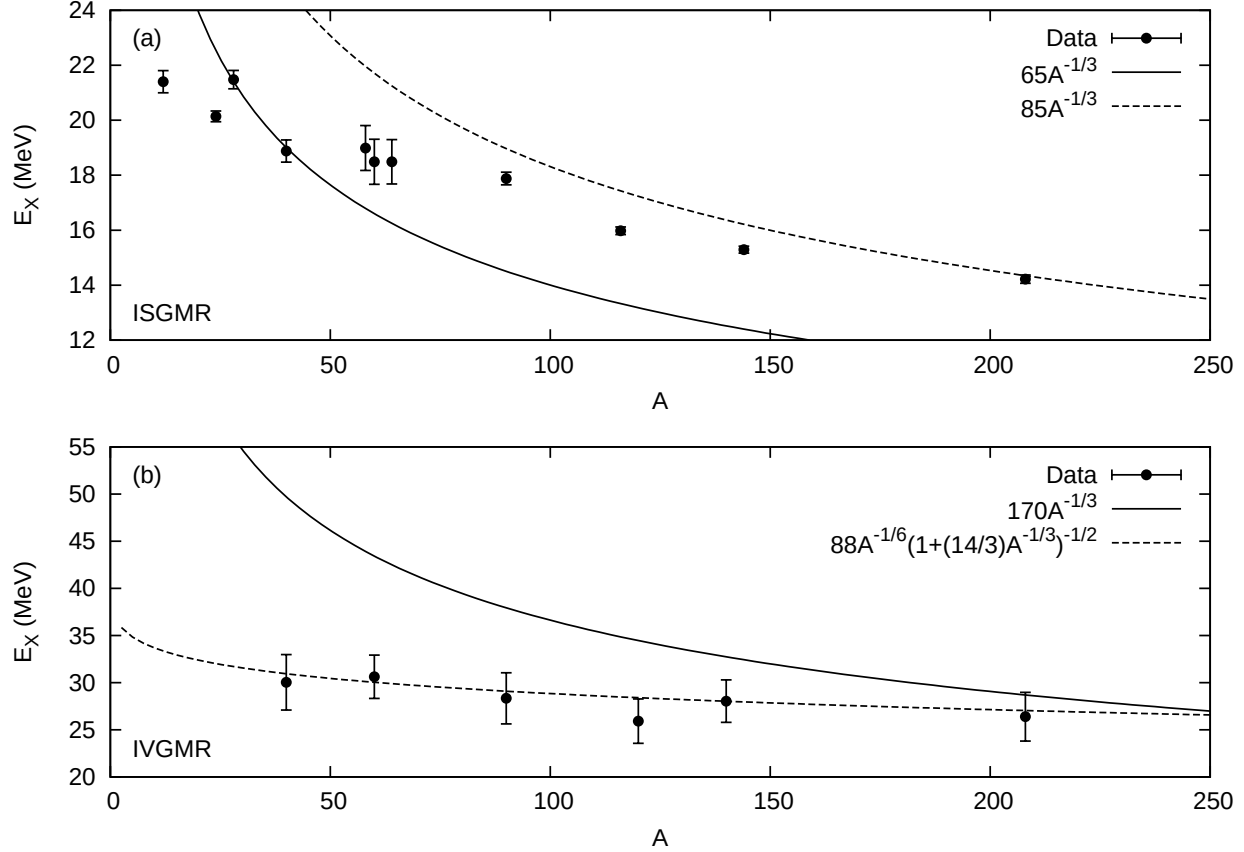


Figure 1.2: (a) Measurements of the ISGMR via inelastic α scattering from Ref. [2]. The solid black line is the location of the ISGMR as a function of A from Ref [3] (Equation 1.2), while the dotted black line is the model using updated information of the nuclear incompressibility (K_{NM}) from Ref [4] (Equation 1.3). (b) Measurements of the IVGMR from pion scattering from Refs [5,6]. The solid line represents a simple model derived from the hydrodynamical model that only includes compressional effects (Equation 1.4), while the dashed line is an improved model that includes surface effects (Equation 1.5). Figure from Ref [7].

tions for giant resonances are found in Refs. [3] and [42], respectively. A cartoon depiction of the macroscopic vibrations for some of these resonances is shown in Figure 1.1. The simplest of these resonances is the isoscalar giant monopole resonance (ISGMR), which is described as a "breathing" mode where the proton and neutron distributions oscillate radially in-phase. Detailed studies of the ISGMR has yielded valuable information about the bulk properties of nuclear matter, such as information about the incompressibility of nuclear matter (K_{NM}) [4,43]. A detailed review of the study of isoscalar resonances, including the

ISGMR, can be found in Ref. [44] and references within.

The first theoretical description and prediction of the location in excitation energy of the ISGMR was performed by Bohr and Mottelson, who described the compressional modes of nuclei as small oscillations in density of the nucleus around the nuclear equilibrium [3]. They found that the energy of the isoscalar resonance as a function of nucleon number (A) to be

$$E_{nL} = \frac{\hbar k_{nL}}{1.2} \sqrt{\frac{K_{NM}}{9m}} A^{-1/3} \text{ MeV} \quad (1.1)$$

where k_{nL} are the eigenvalues of the motion for principle quantum number n and the multipolarity L , K_{NM} is the incompressibility of nuclear matter, and m is the nucleon mass. Using the quantum numbers for the ISGMR ($n = 1$, $L = 0$) and the estimate of the incompressibility at the time ($K_{NM} = 135$ MeV), the location of the ISGMR was given by

$$E_X^{ISGMR} = 65A^{-1/3}. \quad (1.2)$$

As experimental data became available, the incompressibility was determined to be $K_{NM} = 231 \pm 5$ MeV [4]. The new excitation-energy estimate was then defined as

$$E_X^{ISGMR} = 85A^{-1/3}. \quad (1.3)$$

The top of Figure 1.2 shows experimental ISGMR data from Ref. [2] overlaid with Equation 1.2 using a solid black line and Equation 1.3 using the dotted black line. Using the new K_{NM} value, the hydrodynamical model is able to reproduce the location of the ISGMR in ^{208}Pb , while overshooting the other nuclei. This shows that only using the compressional modes is insufficient to describe even the simplest resonant mode.

In the case of the isovector resonances, the hydrodynamical model approaches the nuclei as a liquid drop with degrees of freedom for protons (Z), neutrons (N), and the spin (spin-up and spin-down). The frequency and excitation energy of the resonance are derived using the linearized Navier Stokes equations [45]. When only the compressional vibrational mode is considered, the solution, from Ref. [42], the excitation energy location of the IVGMR is

$$E_X^{IVGMR} = 170A^{-1/3} \text{ MeV} \quad (1.4)$$

The bottom of Figure 1.2 shows Equation 1.4 as the solid line plotted on top of IVGMR measurements using pion charge exchange experiments [5,6]. Like the ISGMR, the IVGMR does not reproduce the data well when only the compressional mode is considered. By including both compressional vibrations and surface vibrations in the calculation [46], the predicted energy becomes

$$E_X(\text{MeV}) = 88A^{-1/6}(1 + (14/3)A^{-1/3})^{-1/2} \quad (1.5)$$

Equation 1.5 is presented as the dotted black line in Figure 1.2 (b). By adding the contribution from surface effects, Equation 1.5 reproduces the data well.

Microscopically, a resonance is described as a coherent superposition of one-particle, one-hole (1p-1h) excitations. A giant resonance must exhaust more than 50% of the operator's sum rule and start several MeV above the ground state. Details of the microscopic calculations are summarized in Refs. [1,47,48]. The strength function of a nucleus in response to an arbitrary one body operator is determined by linking the ground state to the final state by

$$S_O(E) = \sum_f |\langle \phi_f | O | \phi_0 \rangle|^2 \delta(E_f - E) \quad (1.6)$$

where $|\phi_0\rangle$ and $|\phi_f\rangle$ refer to the ground state and final state, respectively. The general form of the one-body operator describing giant resonances is

$$O_{JM}^\mu = r^\lambda \left[\vec{\sigma} \otimes \vec{Y}_L \right]_M^J \tau_\mu \quad (1.7)$$

where $\vec{J} = \vec{S} + \vec{L}$, M is the projection of J , $\vec{\sigma}$ is the spin operator, $\vec{Y}_L$ is the spherical harmoniv associated with L , τ_{mu} is the isovector operator in the direction of μ (-1 or +1), and $\lambda = 2n + L$ where n is the number of major oscillator shells the transition occurs over. For the IVGMR, the operator reduces to

$$O^\mu = r^2 \tau_\mu \quad (1.8)$$

while for the IVSGMR, the operator reduces to

$$O^\mu = r^2 \sigma \tau_\mu. \quad (1.9)$$

From here, it is important to define the moments of the strength function. The non-energy weighted sum rule is defined as the non-energy moment of the strength function. The moments of the strength function are calculated by

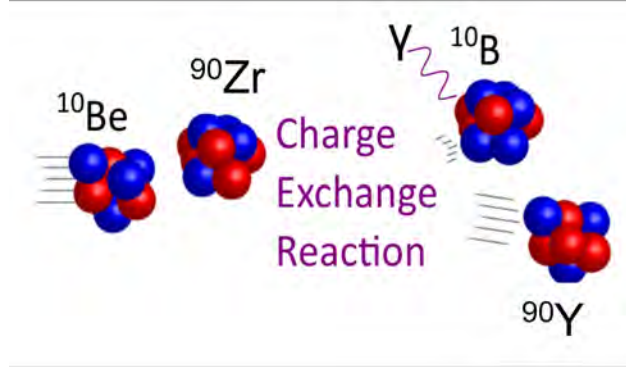


Figure 1.3: Cartoon of the Charge Exchange reaction.

$$m_k(O) = \int_0^\infty (E - E_0)^k S_O(E) dE \quad (1.10)$$

$$= \sum_f (E_f - E_0)^k |\langle \phi_f | O | \phi_0 \rangle|^2 \quad (1.11)$$

where $k = 0, \pm 1, \pm 2, \dots$. Equation 1.10 describes continuum states and Equation 1.11 describes discrete states. The moment for the NEWSR is given by

$$m_0(O) = \sum_f |\langle \phi_f | O | \phi_0 \rangle|^2 \quad (1.12)$$

where $|\phi_0\rangle$ and $|\phi_f\rangle$ refer to the ground state and final state, O is the respective one-body operator, and $m_0(O)$ is the NEWSR.

1.2 Probing the Monopole Resonance

1.2.1 Charge Exchange Reactions

Charge-exchange (CE) reactions are reactions in which the participating nuclei exchange a proton and a neutron. A cartoon of the reaction is shown in Figure 1.3. CE reactions feature a change in isospin ($\Delta T = 1$), necessary for exciting isovector excitations, and can include a spin transfer of angular momentum, i.e. $\Delta L = 0$ (monopole), $\Delta L = 1$ (dipole), $\Delta L = 2$ (quadrupole), etc. For the $\Delta T_z = +1$ ($\Delta T_z = -1$) charge exchange reactions, the interaction is mediated by neutron-particle (proton-particle), proton-hole (neutron-hole) excitations. CE reactions at intermediate energies ($\sim > 100$ AMeV) have proven to be a powerful way to probe spin-isospin response in nuclei. For thorough reviews, see Refs. [47, 49–52].

1.2.2 Historical Studies

The IVGMR and the IVSGMR are both mediated by a change in isospin ($\Delta T = 1$). However, independently studying each resonance has been historically challenging. The first experimental campaign to study the IVGMR employed the pion charge exchange (CE) reaction ($\pi^\pm, \pi^0$) on a variety of targets [5]. The pion CE probe made for a good candidate to study the IVGMR as the reaction is sensitive to the $\Delta T = 1, \Delta S = 0$ reaction. The resulting π^0 pion decays into two ≈ 100 MeV γ rays. However, the coincident measurement of the γ rays added significant experimental uncertainty to the measurement. In addition, there was also a significant background contribution on top of the monopole resonance, complicating the interpretation of the results.

The study of the IVSGMR has subsequently relied mostly on hadronic CE reactions,

especially since pion beams are no longer available. A variety of probes have been used to study the IVSGMR, such as $(^3\text{He}, t)/(t, ^3\text{He})$, and $(^{12}\text{C}, ^{12}\text{N})$, among others. Even though most probes cannot separate the IVGMR and IVSGMR, the latter resonance is dominant at beam energies of 100 MeV and above. The $(^3\text{He}, t)/(t, ^3\text{He})$ reaction have been the dominant probe for measuring the IVSGMR [19, 53, 54]. In a comparison with (p, n) and (n, p) data, an enhancement of the $\Delta L = 0$ cross section at high excitation energies is observed, providing solid evidence of the IVSGMR. The difference in the response is caused by the shape of the transition density of the isovector monopole resonances and the difference in penetrability of the nucleonic and composite CE probes. The transition density for the IVGMR is presented in Figure 1.4. Because there is a node in the transition density close to the nuclear surface for both the IVGMR and IVSGMR, probes that enter the nuclear volume will cancel out transition strength, leading to a reduction in the isovector monopole cross section. As a result, heavier composite probes are strongly preferred when studying the isovector monopole resonances.

Additional studies have been performed to study the monopole resonances using CE reactions, with a particular focus on composite probes that are strongly absorbed at the surface, as mentioned above. Various probe systems have been used, including $(^{13}\text{C}, ^{13}\text{N})$ [55–57], $(^7\text{Li}, ^7\text{Be} + \gamma)$ [58–63], $(^{10}\text{C}, ^{10}\text{B} + \gamma)$ [64–66], $(^6\text{Li}, ^6\text{He})$ [67], $(^{12}\text{C}, ^{12}\text{N})$ and $(^{12}\text{C}, ^{12}\text{B})$ [63, 68–70], $(^{12}\text{N}, ^{12}\text{C})$ [71], and the $(^{10}\text{Be}, ^{10}\text{B} + \gamma)$ reaction [15, 72]. Some probe systems have spin-selectivity for the $\Delta S = 1$ transition, such as $(^6\text{Li}, ^6\text{He})$, $(^{12}\text{C}, ^{12}\text{N})$, $(^{12}\text{C}, ^{12}\text{B})$, and $(^{12}\text{N}, ^{12}\text{C})$, while others are sensitive to the $\Delta S = 0$ transition but excite both resonances, such as $(^{13}\text{C}, ^{13}\text{N})$ and $(^{13}\text{N}, ^{13}\text{C})$. Finally, some probe systems, the $(^7\text{Li}, ^7\text{Be} + \gamma)$, $(^{10}\text{Be}, ^{10}\text{B} + \gamma)$, and $(^{10}\text{C}, ^{10}\text{B} + \gamma)$ systems, can be used to isolate the non-spin-transfer and the spin-transfer channels for simultaneous study by making a coincidence measurement

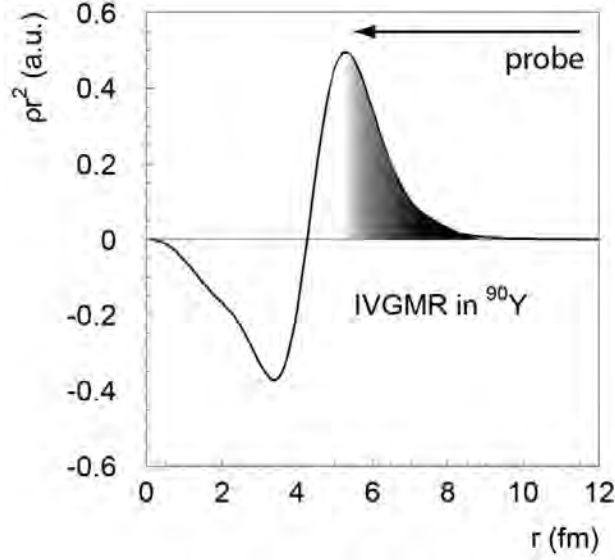


Figure 1.4: Transition density multiplied by r^2 for the excitation of the IVGMR in ^{90}Y from ^{90}Zr . As there is a node in the transition density near the nuclear surface, the probe must be strongly absorbed at the surface to avoid a cancellation of the transition strength and a reduction in the cross section.

between the γ ray released by the excited ejectile and the ejectile itself. By using the γ ray to tag the events that correspond to the spin-transfer or non-spin-transfer channels, the channels can be separated. These probes are advantageous when the goal is to study both the IVGMR and the IVSGMR, as using a single measurement to study both resonances simultaneously eliminates systematic uncertainties that arise when comparing different experiments.

For the ($^7\text{Li}, ^7\text{Be} + \gamma$) probe system, the ^7Be ion is detected in coincidence with the 429 keV γ -ray emitted following the $^7\text{Li}(3/2^-, g.s.) \rightarrow ^7\text{Be}(1/2^-, 0.428 \text{ MeV})$ transition, creating a clean $\Delta S = 1$ filter. The ground state to ground state transition, $^7\text{Li}(3/2^-, g.s.) \rightarrow ^7\text{Be}(3/2^-, g.s.)$, contains contributions from both $\Delta S = 0$ and $\Delta S = 1$ transitions. To isolate the $\Delta S = 0$ transition, the contributions from the $\Delta S = 1$ transition, obtained from the above transition to the $3/2^-$ state in ^7Be , is subtracted from the ground state. This is not ideal, however, as a detailed understanding of the tensor strengths in the nucleon-nucleon

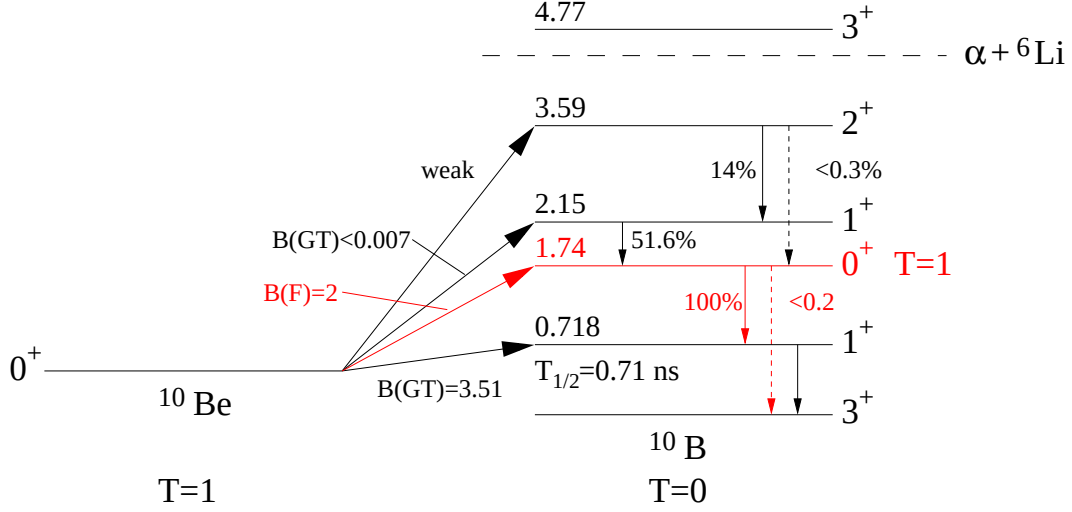


Figure 1.5: Level scheme of the $^{10}\text{Be}, ^{10}\text{B}$ reaction.

interaction and the wave functions for the relevant states are required. As a result, significant uncertainties arise from the extraction of the $\Delta S = 0$ response with this probe.

To reduce the uncertainties due to the subtraction method, the ($^{10}\text{C}, ^{10}\text{B} + \gamma$) and ($^{10}\text{Be}, ^{10}\text{B} + \gamma$) probes were developed to measure the IVGMR and IVSGMR in both directions ($\Delta T_Z = -1$ and $\Delta T_Z = +1$, respectively). Unlike for the $^7\text{Li} \rightarrow ^7\text{Be}$ system, the spin filters for both the $\Delta S = 0$ channel and the $\Delta S = 1$ channel are produced by detecting the ^{10}B in coincidence with γ -rays emitted by excited states in ^{10}B . The $\Delta S = 0$ filter relies upon a super allowed Fermi transition [$^{10}\text{C}/\text{Be}(0^+, gs) \rightarrow ^{10}\text{B}(0_1^+, 1.74 \text{ MeV})$] and the ^{10}B is detected in coincidence with a 1022 keV γ -ray emitted from the 1.74 MeV excited state, while the $\Delta S = 1$ filter relies on the [$^{10}\text{C}/\text{Be}(0^+, gs) \rightarrow ^{10}\text{B}(1_1^+, 0.718 \text{ MeV})$] transition and the ^{10}B is detected in coincidence with the 718 keV γ -ray emitted from the 0.718 MeV excited state. The decay scheme of ^{10}B is shown in Figure 1.5. Because there is a direct measurement of events related to each transition, detailed knowledge of the tensor strengths and wave functions is not needed, making both the ($^{10}\text{C}, ^{10}\text{B} + \gamma$) and ($^{10}\text{Be}, ^{10}\text{B} + \gamma$) systems the preferred method to measure the IVGMR and IVSGMR.

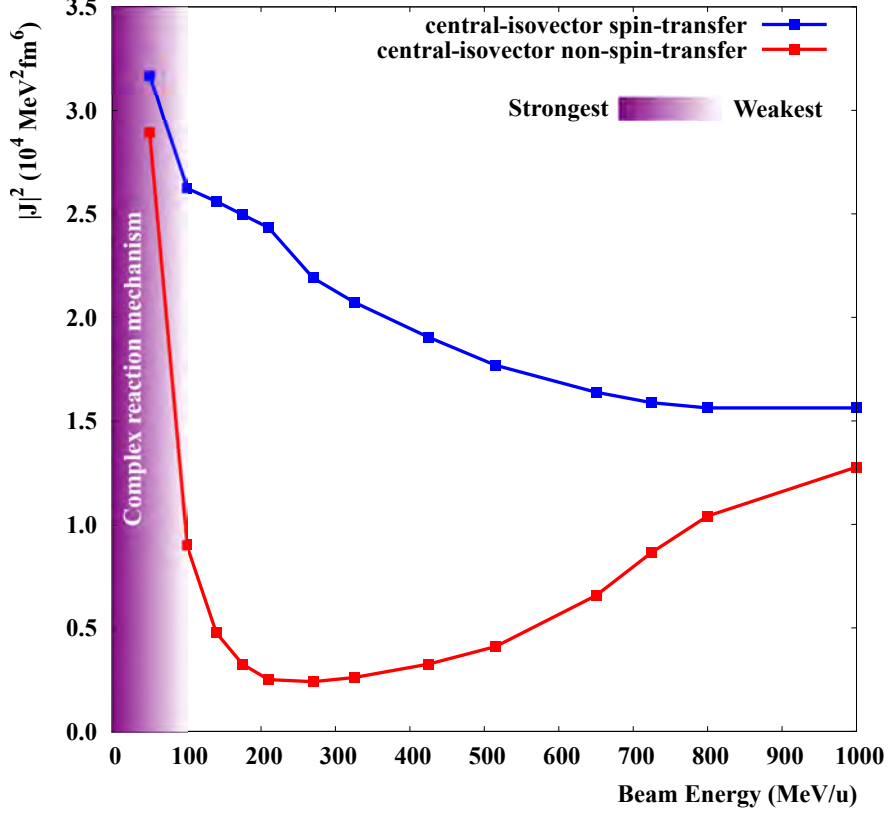


Figure 1.6: Strength of the central components of the effective interaction as a function of energy. The square volume integrals, $|J|^2$, are the square amplitudes for the the t-matrix representing the transition between final and initial states, from [8]. The shading gradient represents the transition from complex reaction mechanisms to the single-step mechanism at 100 MeV/u, as described in [9].

1.2.3 Experimental Considerations for Simultaneous Extraction

The simultaneous study of the IVGMR and IVSGMR in a single measurement has three main experimental considerations. These considerations are:

1. Clean $\Delta S = 0$, $\Delta S = 1$ filters. As both the IVGMR and IVSGMR will be excited by the CE reaction, being able to produce clean spin filters is required.
2. A single-step reaction mechanism. This is necessary for correctly interpreting experimental spectra, as significant multistep contributions to the excitation spectra complicate the calculation of the cross sections. As shown in Figure 1.6, the CE reaction

mechanism can be safely a considered single-step reaction for beam energies at about 100 AMeV and above [63]

3. A probe that is strongly absorbed at the surface. The operator for the isovector monopole resonances ($\Delta S = 0$: $r^2\tau$, $\Delta S = 1$: $r^2\sigma\tau$) have a node close to the nuclear surface. As a result, probes that enter the nuclear volume will destructively interfere with the resonances. This is shown in Figure 1.4.

The ($^{10}\text{C}, ^{10}\text{B} + \gamma$) and ($^{10}\text{Be}, ^{10}\text{B} + \gamma$) probe systems were both developed to satisfy these conditions. As heavy ions, the probes are strongly absorbed at the surface, and the ^{10}B level scheme provides the ability to make clean spin-filters. The ($^{10}\text{C}, ^{10}\text{B} + \gamma$) probe was first performed at 200 AMeV [64, 65] on a ^{90}Zr and ^7Li target. As can be observed in Figure 1.6, the beam energy of 200 AMeV avoids multistep contributions, but the IVGMR transition is quite weak at that energy. Ultimately, the monopole strength could not be extracted due to limited statistics and poor energy resolution for the γ -rays used to isolate the $\Delta S = 0$ and $\Delta S = 1$ response. Encouraged by the efficacy of the previous probe, the ($^{10}\text{Be}, ^{10}\text{B} + \gamma$) system at 100 AMeV was developed as a compliment to its counterpart, and has been successfully applied to study the IVGMR in ^{28}Al [72] and has recently been applied to the simultaneous extraction and study of the IVGMR and IVSGMR in ^{12}B as a part of this work [15]. As mentioned above, both probes rely upon a super allowed Fermi transition ($B(F) = 2$) [$^{10}\text{C}(0^+, gs) \rightarrow ^{10}\text{B}(0_1^+, 1.74\text{ MeV})$] to make the $\Delta S = 0$ filter. The 1.74 MeV excited state decays entirely to the 0.718 MeV state by releasing a 1022 keV γ ray, which acts as a tag for the $\Delta S = 0$ channel. The $\Delta S = 1$ filter relies on the [$^{10}\text{C}(0^+, gs) \rightarrow ^{10}\text{B}(1_1^+, 0.718\text{ MeV})$] transition, which has a $B(GT) = 3.51$. This state decays entirely to the ground state by emitting a 718 keV γ -ray. The clean filters are then

produced by removing the feeding from higher lying excited states. The full process of producing the spin-filters is discussed in detail in Chapters 4 and 5.

1.3 Thesis Focus

The focus of this thesis is on the simultaneous extraction of the IVGMR and the IVSGMR in a single measurement in ^{90}Y using the $(^{10}\text{Be}, ^{10}\text{B} + \gamma)$ reaction. The simultaneous extraction is first applied to ^{12}B , which is described in detail in Chapter 4. As the $^{12}\text{C} \rightarrow ^{12}\text{B}$ reaction is well studied, it made the perfect test case for the novel simultaneous extraction technique. The theoretical calculations used during the analysis will be discussed in Chapter 2, while the experimental setup of both experiments will be discussed in Chapter 3. Finally, the analysis of the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B} + \gamma)^{90}\text{Y}$ experiment is detailed in Chapter 5, and the conclusion and future work will be discussed in Chapter 6.

Chapter 2. Theoretical Tools and Methods

To extract the isovector monopole strength from experimental data and interpret the results, theoretical descriptions of the isovector giant resonances and the charge-exchange reaction cross sections are needed. As the charge-exchange reactions will excite resonances associated with different units of angular momentum transfer, $\Delta L = 0, 1, 2, \dots$, their contributions to the spectrum must be disentangled. This is accomplished by performing a multipole decomposition analysis (MDA), which is discussed in detail in Sections 4.3 and 5.6. In the MDA, the experimental spectrum is decomposed using a linear combination of theoretical angular distributions for different multipolarities. The theoretical angular distributions used in the MDA were calculated using the Distorted Wave Born Approximation (DWBA) using the FOLD code package [73], which consists of three components, WSAW, FOLD, and DWHI. The WSAW code is used to generate the radial wave functions for the nuclear shell-model orbitals, which are then used by FOLD, along with the relevant one-body transition densities (OBTDs) and the effective nucleon-nucleon interaction, to produce a form factor. The OBTDs designate the contribution from each one-particle, 1-hole transition to the overall excitation, and each particle and hole are associated with a nuclear shell-model orbit. The OBTDs for the giant resonances are calculated in the normal-modes formalism [74] using the NORMOD code [75]. The DWHI code uses the form factor produced by FOLD and optical potentials for the incoming and outgoing reaction channels to calculate the transition amplitudes and differential cross sections using the DWBA formalism. The DWBA calculations are discussed further in Section 2.1. The experimentally extracted strengths are compared to the non-energy weighted sum rule (NEWSR) calculated in the normal-modes formalism [74] using the NORMOD code [75], and the strength distributions are compared

to a distribution calculated using a proton neutron relativistic quasiparticle time blocking approximation (pn-RQTBA) calculation [?, 76] and references within.

2.1 Theoretical Differential Cross Section Calculation

To calculate the theoretical angular distributions, this work employs a first order Distorted Wave Born Approximation (DWBA) using the FOLD code package. Thorough descriptions of the DWBA can be found in Refs. [77, 78]. In the DWBA, the incoming and outgoing waves are distorted by the mean field of the target/residual nucleus. The reaction cross section in terms of transition amplitudes connecting the initial and final states (T_{fi}) from a DWBA calculation is written as

$$\frac{d\sigma}{d\Omega} = \left(\frac{\mu}{2\pi\hbar^2} \right)^2 \left(\frac{k_f}{k_i} \right) |T_{fi}|^2 \quad (2.1)$$

where μ is the reduced energy and k_i and k_f are the incoming and outgoing momenta, respectively [79, 80]. For charge exchange reactions, the transition amplitude T_{fi} is calculated using the relation

$$T_{fi} = \langle \chi_f^+(\vec{k}_f, \vec{R}') | F(\vec{R}') | \chi_i^-(\vec{k}_i, \vec{R}') \rangle \quad (2.2)$$

where χ_i^+ and χ_f^- are the incoming and outgoing distorted waves, respectively, and $F(\vec{R}')$ is a form factor that describes the interaction between the projectile and the target and is a function of the distance between the target and the projectile ($\vec{R}'$). The form factor is a double-folding of the nucleon-nucleon (NN) interaction over the projectile and target transition densities that contains the nuclear structure information about the relevant transitions.

Within the FOLD code package, the form factor is calculated using the FOLD component. The WSAW code is used to generate the radial wave functions that are used by FOLD to calculate the form factor. The DWHI code then uses the form factors from FOLD and the optical potentials for the incoming and outgoing channels to calculate transition amplitudes and differential cross sections in the DWBA formalism. In this chapter, the focus is on the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B} + \gamma)^{90}\text{Y}$ reaction. For the calculation of the $^{12}\text{C}(^{10}\text{Be}, ^{10}\text{B} + \gamma)^{12}\text{B}$ reaction discussed in Chapter 4, we refer to the thesis by Mike Scott [7] and Ref. [15]. They follow the same procedure.

2.1.1 WSAW

The WSAW code is used to calculate the single-particle radial wave functions for the one-particle and one hole contribution for the excitations in the projectile-ejectile and the target-residual two-body systems. The potential for generating the radial wave function assumes the form of a Woods-Saxon and includes a Coulomb potential for protons and a spin-orbit term for both protons and neutrons. The code requires a number of nuclear physics inputs, including the nuclear charge of the target nucleus, the core mass, and the binding energies of all individual proton and neutrons and the occupied orbitals that take part in the excitation. The Woods-Saxon is of the form

$$V(R, r_o, a_o) = \frac{V_0}{1 + e^{\frac{R - r_o A^{-1/3}}{a_o}}} \quad (2.3)$$

where V_0 is the depth of the potential, r_o is the radius of the potential, A is the mass of the target nucleus, and a_o is the diffuseness of the potential. The inputs for the nuclear potentials in WSAW are presented in Table 2.1. The full input files are presented in Appendix A. The

WSAW Potential Inputs				
V_0 (MeV)	a_o (fm)	r_o (fm)	r_c (fm)	Spin-Orbit Potential (MeV)
fitted	0.65	1.25	1.25	7.0

Table 2.1: Potential inputs for the WSAW code, where V_o is the potential depth, r_o is the radius of the potential, a_o is the diffuseness of the potential, and r_c is the Coulomb radius.

Radius step (fm)	Maximum radius (fm)	Step size				
0.1	20.	1	150	0		
10BE10B					Total	
Output file					number of points to plot radius	
Core Mass	Core Charge	Potential Depth	Diffuseness	WS Radius	Coulomb Radius	Spin-orbit potential
9.	4.	60.	.65	1.25	1.25	7.0
Particle Binding Energy	21.8	1.	0.	0.	0.5	.5
	particle mass	L	n	charge	Angular Momentum	Particle spin

Figure 2.1: Example input of the first 4 lines for WSAW with labels. This depicts a ${}^9\text{Be}$ core, and the single particle is a neutron with a binding energy of 21.8 in the $0s_{1/2}$ orbital.

first particle state from the ${}^{10}\text{Be}$, ${}^{10}\text{B}$ two-body system, with the inputs labeled, is presented in Figure 2.1. The binding energies for the $({}^{10}\text{Be}, {}^{10}\text{B})$ and $({}^{90}\text{Zr}, {}^{90}\text{Y})$ systems were calculated using the NUSHELLX@MSU package with the DENS function [81], employing the Sk20 Skyrme interaction [82]. The volume V_0 is filled so that the input binding energies are reproduced.

2.1.2 FOLD

The FOLD code is used to calculate the form factor, $F(\vec{R}')$, that is used to calculate the transition amplitude in equation 2.2. It is calculated by double folding an effective nucleon-nucleon (NN) interaction (V_{eff}) over the OBTDs of the projectile-ejectile and target-residual system. The effective NN interaction used in this work is from Love and Franey at 100 MeV/u [83,84] and has real and imaginary components. The OBTDs describe

the overlap of the initial and final states in each two-body system and act as weights for the one-particle, one-hole (1p-1h) transitions. The relevant 1p-1h transitions are determined by considering which combinations are allowed by the excitation represented by the operator O_{JM}^μ from Equation 1.7. The OBTDS for the ($^{10}\text{Be}, ^{10}\text{B}$) system were calculated using NUSHELLX@MSU [81], while the ($^{90}\text{Zr}, ^{90}\text{Y}$) are calculated in the normal modes formalism [74] using the code NORMOD [75]. The OBTDS in the normal modes formalism are produced using the most coherent superposition of the 1p-1h excitations connected by the operator O_{JM}^μ , which maximizes the transition strength. In other words, the normal modes formalism assumes that the NEWSR is entirely exhausted. Figure 2.2 shows the NORMOD input file for the ($^{90}\text{Zr}, ^{90}\text{Y}$) system with the input values labeled. Using the single-particle wave functions from WSAW, the OBTDS, and the NN interaction as inputs, the FOLD code calculates the form factor using the equation

$$F(\vec{R}') = \sum \langle \Phi_{eje} \Phi_{res} | a^\dagger a c^\dagger c | \Phi_{proj} \Phi_{tar} \rangle \langle \phi_{eje} \phi_{res} | V_{eff} | \phi_{proj} \phi_{tar} \rangle \quad (2.4)$$

from Ref. [80], where ϕ are the radial wave functions corresponding to the ejectile (eje), residual (res), projectile (proj), and target (tar), and V_{eff} is the Love-Franey (NN) interaction between the target and projectile nuclei. The $\langle \Phi_{eje} \Phi_{res} | a^\dagger a c^\dagger c | \Phi_{proj} \Phi_{tar} \rangle$ part of the equation contains the OBTDS and the spin-coupling terms. The operators $a^\dagger$ and a are creation and annihilation operators that act on the target wave function to describe the interacting nucleons, while $c^\dagger$ and c act the same way on the projectile. The sum goes over all possible quantum numbers for the system. All FOLD component inputs used in this work are presented in Appendix B. Figure 2.3 shows a FOLD input file for the IVGMR state with the important inputs labeled.

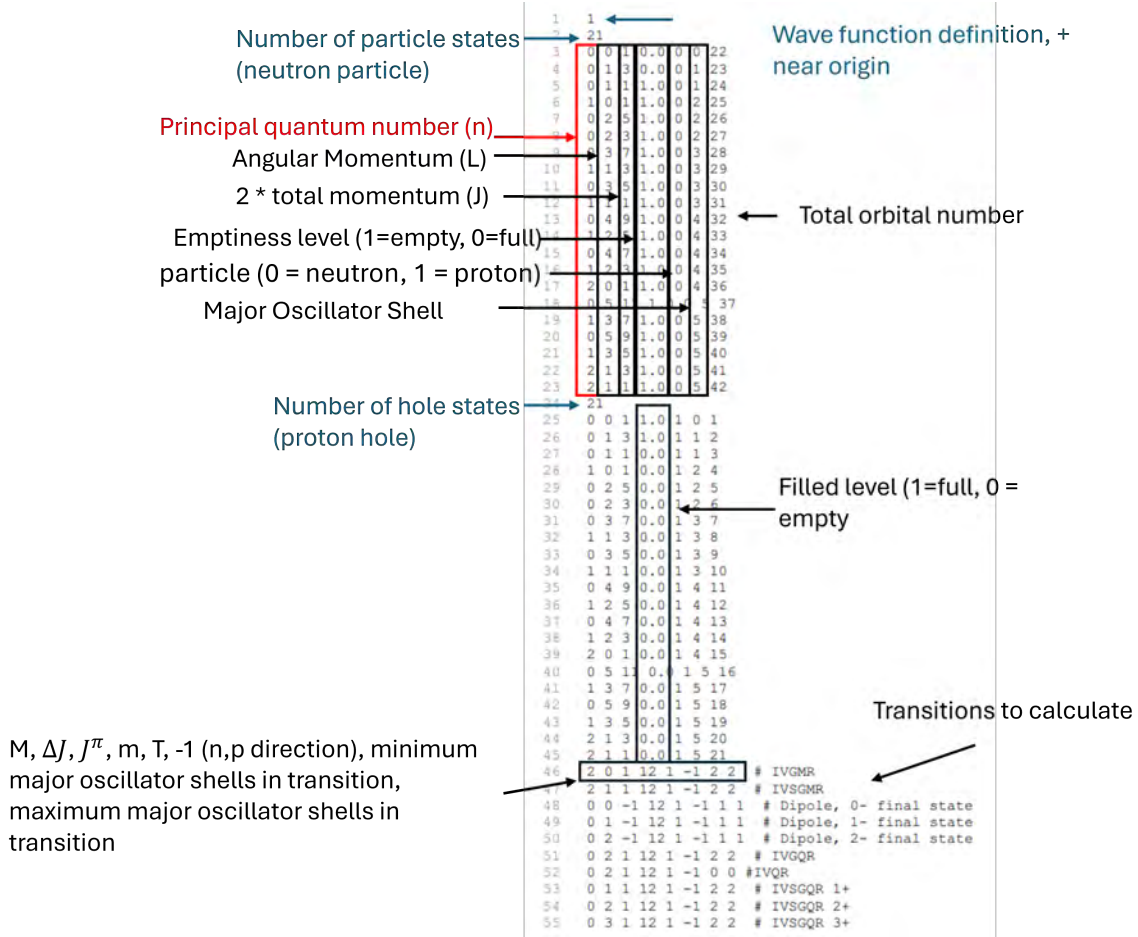


Figure 2.2: Labeled NORMOD inputs for the (^{12}C , ^{12}B) interaction. The hole states have the same inputs as the particle states, except for the difference between emptiness level for the particle state orbitals and the filled level for the hole state orbitals.

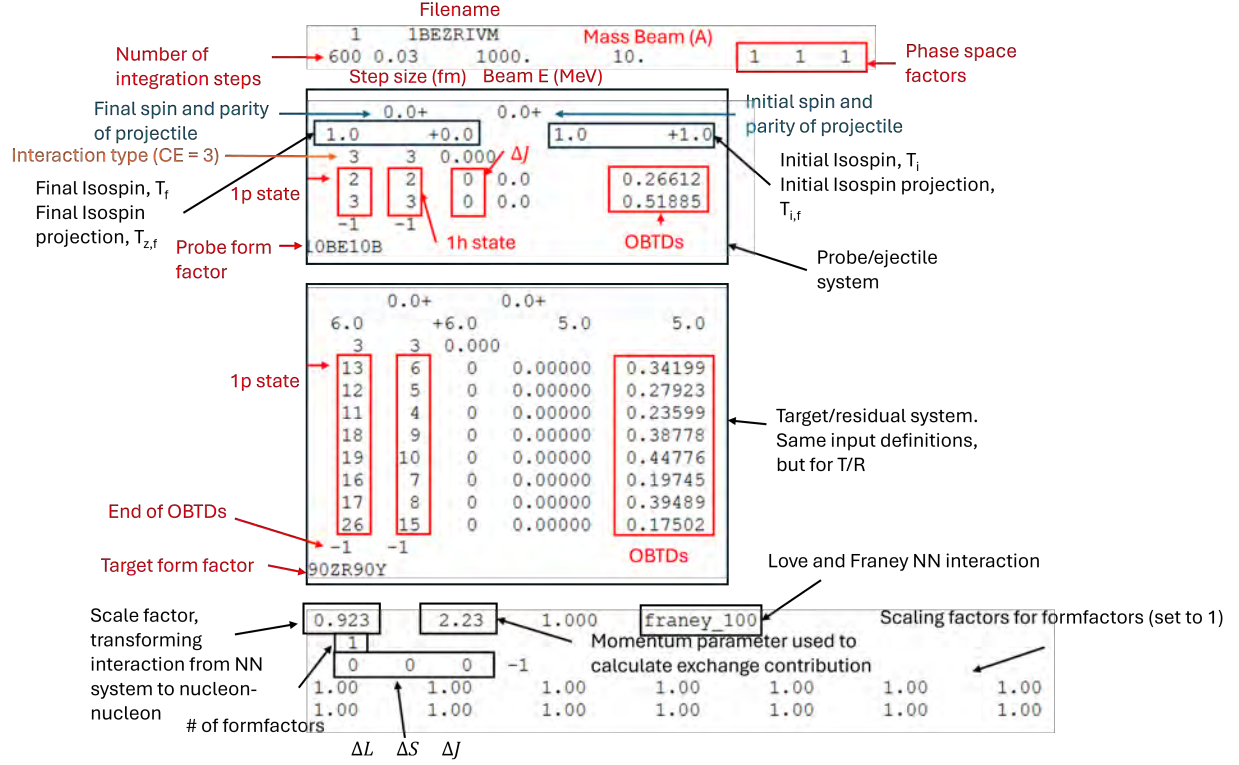


Figure 2.3: FOLD inputs for the IVGMR for the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B})$ reaction.

2.1.3 DWHI

The last component of the FOLD code package is the DWHI code. DWHI uses the form factor produced by FOLD and optical potentials to calculate the transition amplitude (T_{fi} , Equation 2.2) and the cross section ($\frac{d\sigma}{d\Omega}$, Equation 2.1) for each transition (ΔS , ΔL , ΔJ) using a first order DWBA calculation. The optical potential is used to account for the distortion of the incoming and outgoing waves due to the interaction with the nuclear mean-field of the target and residual nucleus, respectively. The optical potential is in the form of a Woods-Saxon consisting of a real and an imaginary component (Equation 2.3), where each component is defined by the potential depth, the radius, and the diffuseness. Optical potentials often come from fits of elastic scattering data using the same beam and target as the reaction under consideration at a similar beam energy. However, there are no such optical

Method	Channel	Real			Imaginary		
		Depth (MeV)	Radius (fm)	Diffusiveness (fm)	Depth (MeV)	Radius (fm)	Diffusiveness (fm)
Ref. [85]	$^{10}\text{Be}+^{90}\text{Zr}$	-127	1.491	0.533	-101	1.491	0.533
	$^{90}\text{Y}+^{10}\text{B}$	-147	1.449	0.56	-118	1.449	0.56
Ref. [87]	$^{10}\text{Be}+^{90}\text{Zr}$	-129	1.40	0.79	-124	1.40	0.79
	$^{90}\text{Y}+^{10}\text{B}$	-129	1.40	0.79	-124	1.40	0.79

Table 2.2: Optical model parameters for the ^{90}Y DWBA calculations. The data is $^{16}\text{O} + ^{90}\text{Zr}$ at 94 AMeV, corrected for using a ^{10}Be projectile instead of ^{16}O .

potentials available for the beam energy and reaction channels for the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B})^{90}\text{Y}$ reaction. The optical potential used in this work, therefore, was calculated using the methods described in Ref. [85]. The calculations of the optical model parameters utilize the double-folding model, assuming the ^{90}Zr and ^{90}Y densities calculated using spherical Hartree-Fock calculations using the SkX parameterization of the Skyrme interaction [86]. For the purpose of estimating the uncertainty, this calculated optical potential model was compared with an optical potential obtained by fitting experimental data from elastic scattering of ^{16}O on ^{90}Zr at $E_{beam} = 94$ AMeV from Ref. [87]. The angular distributions calculated using the method of Ref. [85] were virtually identical in shape to those produced using these elastic scattering data, but the absolute cross sections were significantly smaller in the latter case. The main reason for this is that the optical potentials from elastic scattering data have a significantly larger diffusiveness than the calculated optical potentials, which results in additional absorption. This is discussed more in Section 5.6.1. The values used for the optical potentials are presented in Table 2.2. The inputs of the DWHI calculation for the IVGMR are presented in Figure 2.4. The DWHI input files for all transitions can be found in Appendix C.

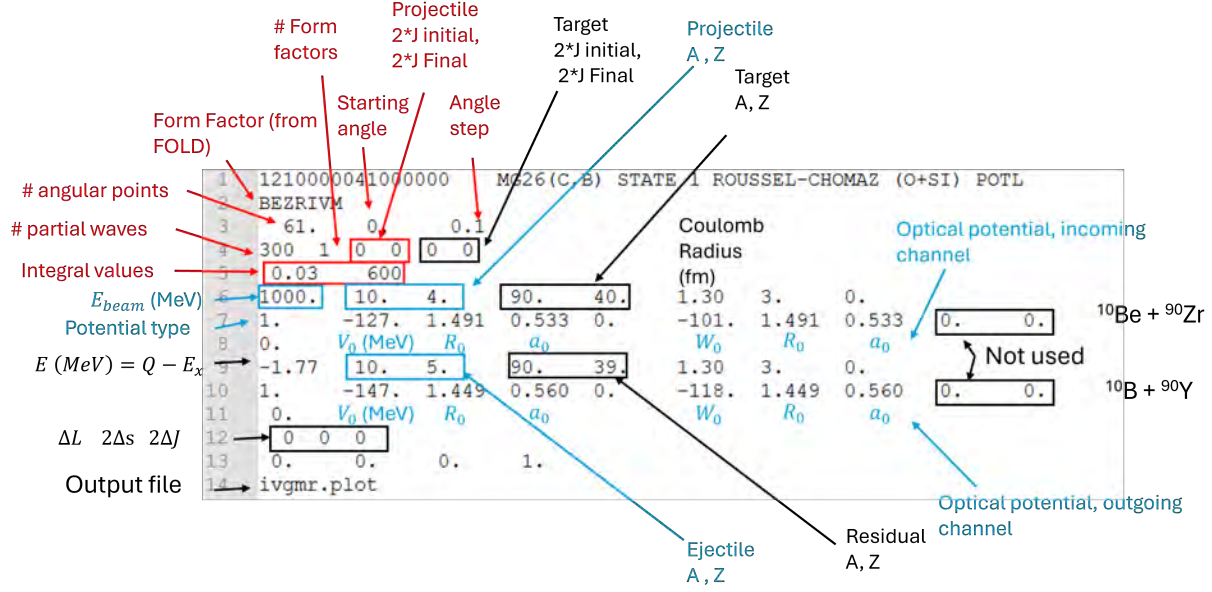


Figure 2.4: Input for the DWHI code for the IVGMR for the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B})^{90}\text{Y}$ reaction.

2.2 Relativistic Time Blocking Approximation

To interpret the results of the extracted monopole strength, a theoretical description that describes the collectivity of the excitation is needed. A number of theoretical models, such as the quasi-particle random-phase approximation (QRPA), have been developed to accurately describe collective 1p-1h states. The QRPA is an extension of the RPA that includes quasiparticles, which reproduce the ground state pairing correlations more accurately than when just using particles. Full descriptions of the QRPA can be found in Refs. [88–90]. However, while the QRPA describes the collective states to give the centroid energies and total strength of the giant resonances, it does not reproduce the total widths and fine structure that are due to more complex configurations, such as 2p-2h contributions.

This work, therefore, uses the proton-neutron relativistic quasiparticle time-blocking approximation (pn-RQTBA) calculations performed by Elena Litvinova. A full description of the pn-RQTBA can be found in Refs. [41, 91–93]. The pn-RQTBA is an extension of the

time-dependent covariant density functional theory which includes particle-vibration coupling in the charge-exchange channel. The inclusion of the particle-vibration coupling allows for realistic fragmentation of the strength distributions. These calculations were also used in the analysis of the $^{28}\text{Si}(^{10}\text{Be}, ^{10}\text{B})$ reaction [7, 72], and provided a good description of the experimental results.

Figure 2.5 shows the IVGMR and IVSGMR before and after smearing with the experimental resolution. Before smearing, some peak structures are observed. Even though the RTBA calculations are probably the most complete EDF framework available for calculating giant-resonance strength, additional redistribution of strength due to components not included in the calculations is likely, leading to a smoother spectrum. After smearing with the experimental resolution, the strength in both channels features broad strength distributions with few defined peaks. The IVGMR features a peak at about 9 MeV, which is due to the $(\pi) 3p_{1/2} \rightarrow (\nu) 2p_{1/2}$ and $(\pi) 3p_{3/2} \rightarrow (\nu) 2p_{3/2}$ particle-hole excitations. The bulk of the strength in the calculation is around 20 MeV. The bulk of the strength in the IVSGMR also sits at around 20 MeV. The total strength in the channel IVGMR is 2426 fm^4 and the total strength in the IVSGMR channel is 10720 fm^4 .

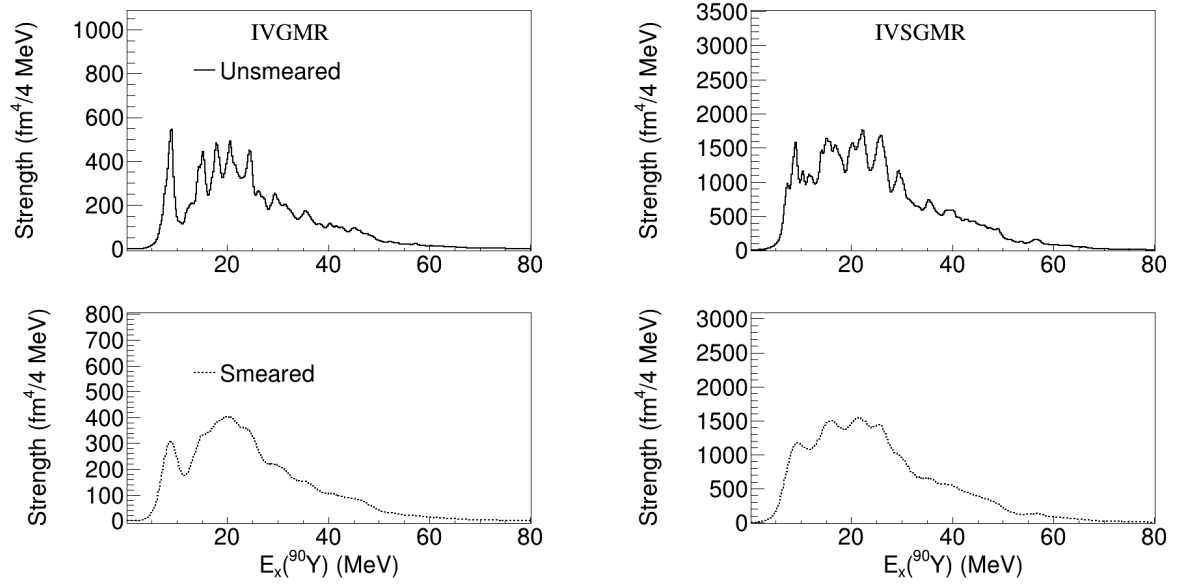


Figure 2.5: The pn-RQTBA before (top) and after (bottom) smearing with the experimental resolution.

Chapter 3. Experimental Tools

This chapter will focus on the experimental tools used to extract the monopole and spin-monopole channels simultaneously using the (^{10}Be , $^{10}\text{B} + \gamma$) probe in two experiments, one on a ^{12}C target and the other on a ^{90}Zr target. The experiments were performed at Michigan State University using different facilities; ^{12}C was studied using the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory (NSCL), while ^{90}Zr was studied using the linear accelerator at the Facility for Rare Isotope Beams (FRIB). In both cases, the secondary beam was created using fast fragmentation and utilized the S800 Spectrograph and the Gamma-Ray Energy Tracking In-beam Nuclear Array (GRETINA) to detect and measure reaction products, while beam production varied between the facilities. Therefore, beam preparation and delivery will be discussed stage by stage while the S800 Spectrograph and GRETINA will be discussed in Section 3.2 and Section 3.3, respectively. While the study of ^{90}Zr is the primary topic of this thesis, the study of ^{12}C is presented (see Chapter 4) to demonstrate the simultaneous extraction of the spin-transfer and non-spin-transfer strength in detail. That method is then applied to ^{90}Zr in Chapter 5.

3.1 Beam Production

The secondary beam in both experiments was produced via in-flight fragmentation. A primary beam of greater mass than the desired secondary beam is accelerated to relativistic speeds and is impinged upon a production target, producing high-energy fragments. These fragments are then transported through a fragment separator, which consists of a series of magnets tuned to separate the desired ion from the other fragments, which results in a pure secondary beam of a rare isotope, or a cocktail beam of a few isotopes. The secondary beam

is then transported to the user experimental area for use in an experiment.

3.1.1 Accelerators

3.1.1.1 Coupled Cyclotrons

Production of the secondary ^{10}Be beam using the coupled cyclotrons at NSCL starts with a stable isotope, in this case ^{18}O , ionized using an electron cyclotron resonance ion source and injected into the K500 cyclotron. The beam is accelerated to energies of 10.9 MeV/ u and extracted from the K500 and injected into the K1200 cyclotron, where the beam is accelerated to an energy of ~ 120 MeV/ u . The beam is then impinged on a 1316 mg/cm ^{2} beryllium production target at the entrance of the A1900 fragment separator. The resulting cocktail beam is directed into the separator where the unwanted beam fragments are removed, resulting in an 88% pure ^{10}Be secondary beam [94].

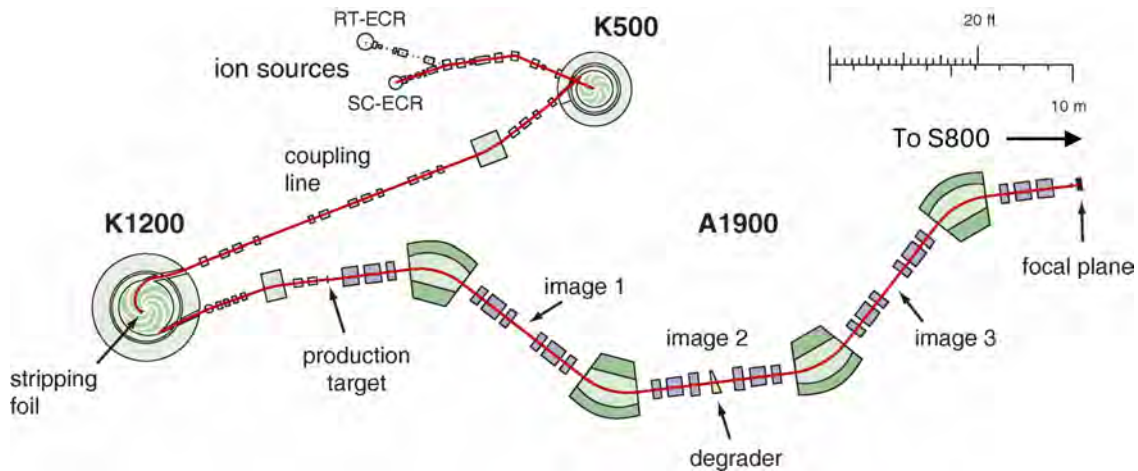


Figure 3.1: Schematic of the K500 and K1200 coupled cyclotrons and the A1900 fragment separator at NSCL.

3.1.1.2 Linear Accelerator

The production of the secondary beam using the linear accelerator also starts with stable ^{18}O , which is ionized using an electron cyclotron resonance ion source. The ions are injected into the FRIB superconducting radio frequency (SRF) heavy-ion linear accelerator (linac) and accelerated to an energy of $\sim 150 \text{ MeV}/u$. The beam is then impinged on a carbon production target of $1802.4 \text{ mg}/\text{cm}^2$ to produce the fragmented beam. Following fragmentation, the resulting cocktail beam passes through the Advanced Rare Isotope Separator (ARIS), resulting in a purified secondary ^{10}Be beam [11].

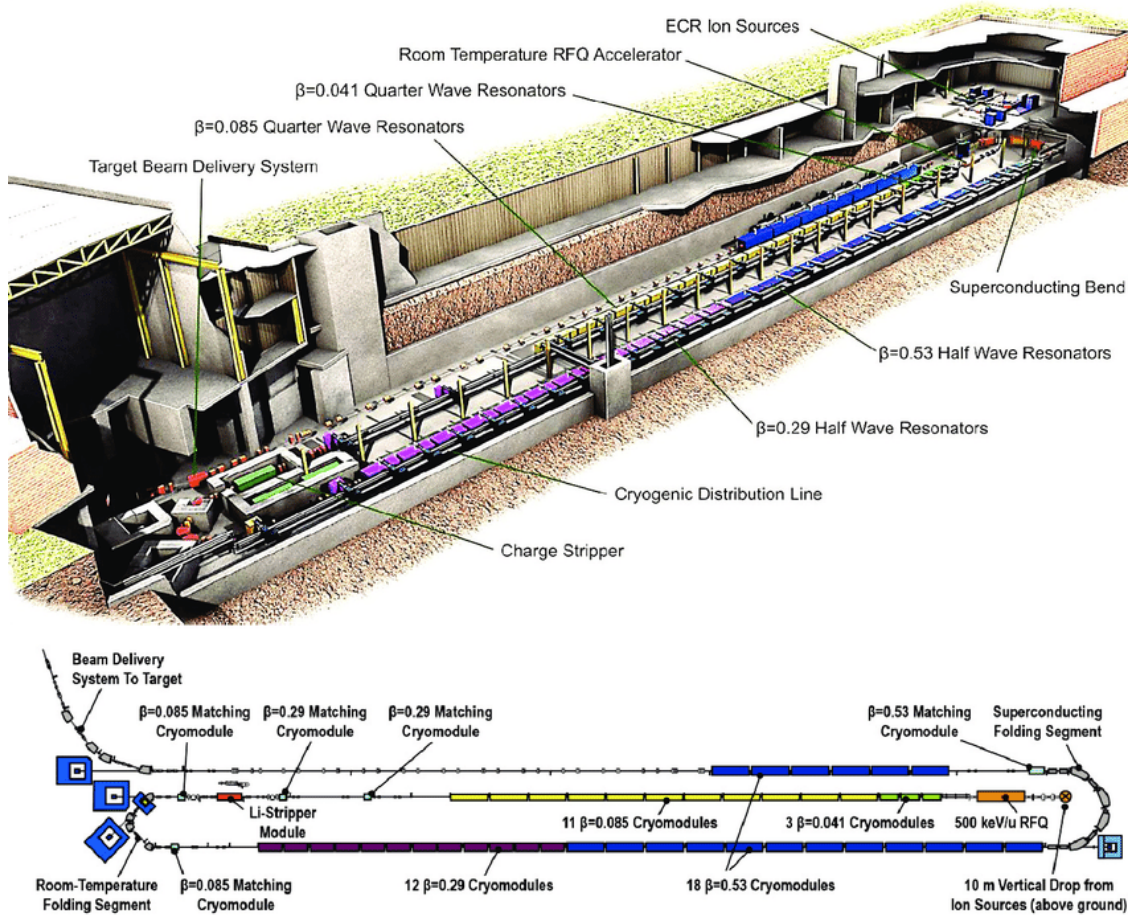


Figure 3.2: Top) 3D rendering of the superconducting radio-frequency driver linear accelerator at FRIB. Bottom) Schematic layout of the FRIB driver linac [10].

3.1.2 Fragment Separation

Fragment separation is achieved by taking advantage of the properties of charged particles in magnetic fields. Dipole magnets create dispersion, quadrupole magnets are used to focus the beam, and higher-order magnets such as sextupole and octopole magnets are used to correct magnetic field aberrations. Combinations of these magnets are used to discard unwanted fragments while preserving the ion of interest, resulting in a purified secondary beam. As the A1900 and ARIS fragment separators function in a similar way, the typical separation process is presented first, followed by dedicated sections for each separator.

Fragment separation starts by using dipole magnets, which create dispersion of ions according to a quantity known as the magnetic rigidity. The force from a dipole magnet causes circular motion and is described by the Lorentz force. This centripetal force can be described as

$$F = \frac{\gamma m v^2}{\rho} = Q v B \quad (3.1)$$

where $\gamma = 1/\sqrt{1 - (v/c)^2}$ is the Lorentz factor to account for relativistic effects, m is the mass of the ion, v is the ion velocity, B is the magnetic field created by the dipole, ρ is the radius of the particle due to the magnetic field of the dipole, and Q is the charge of the ion. The magnetic rigidity is then defined as:

$$B\rho = \frac{\gamma m v}{Q} \quad (3.2)$$

For a constant magnetic field, the magnetic rigidity defines the motion of the ion along a circular path in the presence of the field. From the right hand side of Equation 3.2, the magnetic rigidity is equal to the ratio of the momentum to the total charge of the ion,

also understood as the mass-to-charge ratio. In a cocktail beam consisting of ions with different mass-to-charge ratios which have a different radius of curvature through the field. The magnetic field produced by the dipole magnets is tuned so the $B\rho$ of the ion of interest maintains its trajectory along the beam-line's central position, while those with a different $B\rho$ are deflected into a beam dump or into slits.

Without additional measures, fragments with similar rigidities cannot be separated. To solve this problem, an aluminum wedge, known as an energy degrader, is placed in the beam. The purpose of this wedge is to degrade the beam energy. The energy loss through a medium is proportional to Z^2 as described by the Bethe formula [95], given as,

$$\frac{dE}{dx} = \frac{4\pi e^4 Z^2}{m_0 v^2} n_{abs} z_{abs} \left(\ln \frac{2m_0 v^2}{I} - \ln \left(1 - \frac{v^2}{c^2} \right) - \frac{v^2}{c^2} \right), \quad (3.3)$$

where Z is the number of protons, e is the electron charge, m_0 is the electron rest mass, v is the velocity of the particle moving through the medium, n_{abs} and z_{abs} refer to the number density and atomic number of the absorbing medium, and I refers to the average ionization potential of the absorber medium, respectively. The wedge decreases the energy of different isotopes in the beam based on Z , effectively dispersing fragments that initially had similar rigidities. The fragments are then passed through another set of magnets and the fragment of interest is selected using its new $B\rho$, while the undesired fragments are stopped by a slit. The wedge can also act as a momentum compression tool, compressing the momentum distribution of the isotope of interest.

3.1.2.1 A1900

The A1900 Fragment Separator, pictured in Figure 3.1, is a two-stage separator consisting of four 45° dipole bending magnets for momentum dispersion and 8 quadrupole triplet magnets for beam focusing. In the first stage, the cocktail beam produced by the production target is bent by two dipole magnets and undergoes the first separation based only on $B\rho$ (Equation 3.2). An 800 mg/cm^2 aluminum wedge shaped energy degrader was placed at image 2 in Figure 3.1 to separate ions with similar rigidities by utilizing the differences in energy loss through a medium for isotopes with different Z value, as described in 3.1.2 (Equation 3.3). Because of the differences in energy loss, different isotopes that had the same rigidity before the wedge have different rigidities after the wedge and are spatially separated after the second stage. The isotopes of interest then pass through the slits in the focal plane of the separator, while the contaminants are blocked by the slits. The slits also restrict the momentum spread of the ^{10}Be secondary beam to $\frac{dp}{p} = \pm 0.25\%$. The resulting ^{10}Be beam extracted from the A1900, determined to be 88% isotopically pure, was sent to the experimental area.

3.1.2.2 ARIS

ARIS is a three stage fragment separator, shown in Figure 3.3, designed for efficient collection and purification of rare isotope beams. The first stage is a vertically oriented preseparator with a beam dump, while the second and third sections are reconfigured from the A1900 fragment separator. The first stage consists of four dipole magnets and twelve quadrupole magnets that utilize higher order magnetic focusing elements [11]. The preseparator accepts the cocktail beam from the production target and makes the initial fragment selections using a pair of dipole magnets, one on either side of the primary beam dump. A 6.162 mm thick

energy degrader wedge of Al-7075 alloy is placed between the first pair and the last pair of dipoles, shown in Figure 3.3, to separate ions with similar rigidities. Following the first stage, the beam is bent vertically from the underground level to the above-ground level for stages 2 and 3. Those stages of ARIS are reconfigured from the A1900 Separator at NSCL [94], which consists of additional dipole and quadrupole magnets to purify, focus, and eliminate aberrations in the beam, as well as the slits described in Section 3.1.2.1. A second 4.2 mm thick wedge, also made of Al-7075 alloy, is placed in the same location as the wedge previously described in the A1900 fragment separator between stages 2 and 3. Following the final stage, the beam passed through slits to remove contaminants and restrict the momentum spread of the ^{10}Be beam to $\frac{dp}{p} = \pm 0.6\%$. The ^{10}Be beam, determined to be 99% isotopically pure, was sent to the experimental area.

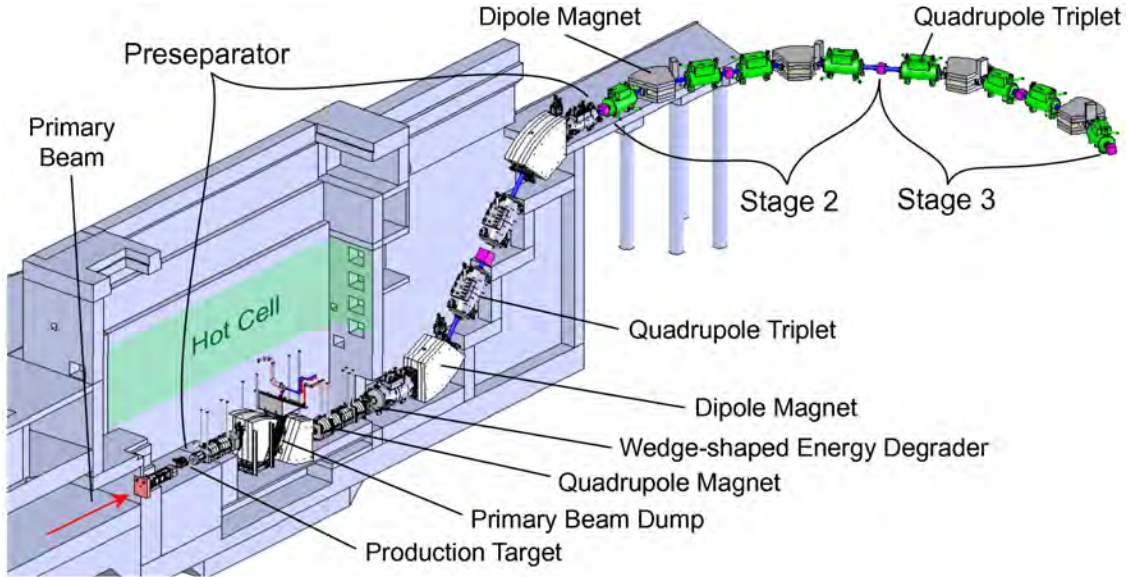


Figure 3.3: Schematic layout of ARIS. The primary beam from the driver linac approaches from the bottom left. The preseparator accepts the cocktail beam produced by the stable primary beam impinging on the production target. The beam then undergoes three separation stages (preseparator, stage 2, and stage 3) before being sent to the experimental area [11].

3.1.3 Beam Rate Measurement

To determine the reaction cross section, the incoming beam rate must be measured. At low beam intensities, this is achieved by inserting a scintillator detector directly into the beam and counting the particles through the detector. However, high beam rates will quickly damage the scintillator detector and can complicate time of flight measurements, limiting this method to low beam intensity. Therefore, non-intercepting probes were used to correlate the primary beam current to ^{10}Be beam rate. During the experiment at the NSCL, a non-intercepting probe was placed at the exit of the K1200 cyclotron and a Faraday bar was placed on the inside wall of the first dipole magnet in the A1900. Only the Faraday bar was used in the analysis due to very low readings in the probe in the later stages of the experiment. At FRIB, a non-intercepting probe was placed at the entrance of ARIS. The probes in both experiments are correlated to the incoming beam rate using unreacted ^{10}Be measured in the focal plane of the S800 Spectrograph (see section 3.2) at relatively low beam intensity. The total number of incoming beam particles in each run is determined by taking the average counting rate over the course of each run and multiplying by the total time for the respective run. Figure 3.4 shows the average beam rate per second during the FRIB experiment, while the same plot for the NSCL experiment can be viewed in Reference [7].

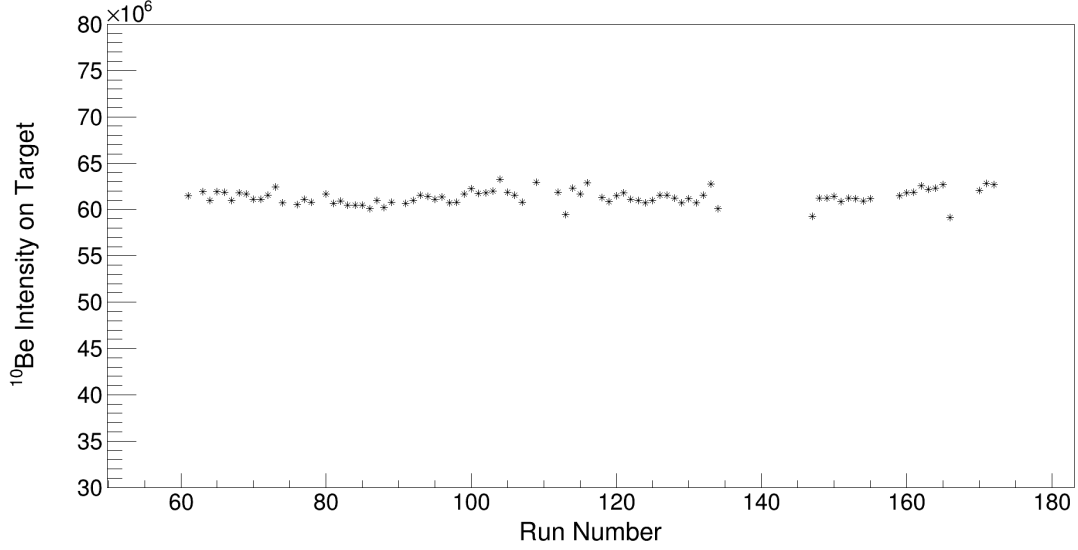


Figure 3.4: Incoming beam rate measured by the non-intercepting probe during experiment 23009 at FRIB.

3.2 S800 Spectrograph

After a reaction occurred in the target, the ejectile is directed into the S800 Spectrograph [96]. The S800 Spectrograph consists of two dipole magnets for spectroscopy and two quadrupole magnets for focusing. The S800 has two primary modes of operation, a focused mode and a dispersion-matched mode. In focused mode, the beam is focused at the target and dispersed in the focal plane. As a result, the dispersion in the S800 is sensitive to the momentum of the beam at the target, significantly limiting energy resolution. In dispersion-matching mode, the dispersion of the beam at the target is matched to that of the S800. The momentum spread in the beam is compensated for, resulting in higher momentum and energy resolution [96]. In focused mode with a ^{10}Be beam of 100 AMeV with a momentum spread of 0.5% (energy spread of 1%), the resolution in the excitation energy from the ($^{10}\text{Be}, ^{10}\text{B}$) reaction can be at best 10 MeV. Since a resolution of a few MeV is required, the dispersion matched mode was adopted. The dispersion-matching results in a beam spot that is 50 mm in the dispersive

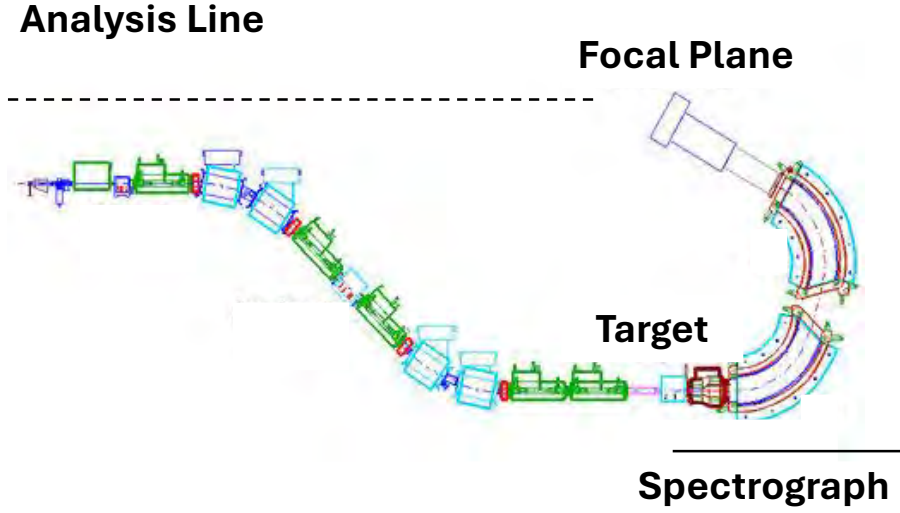


Figure 3.5: Schematic showing components of the analysis line and S800 Spectrograph, adapted from [12].

direction at the S800 target location. Detailed descriptions of each operating mode can be found in Ref. [12].

3.2.1 Focal Plane Detectors

The S800 Spectrograph employs a suite of detectors to measure a particle's trajectory, time-of-flight, energy loss, and position [97]. The schematic of these detectors is shown in Figure 3.6. The position and trajectory of the particles is measured by a pair of cathode readout drift chambers (CRDCs). CRDC1 is located at the focal plane of the spectrograph and CRDC 2 is placed 1.073 m downstream of CRDC1. The operation of a CRDC is illustrated in the left panel of Figure 3.7. Each CRDC has an active detection area of 30 cm x 59 cm and a depth of 1.5 cm. The CRDC chambers are filled with a gas mixture of 80% carbon tetrafluoride and 20% isobutane at a pressure of 50 Torr and experience an electric field

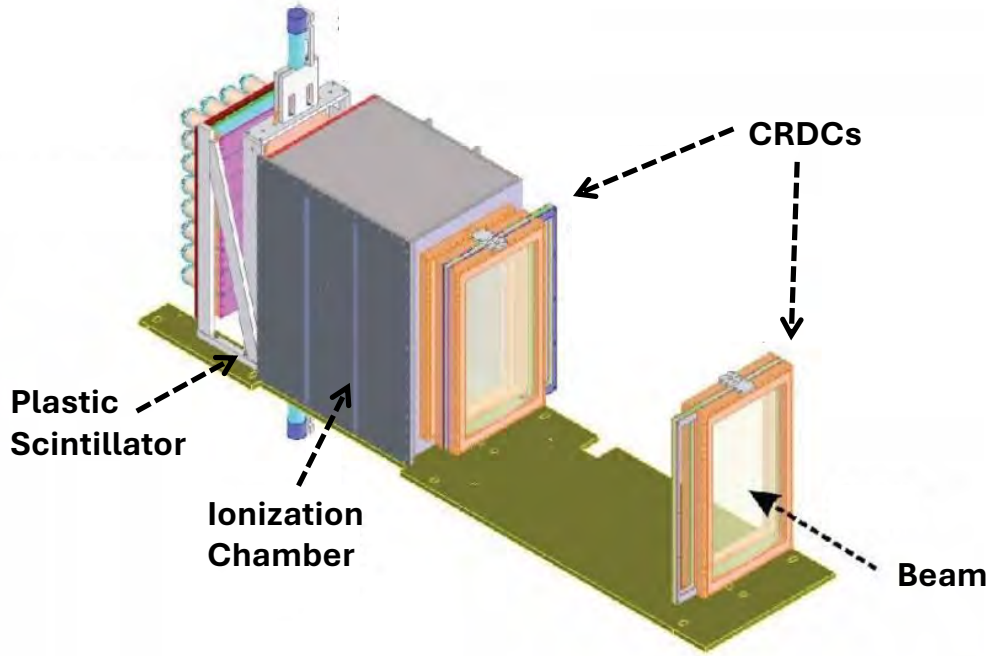


Figure 3.6: Schematic of the Focal Plane detectors of the S800 mass spectrograph from Ref. [12].

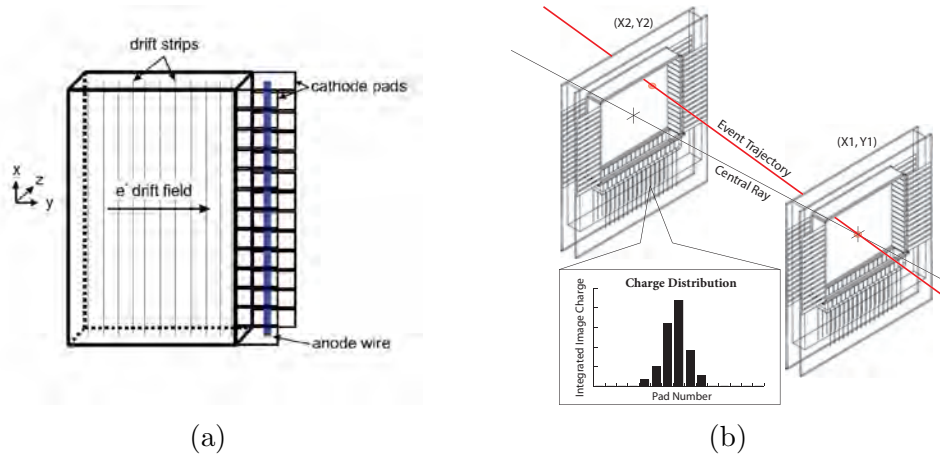


Figure 3.7: (a) Illustration of the operation of a S800 CRDC from Ref. [12], (b) Representation of position and angle reconstruction by the S800 CRDCs, taken from Ref. [12].

along the y -direction. The cathode for each CRDC consists of 224 individual pads, each 2.54 mm long. As the ions move through the chamber, they ionize the gas, and the resulting freed

electrons are collected by the anode. As these electrons are collected, they induce a charge on the cathode pads. A typical charge distribution is shown on the right side of Figure 3.7. The x-position of the event is obtained by fitting the corresponding charge distribution. The y-position of the event is determined using the drift time of the electrons for each event. The drift time is determined from the time difference between the anode signal and the signal given by the E1 scintillator, which is further downstream. The corresponding drift velocity is then corrected on a run-by-run basis in each CRDC to account for any changes in experimental conditions.

Downstream of CRDC2 is the ionization chamber. It is used for particle identification by measuring the energy loss of the projectile nucleus through the medium [97]. This detector was not available for the ^{90}Zr study, but was used for the ^{12}C experiment. The ionization chamber is filled with P10 gas (90 % argon and 10 % methane) and has electrodes on each side that produce a uniform electric field. When an ion passes through the chamber, it ionizes the gas, and the resulting positive ion and freed electrons are detected at the cathode and anode, respectively. The number of ion pairs is proportional to the energy loss of the particle through the medium, which is proportional to Z^2 as described previously by Equation 3.3. As a result, beam particles can be separated based on Z . Ion chambers are described in more detail in Ref. [95].

Downstream of the ion chamber is the S800 focal plane scintillator. The plastic scintillator is 30 cm x 59 cm and 5 mm thick. The scintillator has two photomultiplier tubes (PMTs), one on top and one on bottom of the scintillator. The PMTs provide position (with limited resolution), timing, and deposited energy information for the projectile. The 5 mm thick scintillator was chosen because it can also be used for particle identification by measuring the energy loss of the ion through the detector. For light ions, such as ^{10}B , a thicker scintillator

is preferable to improve the signal height. The energy loss was used for background reduction in the ^{12}C study, while it was used in place of the ion chamber for the ^{90}Zr study. The top photomultiplier tube, E1 up, provided the reference timing for all events in the experiment and serves as the event trigger. The time of flight used for particle identification used the radio frequency (RF) signal from the accelerator relative to E1 up.

3.2.2 Event Reconstruction

The trajectories of the ions are reconstructed using the two CRDCs in the focal plane of the S800 spectrograph. The four values needed are the x-position, y-position, and dispersive and non-dispersive angles of the particle in the focal plane. The x-position and y-position in the focal plane are the x-position and y-position in CRDC1, while the dispersive (afp) and non-dispersive (bfp) angles are determined by

$$afp = \text{atan}\left[\frac{x_1 - x_2}{L}\right] \quad (3.4)$$

and

$$bfp = \text{atan}\left[\frac{y_1 - y_2}{L}\right] \quad (3.5)$$

respectively. The respective target position coordinates are reconstructed using a ray tracing procedure that relates the focal plane coordinates to the target position. The ray tracing is done by fitting the measured magnetic fields with Enge functions of the form

$$E(z) = \frac{1}{1 + \exp[P(z)]} \quad (3.6)$$

where z is a position along the beam path and $P(z)$ is a fifth order polynomial. These func-

tions are used as input in COSY infinity to produce a transfer map of the Spectrograph [96]. A fifth order polynomial is used so that the uncertainty in the transfer map is comparable to the resolution of the CRDCs (0.5 mm) [96].

COSY infinity calculates a 4x4 transfer matrix of the form

$$(dta, yta, ata, bta) = S^{-1}(xfp, yfp, afp, bfp)$$

$$= \begin{pmatrix} (dta|xfp) & (dta|yfp) & (dta|afp) & (dta|bfp) \\ (yta|xfp) & (yta|yfp) & (yta|afp) & (yta|bfp) \\ (ata|xfp) & (ata|yfp) & (ata|afp) & (ata|tabfp) \\ (bta|xfp) & (bta|yfp) & (bta|afp) & (bta|tabfp) \end{pmatrix} \begin{pmatrix} xfp \\ yfp \\ afp \\ bfp \end{pmatrix} \quad (3.7)$$

where the focal plane coordinates end in "fp" and target coordinates end in "ta". dta is the fractional energy spread of the beam

$$dta = \frac{E - E_0}{E_0} \quad (3.8)$$

where E is the reconstructed energy based on ray tracing and E_0 is the energy traveling along the reference path through the spectrometer. The measured focal plane values are used as inputs to the matrix to calculate the respective target coordinates. The laboratory frame scattering angle is calculated using the reconstructed target angles using the relation

$$\theta_{ta} = atan\sqrt{\tan^2(ata) + \tan^2(bta)}. \quad (3.9)$$

The target energy (dta) and angles (ata , bta) of the ^{10}B ejectile are used to reconstruct the

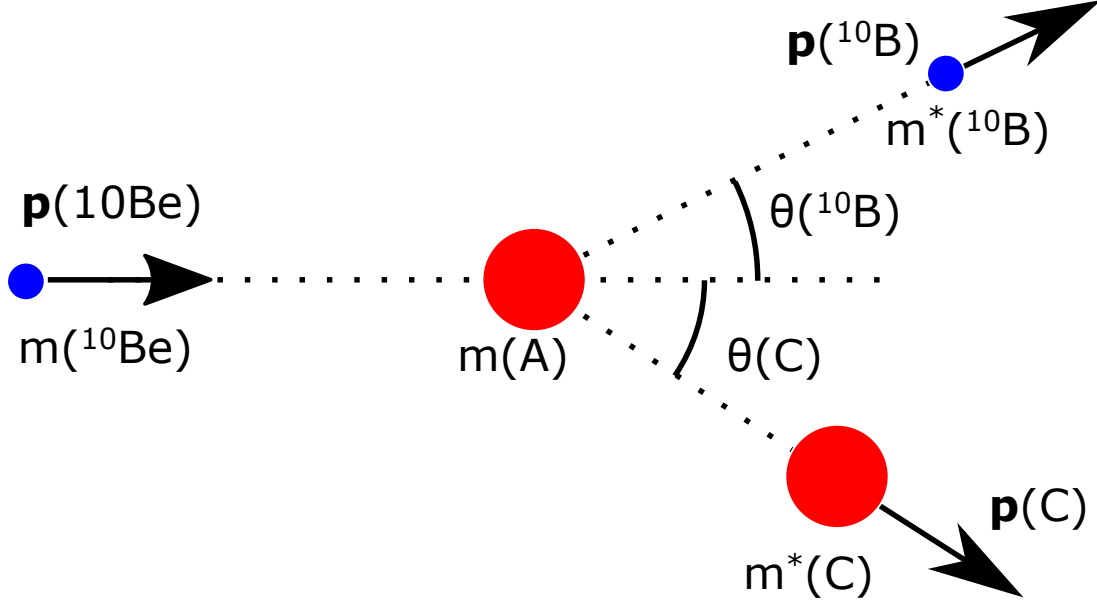


Figure 3.8: Cartoon of the reaction kinematics in the laboratory frame showing labels used in the text.

excitation energy of the reaction residual (^{12}B or ^{90}Y) by calculating the missing-mass in the system, discussed in the next section.

3.2.3 Excitation Energy Reconstruction

The excitation energy of the residual nucleus following the (^{10}Be , ^{10}B) reaction is reconstructed using a missing-mass calculation by relating the energy and coordinates in the ^{10}B ejectile to the missing mass in the system. The derivation starts with the conservation of energy and momentum in the lab frame. Setting $c = 1$ and using A and C to indicate the target nucleus and residual nucleus as presented in Figure 3.8, the conservation equations are

$$m(A) + m(^{10}\text{Be}) + T(^{10}\text{Be}) = m^*(^{10}\text{B}) + T(^{10}\text{B}) + m^*(\text{C}) + T(\text{C}) \quad (3.10)$$

$$\mathbf{p}(^{10}\text{Be}) = \mathbf{p}(\text{C}) + \mathbf{p}(^{10}\text{B}) \quad (3.11)$$

where the residual and ejectile are left in excited states, indicated by *, such that

$$m^*(\text{C}) = m(\text{C}) + E_X(\text{C}) \quad (3.12)$$

$$m^*(^{10}\text{B}) = m(^{10}\text{B}) + E_X(^{10}\text{B}). \quad (3.13)$$

As this is in the laboratory frame, the target nucleus has no kinetic energy or momentum and has been set to zero. Using conservation of energy from Equation 3.10, the total energy of the residual nucleus is then

$$m^*(\text{C}) + T(\text{C}) = m(A) + m(^{10}\text{Be}) + T(^{10}\text{Be}) - m^*(^{10}\text{B}) - T(^{10}\text{B}) \quad (3.14)$$

Using the relation

$$E^2 = p^2 + m^2 \quad (3.15)$$

along with the conservation of momentum in Equation 3.11, Equation 3.14 can be rewritten as

$$m^*(C) + T(C) = \sqrt{m^{*2}(C) + \mathbf{p}^2(C)} \quad (3.16)$$

$$= \sqrt{m^{*2}(C) + (\mathbf{p}^{(10\text{Be})} - \mathbf{p}^{(10\text{B})})^2} \quad (3.17)$$

The excitation energy in the residual nucleus can be inferred from the missing mass in the residual. In Equation 3.17, the missing energy and missing mass of ^{10}B are

$$E_{\text{missing}} = m(^{10}\text{Be}) + T(^{10}\text{Be}) + m(A) - m^*(^{10}\text{B}) - T(^{10}\text{B}) \text{ and} \quad (3.18)$$

$$\mathbf{p}_{\text{missing}} = \mathbf{p}^{(10\text{Be})} - \mathbf{p}^{(10\text{B})}. \quad (3.19)$$

By again using Equation 3.15, the missing mass is written

$$m_{\text{missing}} = \sqrt{E_{\text{missing}}^2 - \mathbf{p}_{\text{missing}}^2} \quad (3.20)$$

while the excitation energy of the residual is written explicitly as

$$E_X(C) = m_{\text{missing}} - m(C). \quad (3.21)$$

To determine the missing momentum, the momentum of the incident ^{10}Be and the ^{10}B ejectile are required. For the incident ^{10}Be , the kinetic energy is first inferred from the rigidity setting of the analysis line. By squaring Equation 3.2, $B\rho$ can be related to the momentum of the incident ^{10}Be by

$$(B\rho)^2 = \frac{m^2(^{10}\text{Be})v^2(^{10}\text{Be})}{Q^2} = \frac{p^2(^{10}\text{Be})}{Q^2}. \quad (3.22)$$

Solving for momentum in Equation 3.22, and by using Equation 3.15 and the total energy $E = m + T$, the rigidity is related to the kinetic energy of the incident ^{10}Be as

$$E(^{10}\text{Be}) = \sqrt{(B\rho Q)^2 + m^2(^{10}\text{Be})} = m(^{10}\text{Be}) + T(^{10}\text{Be}) \quad (3.23)$$

Rewriting Equation 3.23, the kinetic energy of the ^{10}Be is then

$$T(^{10}\text{Be}) = \sqrt{(B\rho Q)^2 + m^2(^{10}\text{Be})} - m(^{10}\text{Be}). \quad (3.24)$$

It is convenient to define the direction of the momentum of the beam to be entirely in the z -direction, as

$$p_x(^{10}\text{Be}) = p_y(^{10}\text{Be}) = 0 \quad (3.25)$$

$$p_z(^{10}\text{Be}) = p(^{10}\text{Be}). \quad (3.26)$$

This is only correct on average, of course, which causes uncertainty in the missing mass calculation and angular reconstruction, which is described later. The momentum for ^{10}Be is found by squaring the relation $E = T + m$ and setting it equal to Equation 3.15, then solving for momentum. The resulting momentum is

$$p(^{10}\text{Be}) = \sqrt{T^2(^{10}\text{Be}) + 2T(^{10}\text{Be})m(^{10}\text{Be})}. \quad (3.27)$$

The kinetic energy for ^{10}B was calculated event-by-event by calculating the energy of a central ray through the spectrometer, T_0 , and using the ray-traced fractional energy dta as

$$T(^{10}\text{B}) = T_0(1 + dta), \quad (3.28)$$

where dta was obtained from the ray tracing described in 3.2.2 and is defined as $dta = \frac{T(^{10}\text{B}) - T_0}{T_0}$. The momentum for ^{10}B is then

$$p(^{10}\text{B}) = \sqrt{T^2(^{10}\text{B}) + 2T(^{10}\text{B})m(^{10}\text{B})}. \quad (3.29)$$

If ^{10}B is in an excited state, then its mass in the previous equations must be replaced with $m^*(^{10}\text{B})$. The results of the excitation energy reconstruction are presented in Chapter 4 for the ^{12}C study and in Chapter 5 for the ^{90}Zr study. To "tag" the ejectile ^{10}B , a coincident measurement between the ejectile and the emitted gamma ray is required. The gamma-ray detection using GRETINA is detailed in the next section.

3.3 GRETINA

To isolate the IVGMR and IVSGMR channels using the $(^{10}\text{Be}, ^{10}\text{B} + \gamma)$ reaction, it is necessary to perform a coincident measurement of the ^{10}B ejectile and the γ ray it emits as it decays. As discussed in Chapter 1, the γ ray acts as a "tag" for the excited state populated in ^{10}B . The ejectile was measured using the S800 Spectrograph as discussed in the previous section, while the Gamma-Ray Energy Tracking In-beam Nuclear Array (GRETINA) was used to measure the energy, position, and emitted angle with respect to the particle direction of γ -rays released in-flight by the ^{10}B [13, 98]. GRETINA consists of a number of detector

modules (7 for ^{12}C and 11 for ^{90}Zr), each module consisting of 4 highly segmented high purity germanium crystals. A γ ray interacts with the detector medium and frees a number of electrons that are then collected by an anode that runs through the central bore of each crystal. The signal produced from the sum of the collected electrons is proportional to the energy of the incoming photon. The main interaction processes of the photons with the detection medium are photoelectric absorption, Compton scattering, and pair-production, and are discussed in Section 3.3.1.

GRETINA was chosen as the optimal detector array for these experiments as it provides high energy resolution resulting in a high signal-to-noise ratio for the desired photopeaks, while retaining adequate detection efficiency. Since the γ rays of interest are emitted in-flight, the measured γ rays require a Doppler correction. The correction is defined as

$$E_{\gamma} = \frac{E_{\gamma,lab}(1 - \beta \cos\theta)}{\sqrt{1 - \beta^2}} \quad (3.30)$$

where E_{γ} is the Doppler-corrected γ -ray energy, θ is the angle between the decaying particle and the emitted γ ray, and $\beta = v/c$, where v is the particle velocity and c is the speed of light. As a result, Doppler broadening in the γ spectrum depends on the uncertainty in the measured lab energy (E_{γ}) and angle of the emitted γ ray with respect to the decaying particle (θ). To optimize resolution, these uncertainties must be minimized. High purity germanium (HPGe) crystals like those in GRETINA are advantageous because they provide high energy resolution compared to alternatives, while the segmented nature of GRETINA allows for the precise position reconstruction necessary for high resolution energy measurements in fast-beam experiments [98]. Retaining good efficiency is important because the charge-exchange cross section is relatively small and drops with increasing mass number.

3.3.1 γ -ray Detection

There are three common interactions between the γ rays and a detector medium that produce an event in the detector: photoelectric absorption, Compton scattering, and pair production [95, 99]. Photoelectric absorption is strongest at low γ energies, up to about 0.2 MeV. In this process, the energy of the incident γ ray is transferred entirely to the detection medium, which then ejects an electron with energy equal to the energy difference between the γ -ray energy and the binding energy of the electron released. The electron is collected by the anode, and the amplitude of the detection signal is directly proportional to the energy of the incident γ ray. Compton scattering is strongest from about 0.2 MeV up to about 8 MeV. In this process, the incident γ ray undergoes an inelastic interaction with an atomic electron, depositing some of its energy to the recoil electron and continuing on a different trajectory. The scattered γ ray can then repeat this process, depositing energy to other recoil electrons in a series of interactions until either the full energy of the original γ ray is deposited into the detector or the resulting γ rays leave the medium. If the detector is large, the full energy of the γ ray can be deposited in the medium and the signal produced by the collected electrons is proportional to the incident γ -ray energy. However, when the γ rays leave the medium the event contributes to the Compton continuum, creating background [95]. The latter is the case with GRETINA. Finally, pair production is energetically possible at 1.02 MeV, when the γ -ray energy is at least as large as the rest mass energy of an electron-positron pair. It is the dominant interaction above 8 MeV. Pair production occurs when the γ ray interacts with the Coulomb field from a nucleus. The γ ray is then converted into an electron-positron pair, and the excess energy is carried away as kinetic energy by the pair. The electron is directed towards the anode, while the positron is directed toward the cathode. The positron

can interact with an electron on the way to the cathode, leading to pair annihilation and the production of two more photons while conserving the energy of the annihilation pair. These gammas will continue to interact via the three processes until all the energy of the incoming γ ray is converted to electrons that are collected by the anode. The threshold for this process is 1.02 MeV, but does not play a role in this work as described in Ref. [7]. In the analysis, the photopeaks are used for identifying specific transitions, whereas the Compton scattering causes background under the photopeaks.

3.3.2 GRETINA Operation and Setup

GRETINA contained 7 modules for the ^{12}C study and 11 modules for the ^{90}Zr study. The modules surrounding the target location in front of the S800 Spectrograph can be centered at 3 angles; there are 4 module positions available at 58° , 8 positions at 90° , and 4 positions at 122° . Experiment 11021 used 7 modules placed at 90° as shown in Figure 3.10, and experiment 23009 used 11 total modules, 8 modules placed at 90° , and 3 at 58° . Each quad module consists of 4 high-purity germanium crystals, shown schematically on the left side of

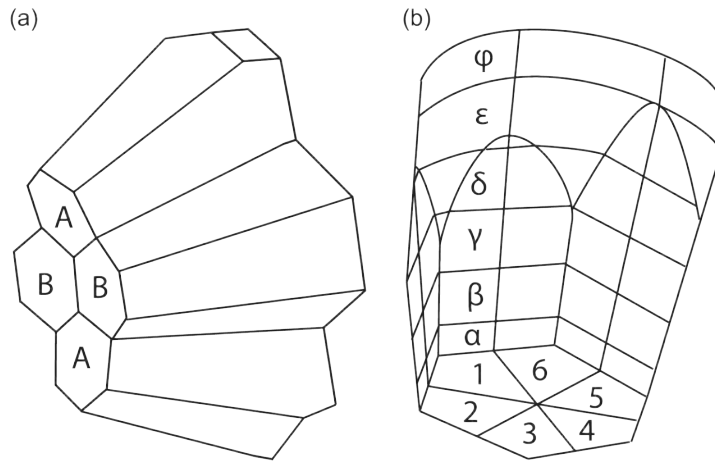


Figure 3.9: Schematic drawing of (a) a GRETINA module consisting of 4 crystals, two A-type and two B-type crystals and (b) electrical segmentation of an individual crystal. Figure is from Reference [13].

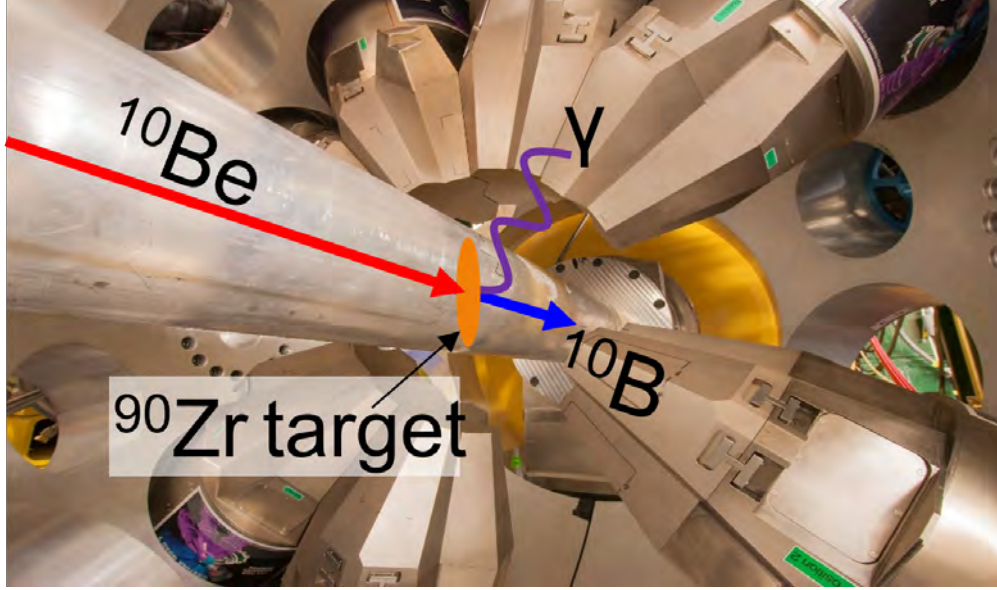


Figure 3.10: GRETINA setup showing 7 modules placed at 90° surrounding the target location, used for experiment 11021 with a cartoon representation of the reaction for experiment 23009. Photograph taken by Shumpei Noji.

Figure 3.9, two A-type and two B-type geometries, with each crystal measuring about 80 mm in diameter and 90 mm long [13]. Each crystal consists of 36 electrically separated segments, shown on the right side of 3.9, along with a central anode that collects freed electrons as discussed in the previous section. Electrical segmentation allows reconstruction of the γ ray interaction point(s) to within 2 mm, significantly increasing the position and energy resolution for γ rays that are emitted in flight. [13,98]. In the experiments described here, the large beam spot in the dispersive direction at the target is a consequence of operating in the dispersion-matched mode. The beam spot adds significant uncertainty to the determination of the angle of the emitted γ ray with respect to the emitting particle, as a reaction that occurs at the top of the target and a reaction that occurs at the bottom of the target will have a significantly different path for a given detector location. This effect is minimized for detectors placed at 90° , as there is little difference in the angle between events that take place at the top and bottom of the target, while it is enhanced in forward-placed detectors

where the difference in angle between reaction events at the top and bottom of the target is significant. Therefore as many modules as possible were placed at 90° and the remaining detectors were placed at 58° .

3.3.3 GRETINA Efficiency

The absolute photopeak efficiency of the GRETINA modules is determined using measurements from four sources placed at the target position of the S800: ^{56}Co , ^{60}Co , ^{152}Eu , and ^{226}Ra . The measurements are used, along with a simulation, to benchmark the efficiency [98]. The efficiency calibrations are verified using source runs at the beginning and end of the experiment using a ^{152}Eu source. This source is used because the decay structure is well understood, emission probabilities from the γ -transitions are well known, and the activity has been measured. The values of the ^{152}Eu decays can be found in Table 3.1

The efficiency is defined as

$$\epsilon(\%) = \frac{N_\gamma}{A * t * \epsilon_{\text{emission}}} * 100 \quad (3.31)$$

where ϵ is the measured efficiency in percent, N_γ is the observed counts in the photopeak, A is the activity of the source, t is the total time of the measurement, and $\epsilon_{\text{emission}}$ is the known emission probability of the γ ray. The activity of the source and the half-life were

Table 3.1: γ -transitions from ^{152}Eu used to verify the efficiency calibration of GRETINA modules before and after the experiments.

^{152}Eu γ -transitions (keV)									
121.8	244.7	344.3	411.1	444.0	778.0	867.4	964.1	1112.1	1213.0
1299.2	1408.0								

used to calculate the current activity of the source using the decay relation

$$A = A_0(0.5)^{\frac{t}{t_0}} \quad (3.32)$$

where A_0 is the activity measured at some reference time, t is the time elapsed between the reference time and the calibration run, and t_0 is the half-life. The activity of the ^{152}Eu source was measured to be $8.46 \mu\text{Ci}$ on May 1, 1978 and the half-life is $13.537 \pm .006$ years. The calibration verification measurements for the experiments and the resulting efficiency functions are shown in the top of Figure 3.11. The efficiency function used for experiment 11021 was a fit of the measured ^{152}Eu efficiencies while the function for experiment 23009 utilized the GRETINA benchmark function [14]. The benchmark was introduced for 12 modules, so the efficiency function was scaled by a factor of 11/12 to account for using 11 quads.

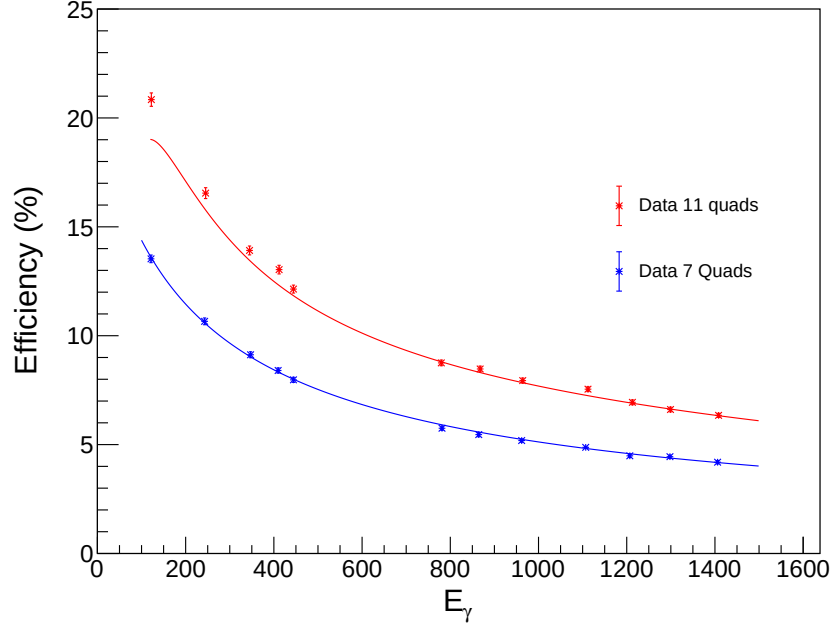
Because ^{10}B is traveling at $\sim 40\%$ the speed of light, γ -rays emitted from ^{10}B will experience Doppler broadening, which will affect the measured γ -ray efficiency function. The impact of Doppler broadening on the efficiency distribution for the 1022 keV γ -ray emitted by ^{10}B in the ^{90}Zr data is shown in the bottom of Figure 3.11. The efficiency is calculated event-by-event using the equations

$$\epsilon_{90\text{Zr}}(\%) = \frac{11}{12} * \frac{1}{x} (199271 - 189618 \log(x) + 69936 \log^2(x) \quad (3.33)$$

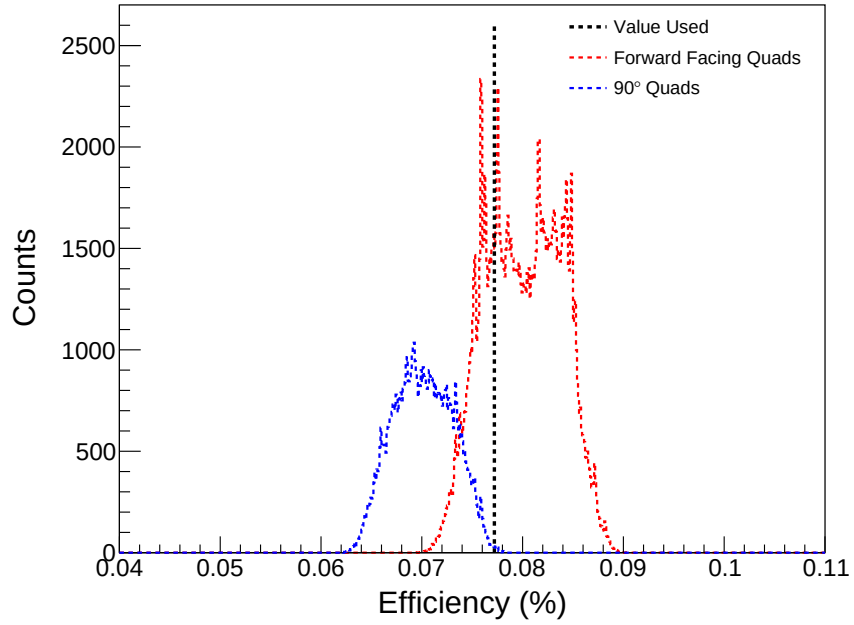
$$- 12561.5 \log^3(x) + 1110.5 \log^4(x) - 38.5 \log^5(x))$$

$$\epsilon_{12\text{C}}(\%) = 595.7 * \exp(-0.67 \log(x + 148.9)). \quad (3.34)$$

for Zirconium and Carbon, respectively, and are displayed in the top plot in Figure 3.11.



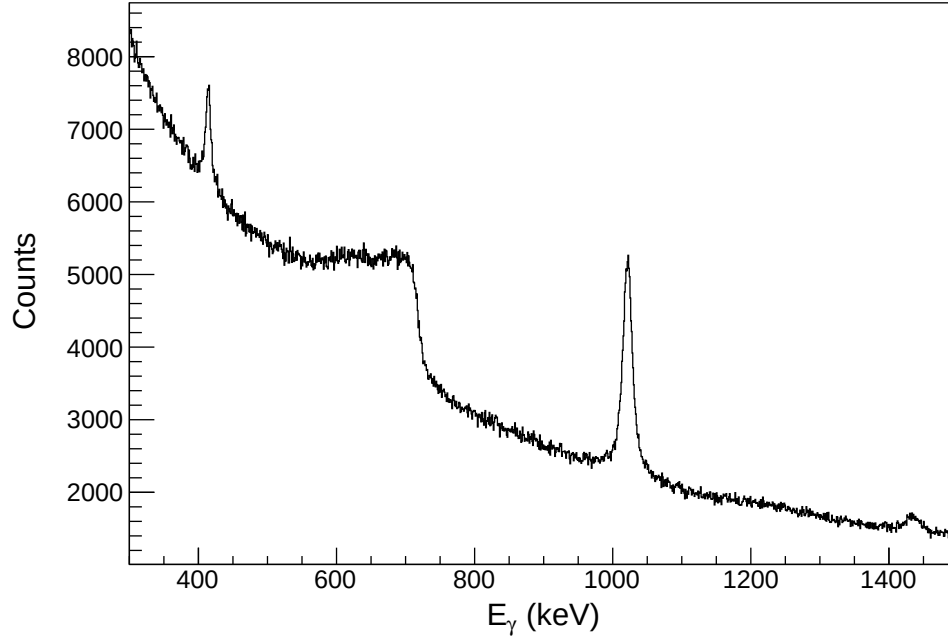
(a)



(b)

Figure 3.11: (a) GREYINA efficiency measured using ^{152}Eu before experiment 11021 and 23009. The efficiency function for experiment 11021 is a fit of the measured efficiency of ^{152}Eu data while the function for experiment 23009 is the efficiency function of the GREYINA benchmark simulation for 12 modules, scaled to 11 modules [14]. (b) The efficiency distribution for the 1022 keV peak in ^{10}B for all GREYINA modules in experiment 23009.

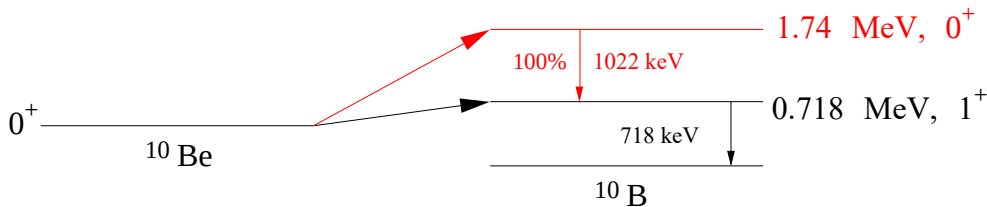
Figure 3.12: Doppler-corrected γ -ray energy spectrum for experiment 23009.



The efficiency distribution for the 90° detectors corresponds to events in which less energy is being deposited in the detector, whereas γ rays emitted at forward angles deposit more energy in the detector, as described by Equation 3.30. Since the 2.15 MeV 1_2^+ and 1.74 MeV 0_1^+ states are short lived and decay immediately, the efficiency used for the decays from these states is simply the average of the respective efficiency distribution, as indicated in the efficiency distribution for the 1022 keV γ -ray transition in the bottom of Figure 3.11.

This approach cannot be used for the decay of the 0.718 MeV 1_1^+ state, as the state is

Figure 3.13: Decay scheme of the 1.74 MeV 0_1^+ and the 0.718 MeV 1_1^+ states.



long lived and can decay downstream of the target. The half life of this state is 0.707 ns, which corresponds to a decay at 9 cm after the target. Decay events are observed down to ~ 520 keV in the data, as shown in Figure 3.12. This corresponds to decays occurring up to 36 cm after the target. To determine the detection efficiency of the 718 keV γ ray, it is necessary to use the data to consider γ - γ coincidences between the 1022 keV γ ray and the 718 keV 1022 keV γ ray. Figure 3.13 shows the decay scheme between the two states: the 1.74 MeV 0_1^+ state decays to the 0.718 MeV 1_1^+ state with 100% probability by emitting a 1022 keV γ ray. The 0.718 MeV 1_1^+ then decays to the ground state via emission of a 718 keV γ ray. Because of this, it has been shown in Ref. [15] that the same detection efficiency can be obtained in two ways:

1. Using the 718 keV γ ray as the photopeak of interest. The detection efficiency of the 718 keV γ ray is determined by using the ratio

$$\epsilon = \frac{N_{718\text{ keV}+1022\text{ keV}}}{N_{718\text{ keV}}} \quad (3.35)$$

where $N_{718\text{ keV}+1022\text{ keV}}$ is the number of counts in the 718 keV photopeak when requiring a coincidence with a 1022 keV γ and $N_{718\text{ keV}}$ is the number of counts in the 718 keV photopeak in the singles spectrum.

2. Using the 1022 keV γ ray as the photopeak of interest. The detection of the 718 keV γ ray is determined by using the ratio

$$\epsilon = \frac{N_{1022\text{ keV}+718\text{ keV}}}{N_{1022\text{ keV}}} \quad (3.36)$$

where $N_{1022\text{ keV}+718\text{ keV}}$ is the number of counts in the 1022 keV photopeak when a

coincidence with a 718 keV γ ray is required and $N_{1022\text{ keV}}$ is the number of counts in the 1022 keV photopeak singles spectrum.

The good events in Equations 3.35 and 3.36 are obtained by applying a sideband subtraction, as described below. Random coincidence events between background and photopeak events are determined by requiring a coincidence between the photopeak of interest and the sideband of the other photopeak. These background coincidence spectra for the 1022 keV γ ray as the photopeak of interest (bottom left) and the 718 keV γ ray as the photopeak of interest (bottom right) are shown in Figure 3.14. The number of coincidence events in the coincidence

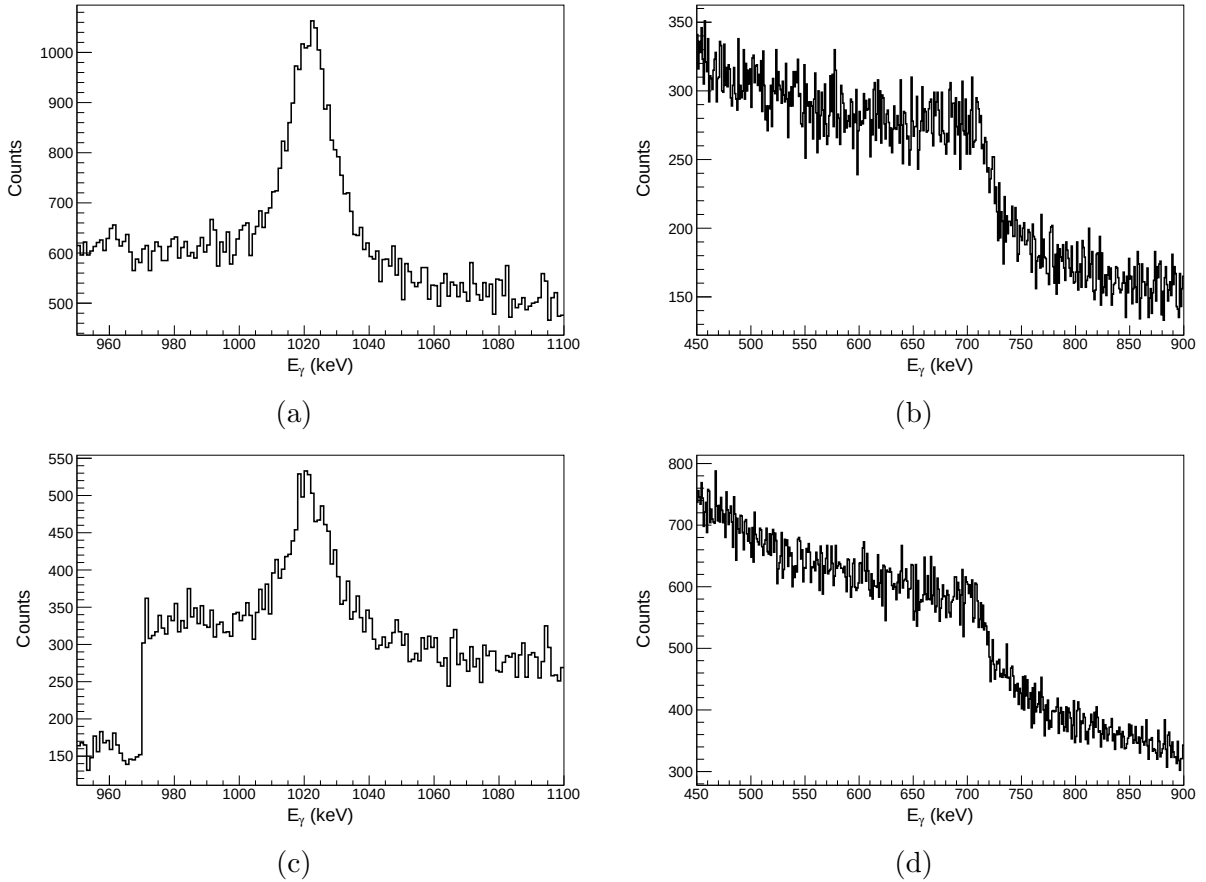


Figure 3.14: Coincidence spectra gated on the peak and sideband of the other γ of interest. (a) The 1022 keV coincidence spectra gated on the 718 keV peak. (b) The 718 keV coincidence spectra gated on 1022 keV peak. (c) The 1022 keV coincidence spectrum gated on the sideband of the 718 keV peak. (d) The 718 keV coincidence spectrum gated on the sideband of the 1022 keV peak.

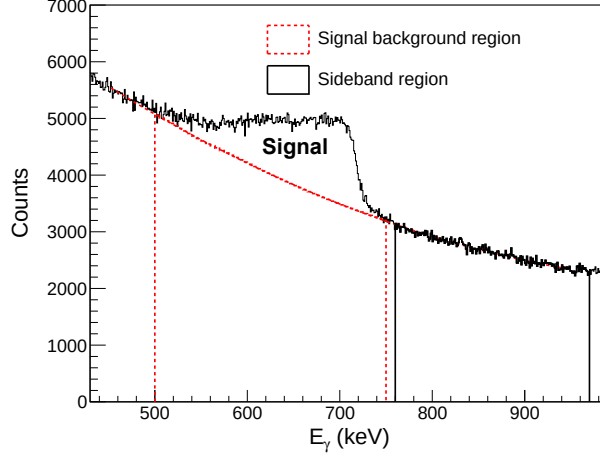


Figure 3.15: Singles spectrum of the Doppler Reconstructed γ -ray spectrum from the ^{90}Zr , data zoomed in on the long-lived state. The background under the signal is modeled using a second order polynomial, indicated by the red fit line. The signal region is indicated by the dotted red box, while the sideband region is indicated by the solid black box.

spectrum and the background coincidence spectrum are extracted by applying a sideband subtraction to each plot. The sideband extraction adds significant uncertainty using the 718 keV γ ray as the photopeak of interest as there are limited statistics in the photopeak when the coincidence gates are applied while there is a large background component. This is clear in Figure 3.14, which uses the 1022 keV γ ray as the primary gate on the left (method 1) and the 718 keV photopeak as the primary gate on the right (method 2). As the two methods have been proven to give an agreeable result, using the 1022 keV photopeak as the primary gate is preferable. For this choice, the uncertainty associated with the coincidences is reduced because the peak region is narrow and there are fewer background events under the peaks.

The signal counts in a photopeak are obtained by performing a sideband subtraction. In the sideband subtraction method, the background events under the photopeak signal are modeled using a side-band of the photopeak. The band is always located at a higher γ energy than the photopeak of interest, as a band at a lower γ energy would include good

	Detection Efficiency of Peak Region (%)		
Experiment	414 keV	718 keV	1022 keV
11021	8.3 ± 0.6	3.1 ± 0.2	5.1 ± 0.3
23009	12.4 ± 0.9	4.5 ± 0.3	7.7 ± 0.6

Table 3.2: GRETINA efficiencies used for each peak of interest in each experiment.

events in which the γ ray interacted with GRETINA via Compton scattering, resulting in good events being removed from the spectrum. The Doppler corrected γ energy spectrum containing the photopeak and its sideband is fit using a polynomial function to model the background and Gaussian function(s) to fit the peak itself. For the long lived state, a second order polynomial is used to model the background in both datasets, while the peak is fit with two Gaussian functions for the ^{12}C study and three for the ^{90}Zr study. Figure 3.15 shows the Doppler corrected γ -ray energy spectrum for the long-lived state and indicates the sideband, signal, and signal background regions, along with the polynomial used to model the background. The number of events in the signal region is defined as

$$N_{signal} = N_{signal\ region} - kN_{sideband\ region} \quad (3.37)$$

where $N_{signal\ region}$ is the total number of counts in the signal region, $N_{sideband\ region}$ is the total number of counts in the sideband region, and k the sideband scale factor defined as

$$k = \frac{N_{sideband}}{N_{signal\ background}} \quad (3.38)$$

where $N_{signal\ background}$ is the number of events under the polynomial function in the signal region.

A sideband subtraction was applied to all plots used to determine the detection efficiency of the long-lived state. The efficiency values adopted for the experiments are reported in

Table 3.2. The uncertainties in the 414 keV photopeak and the 1022 keV photopeak are obtained from the standard deviation in the event-by-event efficiency distribution for the respective peak, while the uncertainties in the 718 keV photopeak contain only the propagated statistical uncertainty from the sideband subtraction.

Chapter 4. The simultaneous extraction of isovector non-spin-transfer and spin-transfer strength

The first simultaneous extraction of the isovector monopole and isovector spin-monopole using the ($^{10}\text{Be}, ^{10}\text{B} + \gamma$) reaction system was performed using a ^{12}C target [15]. The probe was developed to extract the monopole strength from the non-spin-transfer channel [72], but in this work has been expanded to extract the strength from both the non-spin-transfer and spin-transfer channels. In the lead-up to the first ($^{10}\text{Be}, ^{10}\text{B} + \gamma$) experiment, ^{12}C was identified as an ideal test case for the suitability of the probe, as there is a strong Gamow Teller transition $^{12}\text{C}(0^+, gs) \rightarrow ^{12}\text{B}(1^+, gs)$, shown in Figure 4.1. By gating on the transitions to the 1.74 MeV 0_1^+ state and the 0.718 MeV 1_1^+ state in ^{10}B , it is possible to create spin filters that isolate the non-spin and spin transitions, respectively. This process will be discussed in more detail in Section 4.2.

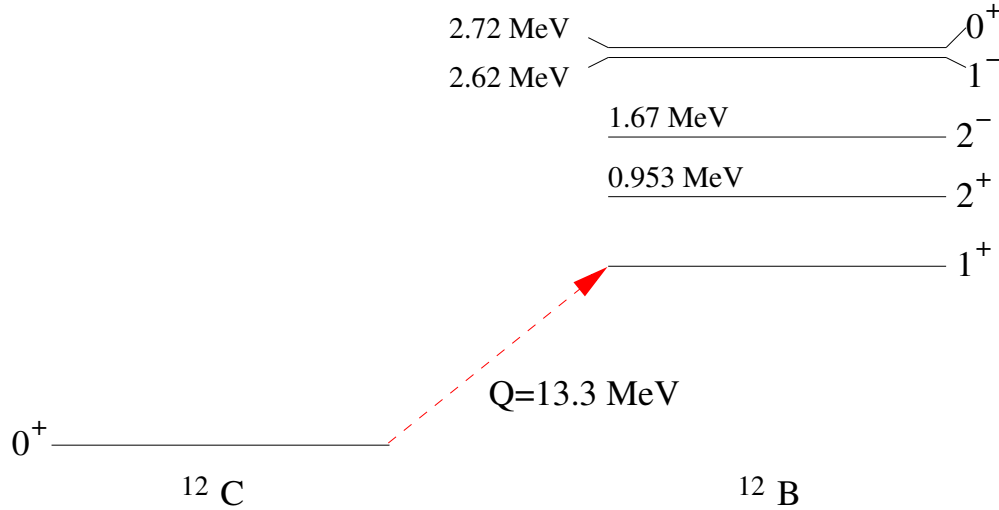


Figure 4.1: Level Scheme of the $^{12}\text{C} \rightarrow ^{12}\text{B}$ reaction.

4.1 Experiment

Experiment E11021 was conducted at the Coupled Cyclotron Facility of the National Superconducting Cyclotron Laboratory (NSCL) in June 2012. A schematic of the Coupled Cyclotron Facility is shown in Figure 3.1. While experimental considerations important to the simultaneous extraction method will be discussed below, the full description of the experiment and associated data calibrations can be found in Ref. [7]. In this work, the extraction of the non-spin-transfer response was the main topic. Here, the same data are used to explore the extraction of non-spin-transfer and spin-transfer excitations in a single measurement. The results of this analysis are published in Ref. [15].

The ^{10}Be secondary beam was produced by impinging a 150 pnA, 120A MeV ^{18}O beam on a 1316 mg/cm²-thick Be production target at the entrance of the A1900 fragment separator [100]. The fragment separator was used to purify the beam as described in Section 3.1.2.1, resulting in an 88% pure ^{10}Be beam at an energy of 100A MeV. The secondary beam was transported to the S800 target station in dispersion-matched mode [101], discussed in Section 3.2, and impinged upon a 56.33 mg/cm²-thick $^{\text{nat}}\text{C}$ target (98.88% ^{12}C) placed at the pivot point of the S800 Spectrograph [96]. The resulting ^{10}B ejectiles were then detected in the focal plane of the S800 spectrograph, while seven GRETINA modules placed around the target location at 90° relative to the beam direction were used to tag the events of interest.

To identify the ^{10}B in the focal plane, a particle-identification (PID) plot was produced by plotting the deposited energy in the ion chamber as a function of its time of flight. The time of flight was determined by taking the time difference between the RF time signal from the accelerator and the time signal from the S800 focal plane scintillator. The deposited energy

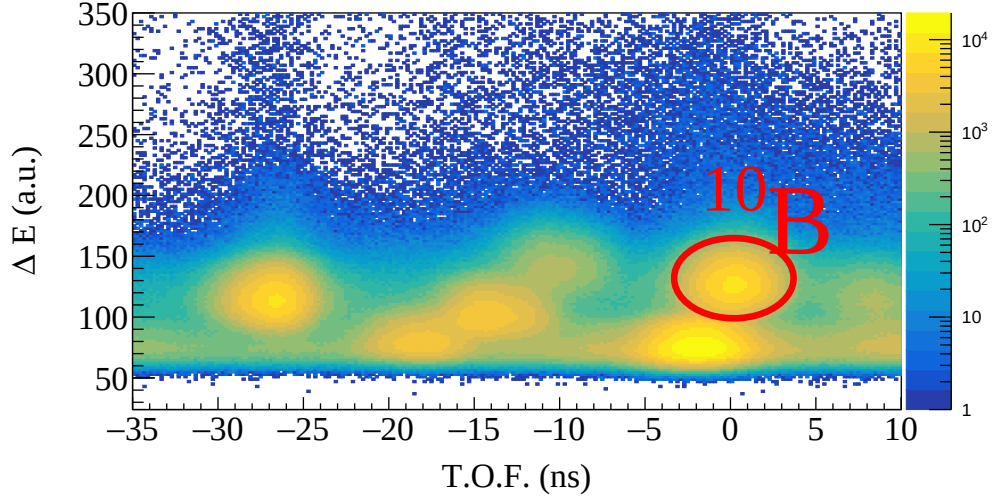


Figure 4.2: PID indicating ^{10}B particles, including corrections to time-of-flight and deposited energy spectrum.

was measured in the ion chamber and the deposited energy in the focal plane scintillator was used to reduce background events. The PID is shown in Figure 4.2. The time of flight and deposited energy were observed to be correlated with the dispersive position and angle in the focal plane and were corrected as discussed in Ref. [7]. A similar correction process for the ^{90}Zr data is shown in Section 5.2.1. The Doppler-Corrected γ -ray spectrum was also corrected for target position by adjusting the z-offset of the target location so that the 1022 keV photopeak would be centered at 1022 keV. A similar correction was applied to the Zirconium data as discussed in Section 5.2.6.

4.2 Creating Spin Filters

Creating the spin filters for the $(^{10}\text{Be}, ^{10}\text{B} + \gamma)$ system takes advantage of the level scheme of ^{10}B , shown in Figure 4.3. The goal is to isolate the excitation energy spectra corresponding to the N_1 (spin-channel) transition and N_2 (non-spin channel) transition in Figure 4.3. The resulting spectra are then decomposed into multipolarity contributions using a Multipole

Decomposition Analysis (MDA) and the monopole strength for each state is extracted.

The N_1 and N_2 transitions are isolated by applying gates to each photopeak and sideband in the Doppler-Corrected γ -ray energy spectrum for each decay of interest, shown in Figure 4.4. This creates an excitation-energy spectrum for each peak and sideband associated with the ^{10}B decay. The background contributions in each photopeak spectrum are removed using a sideband subtraction, and the feeding contributions from higher lying states are subtracted from the spin and non-spin channels of interest.

4.2.1 Sideband Subtraction

The sideband subtraction method removes background events under a photopeak by modeling the background under the peak using events in a side-band at a slightly higher γ -energy than the photopeak. A similar sideband subtraction was applied to the Doppler-Corrected singles spectra to determine the detection efficiency of the 718 keV γ -ray, described in Section 3.3.3. In this case, excitation-energy spectra are produced by applying gates to the photopeak (signal region) and the associated sideband (sideband region). The background

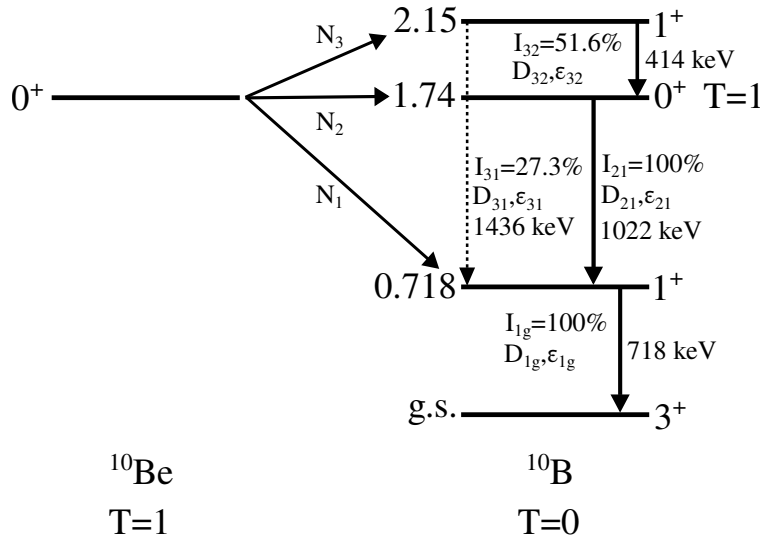


Figure 4.3: Level Scheme of the $^{10}\text{Be} \rightarrow ^{10}\text{B}$ reaction showing branching ratios.

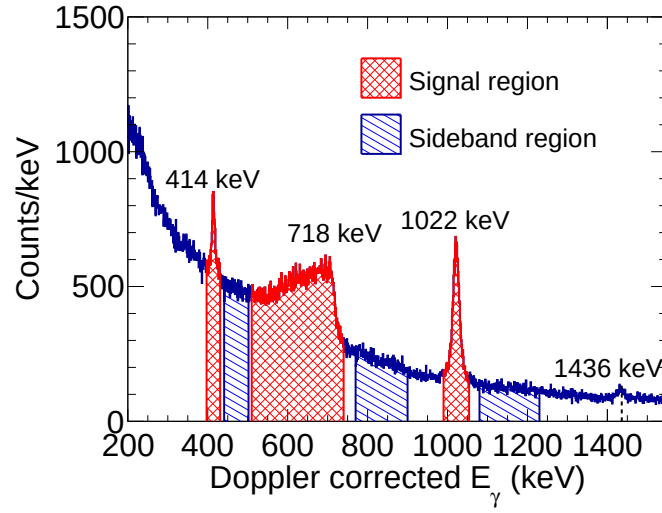


Figure 4.4: Signal and sideband regions used in ^{12}C analysis.

in the signal region is removed by scaling and subtracting the associated sideband region by applying Equation 3.37. The background counts are determined by fitting each region with a combination of Gaussian function(s) for the peak and a polynomial for the background. The fit for the 1022 keV signal and the corresponding sideband region is shown in Figure 4.5. The scale factor is determined using Equation 3.38. The 414 keV region was fit with a Gaussian function and a second order polynomial, the 718 keV region was fit with two Gaussian functions and a second order polynomial, and the 1022 keV region was fit with a Gaussian function and a second order polynomial.

The γ -gates for the signal regions were chosen to ensure the vast majority of signal events were included in the gate. For the 414 keV and 1022 keV signal-region gates, this was accomplished by fitting the respective peak in one GRETINA crystal and defining the width of each gate as twice the full width at half maximum (FWHM) from by the fit. The 718 keV signal region is unique, as the $0.718 \text{ MeV } 1_1^+$ state is long-lived, with a half life of 0.707 ns. As the ^{10}B is traveling at a velocity of $\sim 40\%$ the speed of light, this corresponds

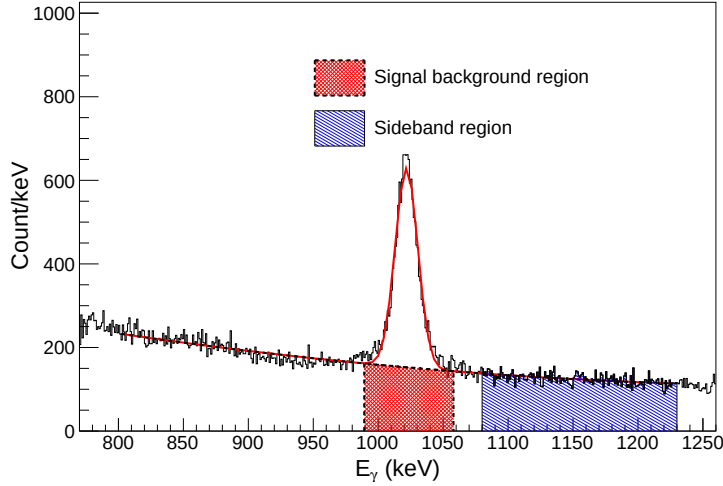


Figure 4.5: The fit of the 1022 keV state used in the side-band subtraction.

to a decay occurring 9 cm after the target. Events associated with the decay are observed down to a deposited γ energy of 520 keV, corresponding to decays occurring 36 cm after the target. The width of the sideband gates were chosen to minimize the statistical uncertainty in the scale factor k while ensuring the background shape was independent of the width of the gate. The results of the sideband comparison for the 1022 keV sideband region are shown in Figure 4.5. The Doppler Corrected γ -energy spectrum indicating the signal and sideband gates for the ^{12}C data is presented in Figure 4.4. The shape of the peak region is clearly different than the background, and each slice of the sideband used has essentially the same shape, showing that the shape of the background is independent of the width of the gate used. The signal region gates, sideband region gates, and the resulting scale factors used in the sideband subtraction are presented in Table 4.1.

γ -Energy (keV)	Signal Start (keV)	Signal End (keV)	Sideband Start (keV)	Sideband End (keV)	Scale Factor
414 keV	397	431	441	502	0.572
718 keV	500	720	770	900	1.198
1022 keV	990	1054	1080	1230	0.46

Table 4.1: γ -gates and corresponding scale factors used in the side-band analysis for ^{12}C

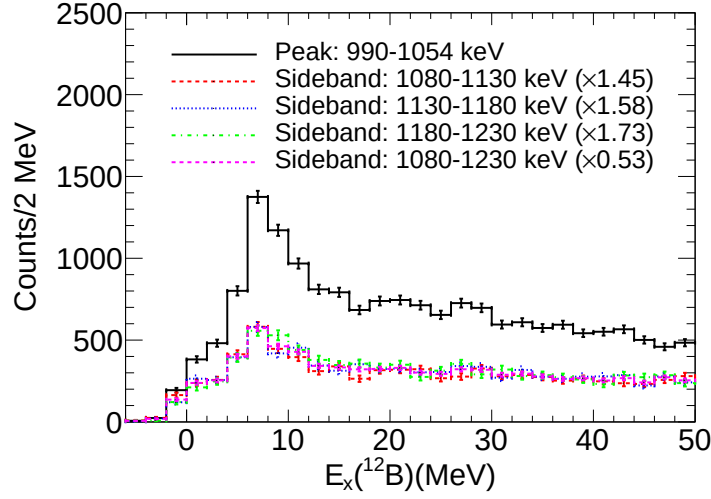


Figure 4.6: Sideband study for the 1022 keV peak in ^{12}C data.

4.2.2 Feeding Subtraction

The feeding from higher-energy excited states in the ^{10}B γ -ray spectrum was removed from the spin- and non-spin-transfer states following the sideband subtraction. As presented in the level diagram in Figure 4.3, the non-spin state is populated by feeding from the 2.15 MeV 1_2^+ state, which is tagged by the 414 keV γ ray. Feeding from the 3.59 MeV 2_1^+ state is also possible, but the population of this 2_1^+ state through the charge-exchange reaction is very weak and was not observed in this experiment. Feeding from this state was therefore ignored. The excitation-energy spectrum associated with the N_2 transition to the 1.74 MeV 0_1^+ state is obtained by using:

$$N_2 = \frac{D_{21}}{\epsilon_{21}} - \frac{D_{32}}{\epsilon_{32}}. \quad (4.1)$$

where D_{21} is the number of events associated with the 1022 keV photopeak following the sideband subtraction, ϵ_{21} is the detection efficiency of the 1022 keV γ ray, D_{32} is the number

of events associated with the 414 keV photopeak following the sideband subtraction, and ϵ_{32} is the detection efficiency of the 414 keV γ ray.

The spin-state is populated by feeding from both the 2.15 MeV 1_2^+ state and the 1.74 MeV 0_1^+ state. While the 2.15 MeV 1_2^+ state is also associated with a spin-transfer, the state is likely complicated by the interference between the $\Delta L = 0$ and $\Delta L = 2$ amplitudes mediated by the tensor- τ component of the nucleon-nucleon interaction. Therefore, it was treated as a feeding state and its contributions removed. As shown in Figure 4.4, the corresponding 1436 keV γ -ray peak is very weak and the signal-to-noise of the photopeak to the background is significantly reduced compared to the 414 keV γ ray. As a result, the spectrum for the 414 keV γ ray was used to subtract the feeding from the 2.15 MeV 1_2^+ state using the relevant branching ratios. This was accomplished by

$$N_1 = \frac{D_{1g}}{\epsilon_{1g}} - \frac{D_{21}}{\epsilon_{21}} - \frac{D_{31}}{\epsilon_{31}} = \frac{D_{1g}}{\epsilon_{1g}} - \frac{D_{21}}{\epsilon_{21}} - \frac{D_{32}}{\epsilon_{32}} \frac{I_{31}}{I_{32}}. \quad (4.2)$$

where D_{1g} is the number of events associated with the 718 keV photopeak following the sideband subtraction, ϵ_{1g} is the detection efficiency of the 718 keV γ ray, D_{31} is the number of events associated with the 1436 keV photopeak following the sideband subtraction, ϵ_{31} is the detection efficiency of the 1436 keV γ ray, I_{31} is the branching ratio for the 1436 keV γ ray, and I_{32} is the branching ratio for the 414 keV γ ray. The results of the feeding subtraction are shown in Figure 4.7. The strong Gamow Teller transition to the ground state in ^{12}B is fully removed in the resulting non-spin-transfer channel, while the transition is prevalent in the spin-transfer channel, proving the spin filter works as intended.

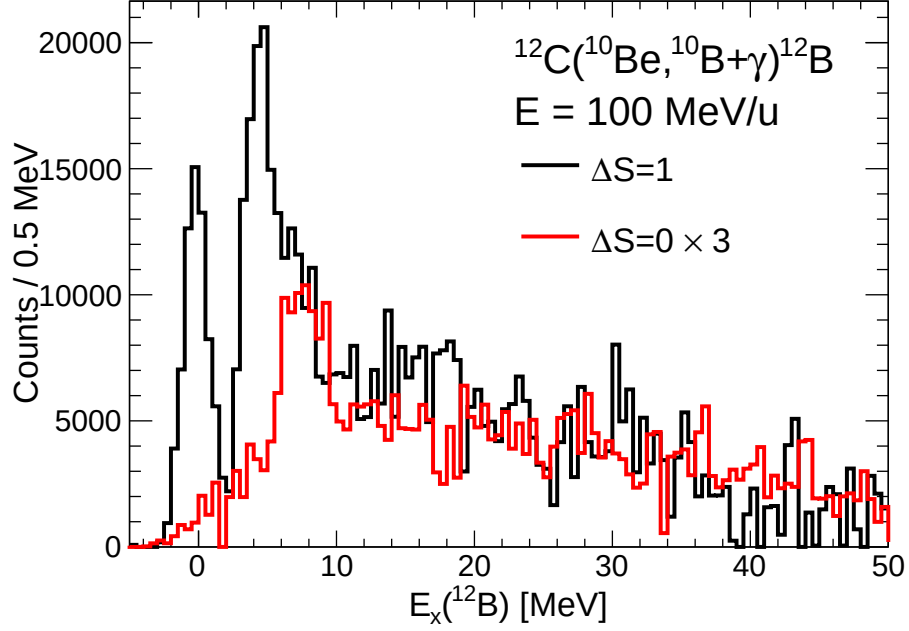


Figure 4.7: The excitation energy spectrum of the spin channel (black line) and non-spin channel (red line) in ^{12}B . The non-spin channel is scaled by a factor of 3 for visualization purposes.

4.3 Multipole Decomposition Analysis

The multipolarity contributions in the resulting double differential cross sections are disentangled using a Multipole Decomposition Analysis (MDA) [102, 103]. The MDA takes advantage of the different characteristic shapes for each ΔL value. The $\Delta L = 0$ transition peaks near 0° , while higher polarity transitions are strongest at larger scattering angles, with the $\Delta L = 1$ peaking at $\theta_{c.m.} \simeq 1^\circ$ in ^{12}B while the $\Delta L = 2$ component peaks at $\theta_{c.m.} > 3^\circ$. As a result, the multipole contributions can be separated by fitting the data with a linear combination of angular distributions representing each ΔL value.

To prepare the data for decomposition, the excitation-energy spectra are binned in 2 MeV wide bins and plotted as a function of scattering angle using 0.5° bins up to 3° . The

Possible final state in ^{12}B			
	$\Delta L = 0$	$\Delta L = 1$	$\Delta L = 2$
$\Delta S = 0$	$J^\pi = \mathbf{0}^+$	$J^\pi = \mathbf{1}^-$	$J^\pi = \mathbf{2}^+$
$\Delta S = 1$	$J^\pi = \mathbf{1}^+$	$J^\pi = 0^-, 1^-, \mathbf{2}^-$	$J^\pi = 1^+, \mathbf{2}^+, 3^+$

Table 4.2: Selection rules for $^{12}\text{C}(0^+, gs) \rightarrow ^{12}\text{B}$ mediated by each transition used in the MDA for ^{12}B . The distribution shapes used are in bold.

resulting angular distributions for each energy bin are fit using the least-squares method with a linear combination of theoretical cross sections as

$$\left. \frac{d\sigma}{d\Omega} \right|_{total}^{DWBA} = a \left. \frac{d\sigma}{d\Omega} \right|_{\Delta L=0} + b \left. \frac{d\sigma}{d\Omega} \right|_{\Delta L=1} + c \left. \frac{d\sigma}{d\Omega} \right|_{\Delta L=2} + \dots \quad (4.3)$$

where a , b , c , etc are fit parameters and $\left. \frac{d\sigma}{d\Omega} \right|_{\Delta L=i}$ is the theoretical angular distribution for the respective multipole. The parameters are constrained to be positive, but are otherwise allowed to vary to produce the best fit, which was determined by χ^2/ν minimization, where ν is the degrees of freedom from the fit. The theoretical distributions were calculated using a distorted wave Born approximation, discussed in Chapter 2.

The angular distributions $\Delta L \leq 2$ were used in the MDA for both channels, as the inclusion of higher multipoles had no impact on the result of the fits. As a result, it was determined that the $\Delta L = 2$ component effectively incorporates possible contributions from higher-order multipolarities. The theoretical distributions are calculated in steps of 0.5 MeV along the entire excitation-energy spectrum, in 0.1° increments from $0.0^\circ < \theta_{c.m.} < 8.0^\circ$. While the distributions were calculated in steps of 0.5 MeV, only the distribution for each bin center of the double differential cross section was used in the MDA. The selection rules for the non-spin and spin states in the $^{12}\text{C}(0^+, gs) \rightarrow ^{12}\text{B}$ reaction are shown in Table 4.2. Since the transitions for each ΔL have very similar angular distributions, only one distribution for each ΔL was used in the MDA. These states are indicated in bold in Table 4.2.

Before the MDA can be applied, the theoretical distributions are smeared and rebinned to match experimental conditions. Since the theoretical angular distributions are calculated in the center-of-mass frame and the resolutions are measured in the lab frame, the angular distributions are converted to the lab frame, smeared, and then converted back to the center of mass frame for use in the MDA. The excitation-energy resolution was obtained from the width of the Gamow Teller transition, and was determined to be 2 MeV. To determine the angular resolution, the dispersive and non-dispersive scattering angles of the unreacted ^{10}Be beam were measured in the focal plane of the S800 spectrograph. The resulting angular resolution is 0.7° . The distributions before and after smearing are shown in Figure 4.8.

4.3.1 Results

The resulting differential cross sections for different excitation-energy ranges are shown in Figure 4.9. The results from the MDA are also shown in decomposed double differential cross sections, plotted as a function of excitation energy in ^{12}B , are presented in Figure 4.10. The strong Gamow-Teller (GT) transition ($\Delta S = 1$, $\Delta L = 0$) from the ground state of ^{12}C to the ground state of ^{12}B , with $B(\text{GT}) = 0.99$ (from Ref. [104]), is clearly observed in Figures 4.10(b) and 4.9(b), peaking at forward angles. The extracted monopole cross section for this transition in the first angular bin in Figure 4.9(b) is 7.4 ± 1.3 mb/sr, which is a factor of 1.95 ± 0.34 larger than expected based on the DWBA calculations with the shell-model inputs. This factor was obtained following a correction for the measured GT strength of the $^{10}\text{Be}(gs) \rightarrow ^{10}\text{B}(1^+, 0.718 \text{ MeV})$ transition being 21% smaller than the value obtained in the shell-model calculations. The GT strength for the transition to the ^{12}B ground state is identical to the shell-model calculations and a correction before the measured and theoretical cross sections could be compared was not necessary.

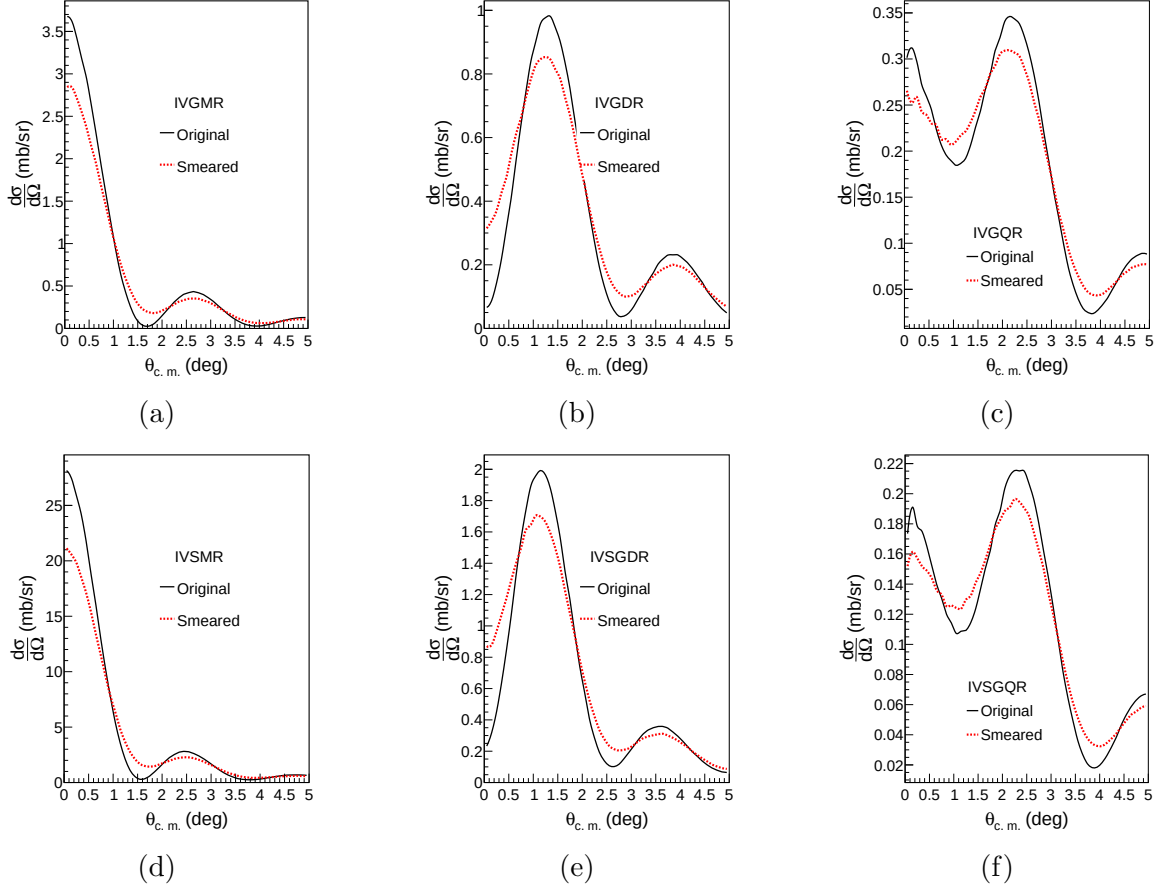


Figure 4.8: DWBA angular distributions at $E_x(^{12}\text{B}) = 0$ MeV. The black line is the original output from the DWBA calculation, the red dotted line is the smeared distribution. a) isovector monopole resonance, b) isovector dipole resonance, c) isovector quadrupole resonance, d) isovector spin monopole resonance, e) isovector spin dipole resonance, f) isovector spin quadrupole resonance.

Interestingly, the MDA shows fragmented $\Delta L = 0$ strength in the non-spin-transfer channel. As there is no isobaric analog state of the ^{12}C ground state in ^{12}B , all $\Delta L = 0$ strength in the non-spin-transfer channel is expected to come from the monopole resonance. However, only minor monopole strength is identified in the spin-transfer channel. As noted in Ref. [15], the lower signal-to-background ratio for the $\Delta S = 1$ filter compared to the $\Delta S = 0$ filter makes the statistical uncertainties higher for the $\Delta S = 1$ channel. As a result, the probe system is more sensitive to the $\Delta S = 0$ channel than the $\Delta S = 1$ channel. In such a light system, monopole strength in both channels is likely highly fragmented. As a

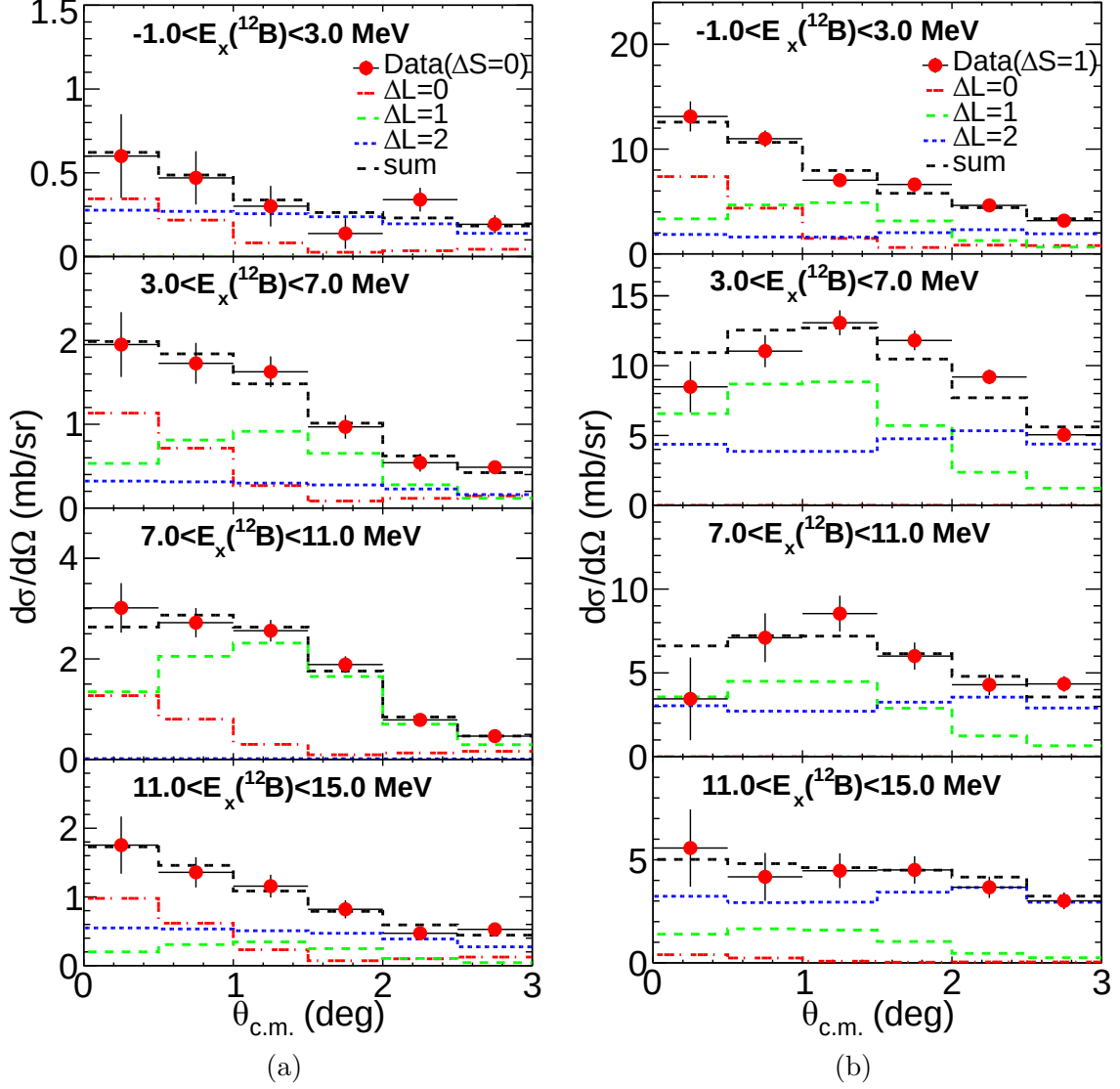


Figure 4.9: Results of fits in 4 MeV bins for a) the $\Delta S = 0$ channel and b) the $\Delta S = 1$ channel. .

result, a higher-statistics study would be necessary to further study both monopole channels in ^{12}B . As a consequence, the dipole resonances extracted from $^{12}\text{C} \rightarrow ^{12}\text{B}$ system following the MDA were compared to previous experimental results to further validate the analysis.

The MDA results in Figure 4.10 show strong dipole ($\Delta L = 1$) excitations in both the $\Delta S = 0$ and $\Delta S = 1$ channels, peaking at $\theta_{\text{c.m.}} = 1.25^\circ$, which are identified as the isovector giant dipole resonance (IVGDR, $\Delta S = 0$ and $\Delta L = 1$) and the isovector spin giant

dipole resonance (IVSGDR, $\Delta S = 1$ and $\Delta L = 1$). The extracted double-differential cross sections of these resonances are shown in Figure 4.11. The IVGDR is concentrated around $E_x \approx 7.5$ MeV. For comparison, the photonuclear cross section from the $^{12}\text{C}(\gamma, n)^{11}\text{C}$ reaction [16, 105], which excites the dipole resonance, is shown in Fig. 4.11(c). Both datasets show a peak around 7.5 MeV. Dipole strength around $E_x = 7.5$ MeV was also observed in the $^{12}\text{C}(n, p)^{12}\text{B}$ [105, 106] and $^{12}\text{C}(^{13}\text{C}, ^{13}\text{N})^{12}\text{B}$ [70] charge exchange experiments, which are sensitive to both $\Delta S = 0$ and $\Delta S = 1$ excitations. Figure 4.11(d) shows the double

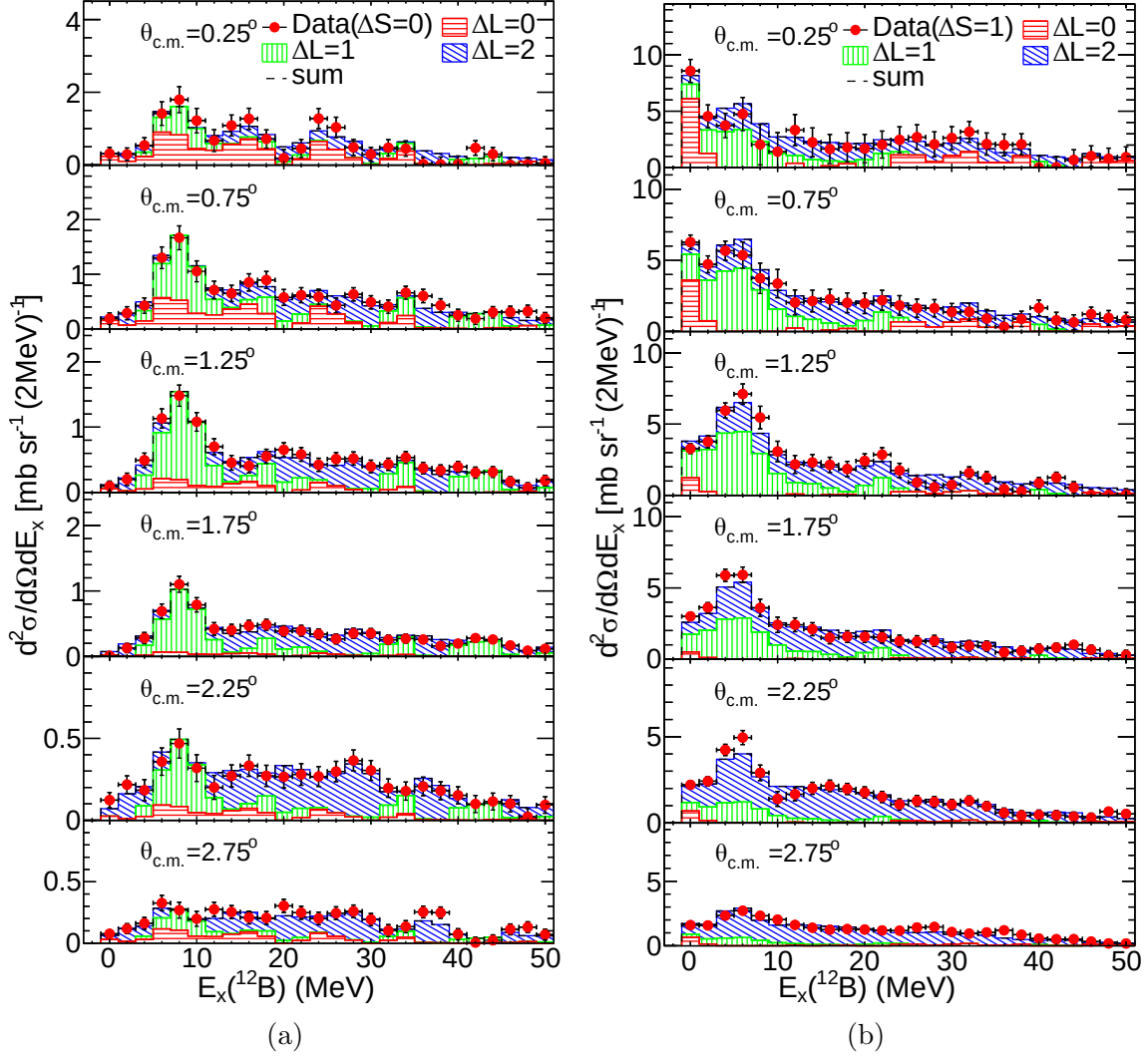


Figure 4.10: Double-differential cross section for the $^{12}\text{C}(^{10}\text{Be}, ^{10}\text{B})^{12}\text{B}$ as a function of excitation energy in ^{12}B from [15]. a) is produced by gating on the 1.74 MeV excited state in ^{10}B , b) is produced by gating on the 0.718 MeV excited state in ^{10}B .

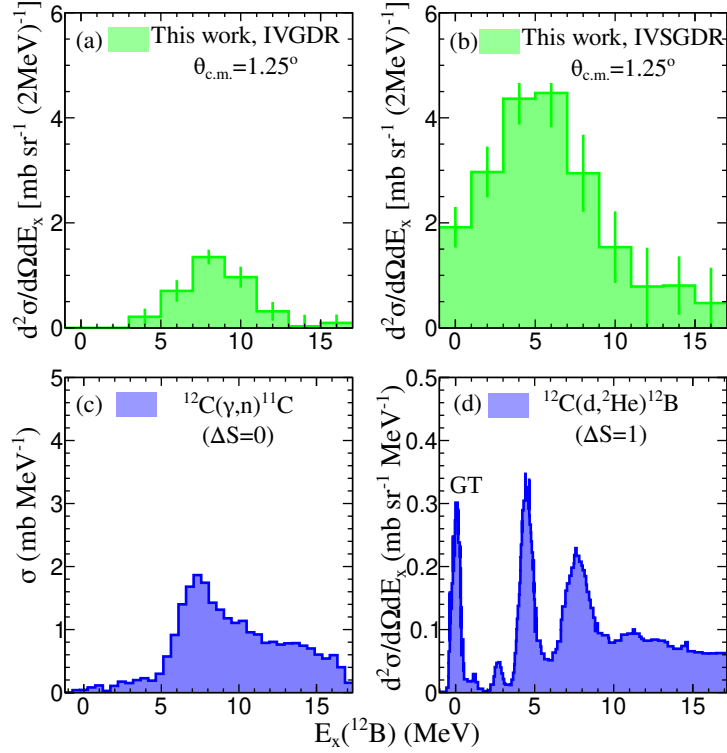


Figure 4.11: a) results of the isovector giant dipole resonance and b) results of the isovector giants spin dipole resonance. c) Photonuclear cross section from the $^{12}\text{C}(\gamma, n)^{11}\text{C}$ reaction [16], which is sensitive to the $\Delta S = 0$ channel. d) Cross section for the $^{12}\text{C}(d, ^2\text{He})^{12}\text{B}$ reaction at $E_d = 270$ MeV ($\theta_{\text{c.m.}} = 6^\circ\text{--}8^\circ$) [17], which is sensitive to the $\Delta S = 1$ channel. Figure from Ref. [15].

differential cross section of the $^{12}\text{C}(d, ^2\text{He})$ reaction at $E_d = 270$ MeV, $\theta_{\text{c.m.}} = 6^\circ\text{--}8^\circ$ [17]. The $(d, ^2\text{He})$ probe is only selective to the $\Delta S = 1$ channel. This figure shows the GT transition at $E_x = 0$ MeV, along with two peaks at $E_x = 4.5$ and 7.5 MeV that correspond to spin-dipole states. These spin-dipole states at 4.5 and 7.5 MeV were also observed in the $^{12}\text{C}(^{12}\text{C}, ^{12}\text{N})$ reaction at $E = 135$ MeV/ u [68, 69] and the $^{12}\text{C}(^7\text{Li}, ^7\text{Be})$ reaction [58, 107, 108], which are both selective to spin-transfer excitations. In the present spin-dipole distribution, a broad peak centered at $E_x = 5$ MeV is observed in Fig. 4.11(b). As the experimental energy resolution, which was determined to be 2 MeV in this work, is limited, these two dipole peaks could not be separated in the data. The cross section observed for dipole transitions near $E_x = 0$ MeV is likely due to the excitation of the 2^- and 1^- states

at $E_x = 1.67$ and 2.62 MeV in ^{12}B .

The extracted distributions are consistent with previous charge exchange experiments studying the isovector excitations in the $^{12}\text{C} \rightarrow ^{12}\text{B}$ system, validating the use of the $(^{10}\text{Be}, ^{10}\text{B} + \gamma)$ probe in isolating spin-isospin excitations in the same measurement. Isolating the spin-transfer channels only depends on the known branching ratios of the γ rays from the decaying ^{10}B and does not rely on details of the reaction mechanism, minimizing systematic uncertainties. However, the statistical uncertainties and experimental resolutions achieved in this experiment were larger than other charge exchange probes because the use of a thick target was necessary to achieve adequate statistics due to the relatively low beam intensities available at the NSCL. The ^{10}Be beam intensities at next-generation rare-isotope facilities exceed the intensities of this experiment by multiple orders of magnitude, which makes it possible to study heavier nuclei, such as the ^{90}Zr discussed in the next chapter, and will allow for thinner targets to achieve higher energy resolution.

Chapter 5. Analysis of the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B} + \gamma)$ reaction

The purpose of this chapter is to discuss the analysis of the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B} + \gamma)$ data, from unpacking the event file through the extraction of the monopole strength in the non-spin-transfer and spin-transfer channels. The data was taken during experiment e23009 in February 2024 at the Facility for Rare Isotope Beams (FRIB) at Michigan State University. The focus of the experiment was to extract the strength of the isovector monopole resonance (IVGMR) in ^{90}Y using the $(^{10}\text{Be}, ^{10}\text{B} + \gamma)$ probe system, but following the successful application of the simultaneous extraction of the spin and non-spin channels in the ^{12}C data, the isovector spin monopole strength was also extracted. The raw data was unpacked and analyzed using the GRUTinizer code package, detailed in Appendix A of Ref. [109]. GRUTinizer allows for the sorting of raw data from multiple detector systems using customizable configurations, and minimal maintenance was required for the S800-GRETINA configuration.

5.1 Experiment

The ^{10}Be secondary beam was produced by impinging a 3699 pnA, 150A MeV ^{18}O beam on a 1802.4 mg/cm²-thick carbon production target at the beginning of the ARIS fragment separator [11]. As discussed in Section 3.1.1, the ARIS fragment separator is used to purify the secondary beam, resulting in a 99% isotopically pure ^{10}Be secondary beam at 100 AMeV. The secondary beam was transported to the S800 target station in the dispersion-matched ion-optical mode [101], discussed in Section 3.2, and impinged a ^{90}Zr target with an average

Run Numbers	Target	Magnetic Rigidity (Tm)
63-109	^{90}Zr	2.89443
112-134	^{90}Zr	2.91767
143-145	C_3H_6	2.91767
147-172	^{90}Zr	2.91767

Table 5.1: Magnetic rigidity of experimental runs.

thickness of 50.6 mg/cm^2 placed at the pivot point of the S800 Spectrograph [96]. The resulting ^{10}B ejectiles were then detected in the focal plane of the S800 spectrograph, while eight GRETINA modules were placed around the target location at 90° relative to the beam direction and three GRETINA modules were placed at 58° relative to the beam direction. The γ -rays were used to tag the events of interest.

During the experiment, a section of CRDC 1 was observed to have very low detection efficiency. The rigidity of the spectrograph was adjusted from 2.89443 Tm to 2.91767 Tm to avoid the impacted region, but still impacted the analysis for low excitation energies. The run numbers and the corresponding magnetic rigidity in the S800 spectrograph are presented in Table 5.1.

5.1.1 Target Selection

While ^{90}Zr was the main target utilized in this work, three target foils were used during the experiment: a 24.5 mg/cm^2 polypropylene (C_3H_6) target, a 25.8 mg/cm^2 ^{12}C , and a ^{90}Zr target with an average thickness of 50.6 mg/cm^2 . Only data from the ^{90}Zr target and the C_3H_6 target were analyzed. The ^{12}C target was used to tune the beam, as the cross section is much higher for ^{12}C than it is for ^{90}Zr and accelerates the tuning process. The polypropylene target was used in case hydrogen was present in the zirconium target, as the $^{10}\text{Be}(p, n)^{10}\text{B}$ reaction would strongly overlap with the charge exchange reaction on zirconium and would

need to be removed. Based on the excitation-energy spectrum, it was determined that there was no detectable hydrogen present in the zirconium target, but the polypropylene data was used to test and correct the ray-tracing for the ^{90}Zr data. This correction will be discussed in Section 5.3.

Finally, the selection of the ^{90}Zr target was discussed in section ???. The target consisted of three separate foils, each measured 2.54 cm x 2.54 cm with thicknesses of 45 mg/cm², 52.3 mg/cm², and 54.5 mg/cm². The target foils were mounted in a frame as shown in Figure 5.1. The foils closest in density were placed at the center of the target frame, while the last foil was cut in half and mounted on the top and bottom of the frame. The beam size in the dispersive direction was ~ 5 cm and was centered on the middle target foils. Therefore, it was assumed that all interactions would occur within the middle foils.

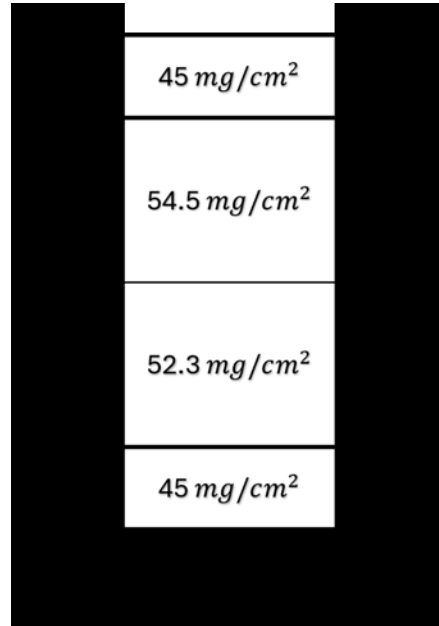


Figure 5.1: Mounting of the ^{90}Zr target foils. The dispersive direction is vertical.

5.2 Calibrations

5.2.1 CRDC Calibrations

As discussed in Section 3.2, the focal plane detector suite of the S800 Spectrograph is used to reconstruct the excitation energy spectrum and scattering angle of the ejectile ^{10}B . The raw data are converted to physical quantities by calibrating the energies and positions of the CRDCs. The calibrated focal plane coordinates are then used to reconstruct the target coordinates and excitation energy using a ray-tracing procedure described in Section 3.2.2. The CRDC energy calibrations are discussed in Section 5.2.1.1 and the position calibrations are discussed in Section 5.2.1.2. Following the calibrations, the x-spectrum for both CRDCs showed evidence of position-dependent inefficiencies. The efficiency corrections are discussed in Section 5.2.5.

5.2.1.1 CRDC Energy Calibrations

Before the CRDC events are mapped to a location, the response of the CRDC pads must first be calibrated. As described in Section 3.2.1, the interaction point in the dispersive-direction in the drift chamber is determined by fitting the charge distribution induced on the cathode pads. The signal from each pad consists of a trace of 1-4 data points called samples. The raw pad energy, E_{pad} , is obtained by summing all samples in the trace for each pad. Some traces for various pads in CRDC 2 were observed have missing pads or included pads that had significantly higher signals than neighboring pads in the same trace. Several pads were also observed to be noisy at low energies, suggesting that thresholds were too low. The pads were corrected in a multi-step procedure. First, the pad energies were normalized between

the pads, then the corrections were applied event-by-event, and then the pad energies were re-normalized with the corrections.

The raw pad energies were converted to calibrated pad energies using the relation

$$E_{pad}^{cal} = gain_{pad} \times (E_{pad} - pedestal_{pad}) \quad (5.1)$$

where $gain_{pad}$ is the scaling factor between the raw energies and the calibrated energies and $pedestal_{pad}$ is the raw energy's offset from zero. The $pedestal_{pad}$ value was determined in a dedicated pedestal run where the CRDC thresholds were set very low so that the CRDC reads the lowest signal when triggered with a pulse. The pedestal value for each pad was determined by the average value of all events associated with that pad during the run. For pads that had thresholds that were set too low, the pedestal value was manually increased to remove the very low energies peaks. The $gain_{pad}$ value was determined by gain-matching the average pedestal-subtracted pad energies, $\bar{E}_{pad}$, to the average of all pads $\bar{E}_{all\ pads}$ using the relation

$$gain_{pad} = \frac{\bar{E}_{all\ pads}}{\bar{E}_{pad}}. \quad (5.2)$$

The events used for the correction process are obtained by gating on ^{10}B events, as a normalized response to the particle of interest is necessary. The particle identification is discussed in Section 5.2.2.

After the pads are gain-matched using Equation 5.2, event-by-event corrections were applied to the traces of some events in impacted pads. These corrections were developed because the pads were acting normally except for the affected events. Events in which the pad signal is very low compared to surrounding pads were corrected by replacing the energy

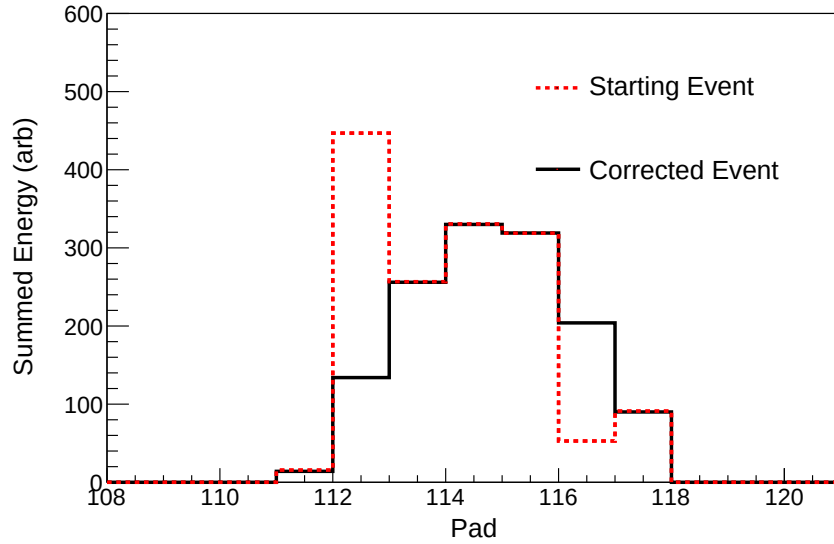


Figure 5.2: The trace for an event in CRDC 2 before (red) and after (black) the trace correction.

of the affected pad with the average energy of the neighboring pads. CRDC 2 pads 112 and 113 showed outlier samples that were much higher than the other samples. These samples were replaced with the average of the samples for the pad in the trace without the outlier. Sometimes, a pad would not have data even though the pads appeared otherwise reasonable. These pads were ignored in the fitting process for the impacted events. Figure 5.2 shows a trace before and after correction. Following the application of these trace corrections, the gain-matching was redone to incorporate the corrections. The CRDC response before and after the multi-step correction procedure for each CRDC is shown in Figure 5.3. Note that events on the far left side of each CRDC correspond to background events. Each CRDC had a number of "bad" pads that gave no signal or an unusable signal. These pads were ignored during the calibration process and correspond to the empty pads shown in Figures 5.3(c) and 5.3(d).

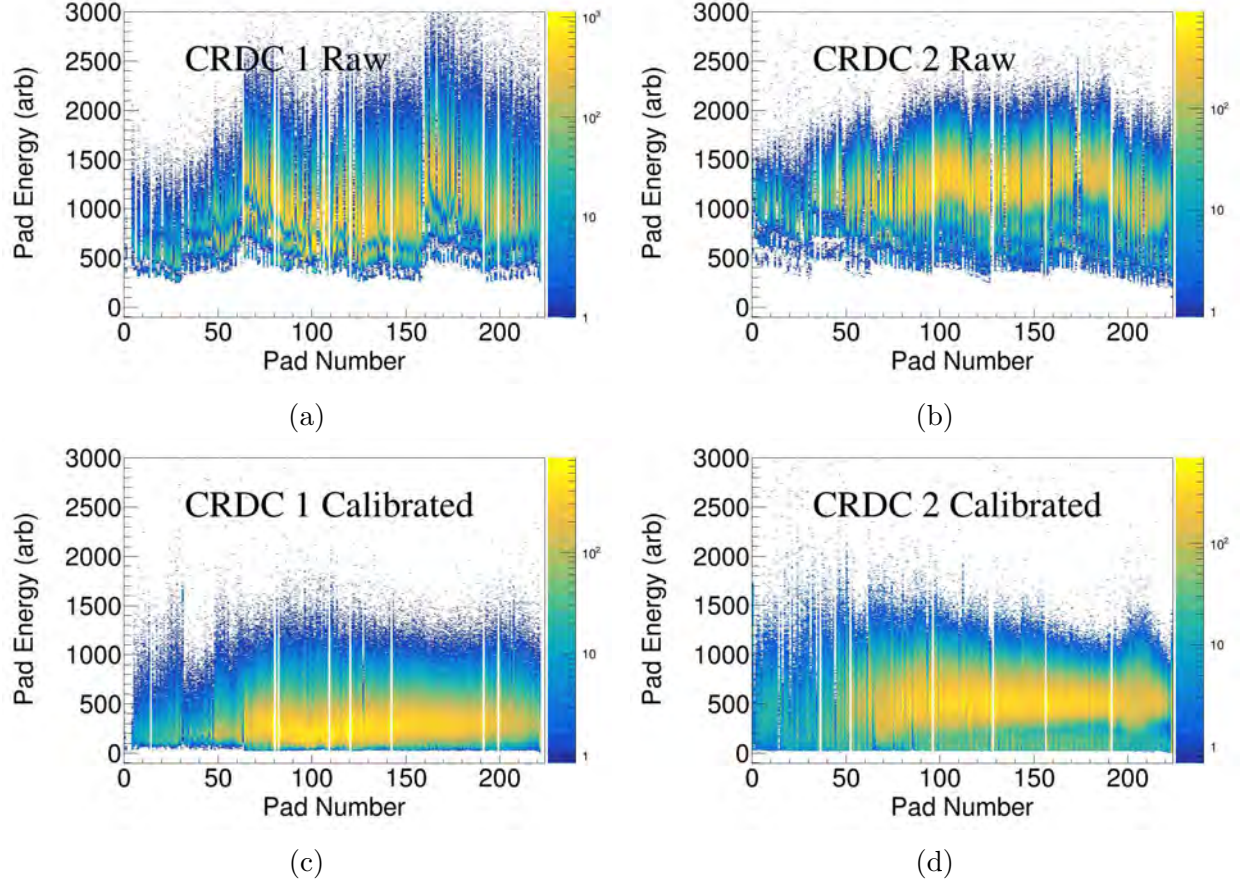


Figure 5.3: CRDC pad response for CRDC 1 and CRDC 2 before and after calibration.

5.2.1.2 CRDC Position Calibrations

The particle location detected in the focal plane is mapped to a physical position by inserting a "mask" directly upstream of the CRDC. The "mask" is a thick tungsten plate with a precision slit and hole pattern which is shown in Figure 5.4. Particles detected in the CRDC are events that pass through a hole in the mask, and the resulting 2-D spectrum in the CRDC is an impression of the mask.

The resulting spectrum is calibrated using first-order polynomials in the dispersive and non-dispersive directions by mapping the channel number of the hole observed in the CRDC to the known hole position in *mm*, where the units are pads in the dispersive (x) direction

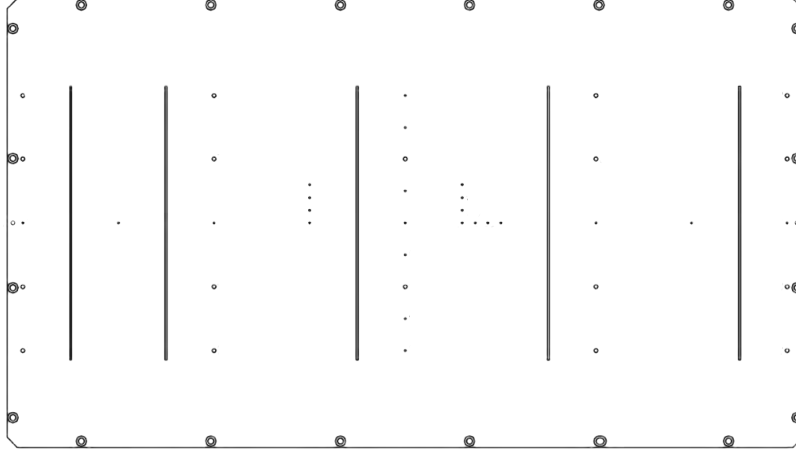


Figure 5.4: Diagram depicting the hole and slit pattern in the CRDC masks.

and ns in the non-dispersive (y) direction. The CRDCs are calibrated separately as:

$$x_{1,2}(mm) = m_{1,2}(mm/pad) \times x_{1,2}(pad) + b_{1,2}(mm) \quad (5.3)$$

$$y_{1,2}(ns) = n_{1,2}(mm/ns) \times y_{1,2}(ns) + c_{1,2}(mm) \quad (5.4)$$

The slope in the dispersive (x) direction, $m_{1,2}$, is set by the segmentation of the CRDC cathode pads to be $2.54 \text{ mm}/pad$. The slope in the non-dispersive (y) direction is determined from the drift velocity of the electrons to the anode wire. The offsets $b_{1,2}(mm)$ and $c_{1,2}(mm)$ are set so that the corner of the "L" shape in the mask is located at position $45 \text{ mm}, 0 \text{ mm}$. The results of the mask calibration for CRDC 1 is shown in Figure 5.5 and the parameter values are listed in Table 5.2.

While the x -position has a fixed geometry, the slope in the y -direction is subject to

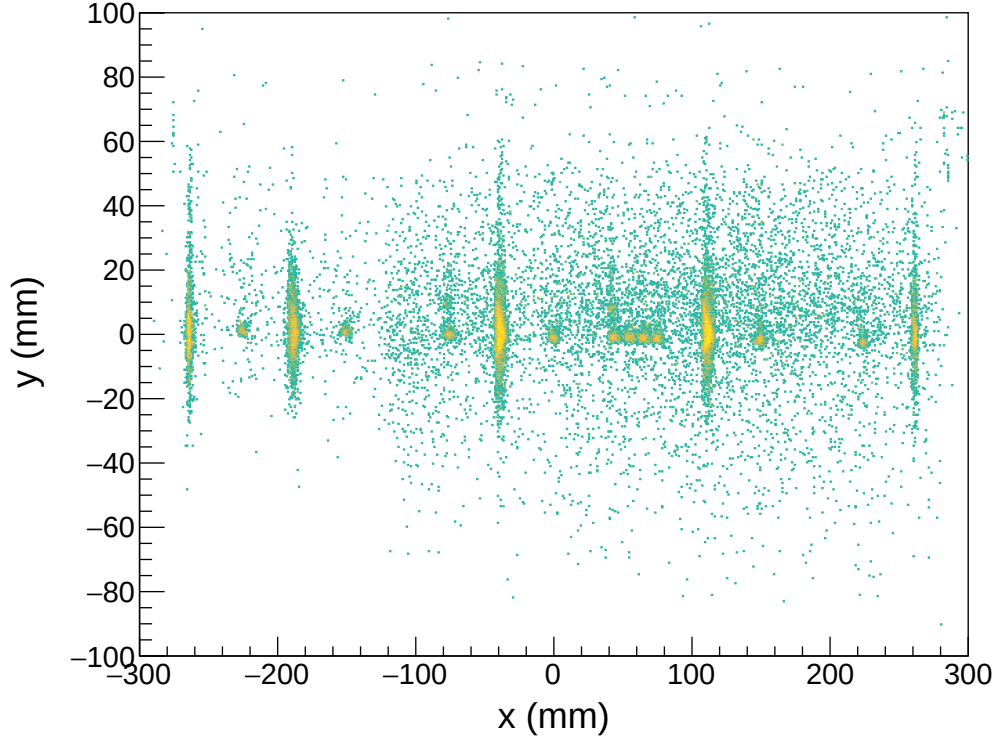


Figure 5.5: Mask calibration for CRDC 1 gated on ^{10}B . The background events are due to interactions occurring with the tungsten plate, producing light particles that can make it to the CRDC.

variability as it is determined by the drift velocity. The drift velocity is dependent upon the gas composition and pressure, as well as other experimental parameters that can vary throughout the experiment. The measured y -position of ^{10}B drifted smoothly as a function of run number, indicating the calibration drifted smoothly throughout the experiment. To correct the drift velocity, the centroid channel of the ejectile's y -distribution in each run is observed and compared to the same value in the run directly after the mask calibration. The slope is then corrected by

$$n_{corrected}(mm/ns) = n_{measured}(mm/ns) \times \frac{y_{reference}(channel)}{y_{observed}(channel)} \quad (5.5)$$

where $n_{corrected}$ is the corrected drift velocity, $n_{measured}$ is the drift velocity determined

m_1	b_1	m_2	b_2	n_1	c_1	n_2	c_2
2.54	-281.94	2.54	-279.4	-0.117	98.58	0.106	-103.82

Table 5.2: Mask calibration parameter values obtained from fitting the CRDC mask measurement runs.

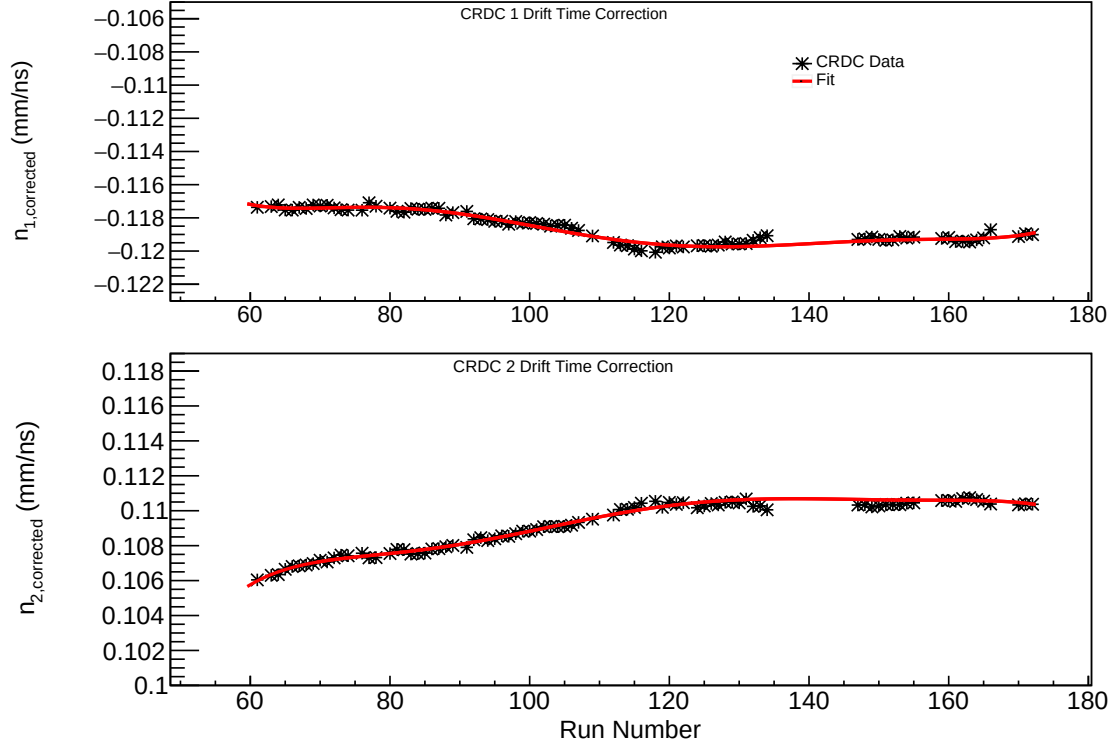


Figure 5.6: Fit of CRDC TAC data to track changes in drift velocity in the CRDC chamber over the course of experiment e23009.

by the mask calibration run, $y_{reference}$ is the y -position in the run directly after the mask calibration run, and $y_{observed}$ is the y -position in the run of interest. The result of the corrections using the ^{90}Zr target are shown in Figure 5.6. The corrections for each CRDC were then fit with a fifth order polynomial, and the final drift velocity for each detector was determined by the result of the respective fit for each run.

The ray tracing described in Section 3.2.2 was used to determine the target position parameters from the focal plane positions and angles. However, due to a hardware issue before the experiment, the CRDCs were in less than optimal condition during the experiment

and required an additional position-dependent efficiency correction which will be detailed in Section 5.2.5.

5.2.2 Particle Identification

The ^{10}B ejectile was identified in the focal plane of the S800 Spectrograph using a particle identification plot. This is achieved by plotting the energy deposited in the focal plane scintillator as a function of the time of flight. Isotopes with different masses will have different time of flight values, while the energy loss through the scintillator is proportional to the square of the proton number as shown in Equation 3.3. Plotting them against each other allows for the identification of various isotopes. The energy loss in the scintillator and the time of flight can each be correlated with the position and angle of the event in the focal plane. To achieve the best resolution, these correlations must first be corrected. However, before the time of flight can be corrected for correlations, a timing jitter observed in some runs was corrected.

5.2.3 RF Jitter Correction

The time-of-flight (ToF) was determined by the time difference between the RF signal from the accelerator and the timing signal produced by the focal plane scintillator. While the ToF from the RF signal is typically bi-modal with the ToF split into two "bands", a jitter in the the timing signal was observed during about a quarter of the experimental runs, shifting the ToF for all events for some length of time by ~ 5 ns. When the jitter occurred and its duration were seemingly random, making it difficult to predict. An investigation revealed that the jump in ToF came from the RF signal, but the exact cause of the jitter

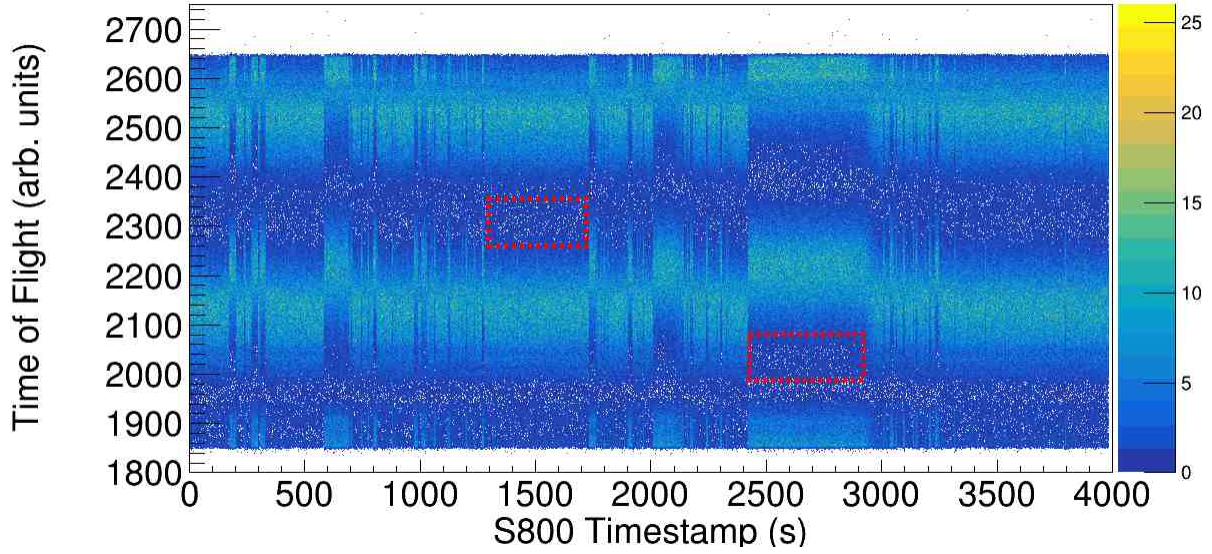


Figure 5.7: The time of flight as a function of S800 timestamp for experiment run 84. The random jump in the time of flight is clearly observed over the course of the run. The red boxes indicate noise regions removed during the identification of shift events.

was not found. The uncorrected ToF as a function of the S800 timestamp for run 84 is shown in Figure 5.7. The shifts in the timing data complicated the particle identification, as it removed good events in the ToF windows and added bad events into those windows, and therefore required correction.

An event-by-event correction was developed to determine the start and end of the shifts so a correction could be applied to all events within the shift. To simplify the correction process, only one band in each run was investigated. The lower band was the optimal choice, as the shift caused events in the upper band to wrap around the timing band as observed in Figure 5.7. These wraparound events were shifted to the correct band after the jitter was corrected. Due to significant variation in the timing value event-by-event, the average of every 20 events in the band was used to identify shifted events, as shown in black in Figure 5.8. The midpoint between the peaks served as the classification point; events with a higher ToF than the midpoint were shifted, while those below were not shifted.

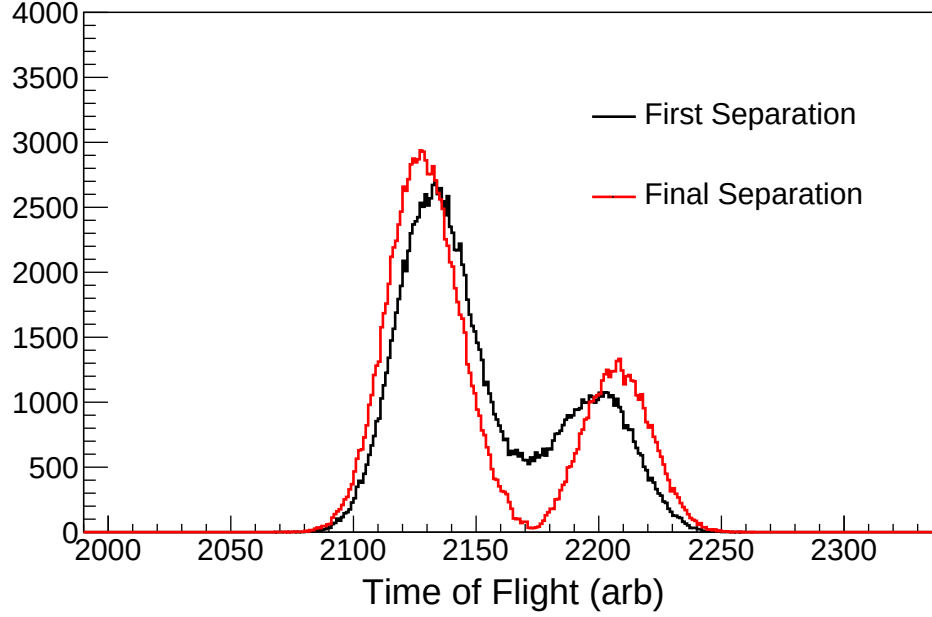


Figure 5.8: Average time of flight of every 20 events before (black) and after (red) removing noise events.

To remove noise events present on the edges of the ToF band, additional timing cuts were applied event-by-event based on the average in black from Figure 5.8. If the event was in a non-shifted region, the higher ToF events, indicated by the top left red box in Figure 5.7, were removed. For shifted events, the lower ToF events indicated by the bottom right red box were removed. The resulting averaged timing distribution for the lower band in run 84 is shown in red in Figure 5.8, showing clear peak separation. The midpoint between the peaks of the final spectrum is the classification point, and the correction applied to the shifted events is defined as the ToF difference between the peaks. The beginning and end of a shift is determined by the first averaged event above and below the classification line, respectively. It was observed that the rise-time and fall-time of the shifts is approximately 10 events long, so the 10 events before the start and end of the shift were removed. The results of the correction to the Rf vs Timestamp plot are shown in Figure 5.9. In total, 1.05% of total events were lost in this procedure.

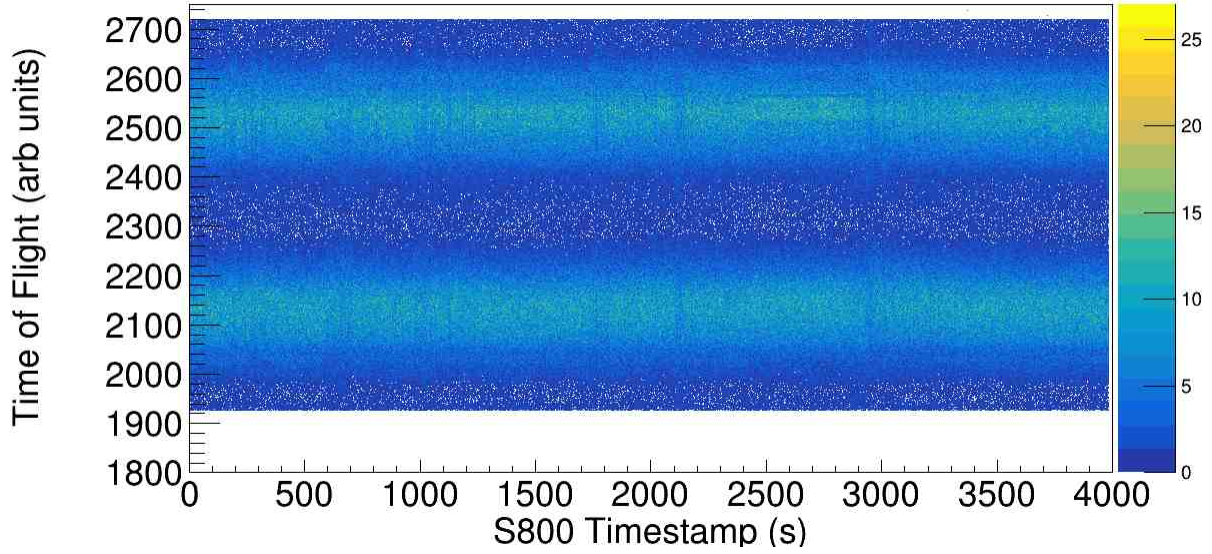


Figure 5.9: The time of flight as a function of the S800 timestamp corrected for the RF jitter for run 84.

5.2.4 PID Corrections

The S800 Spectrograph was tuned to measure the ejectile ^{10}B in the focal plane. In addition to the ^{10}B , ^{10}Be was clearly visible in the focal plane, along with ^6Li and α particles from the α -decay of ^{10}B above 4.46 MeV (Figure 1.5). To separate the ^{10}B from the other fragments, the energy-loss vs time-of-flight particle-identification technique was applied.

As discussed in Section 3.1.2, the energy loss of a particle through a medium is proportional to the proton number squared (Z^2). Therefore, by measuring the energy deposited in the scintillator, isotopes with different proton values can be separated. Analyzing the time-of-flight measurement yields the velocity, which by Equation 3.2 provides information about the magnetic rigidity. By plotting ΔE vs ToF in Figure 4.2, the ^{10}B can be isolated.

The energy loss (ΔE) and ToF were observed to be correlated with the focal plane position and angle. To separate ^{10}B from the other fragments, the correlations must be removed. The correlation between ToF and xfp was found to be a linear, while the correlation

between ToF and afp required a fourth order polynomial for correction. The correction for the x-position was applied first, and the resulting spectrum was used to determine the ToF vs afp correction. ToF vs xfp and ToF vs afp before and after correction are shown in Figure 5.11.

The same process was used to remove the correlations between ΔE vs xfp and ΔE vs afp . The correlation was observed to be different between heavier and lighter ions detected in the focal plane. As a result, the focal plane energy region was split into two "zones", one containing ^{10}B and one containing ^6Li and α , and were calibrated separately. The cut point between the regions was $\Delta E = 510$. The xfp and afp corrections each used fourth order

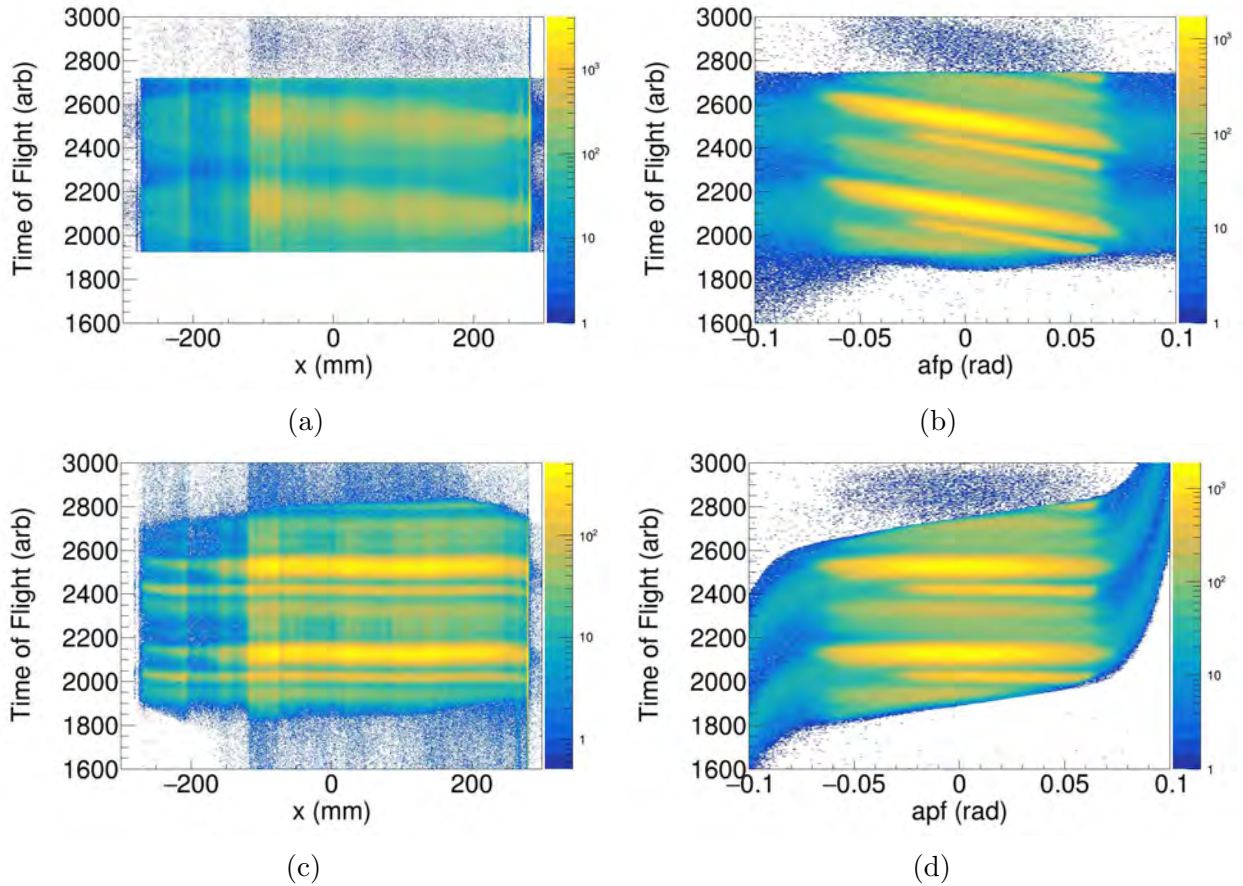


Figure 5.10: Time of flight vs dispersive position and angle before and after correcting correlations. (a) uncorrected Time of flight vs x position, (b) uncorrected Time of flight vs afp , (c) corrected Time of flight vs x position, and (d) corrected Time of flight vs afp .

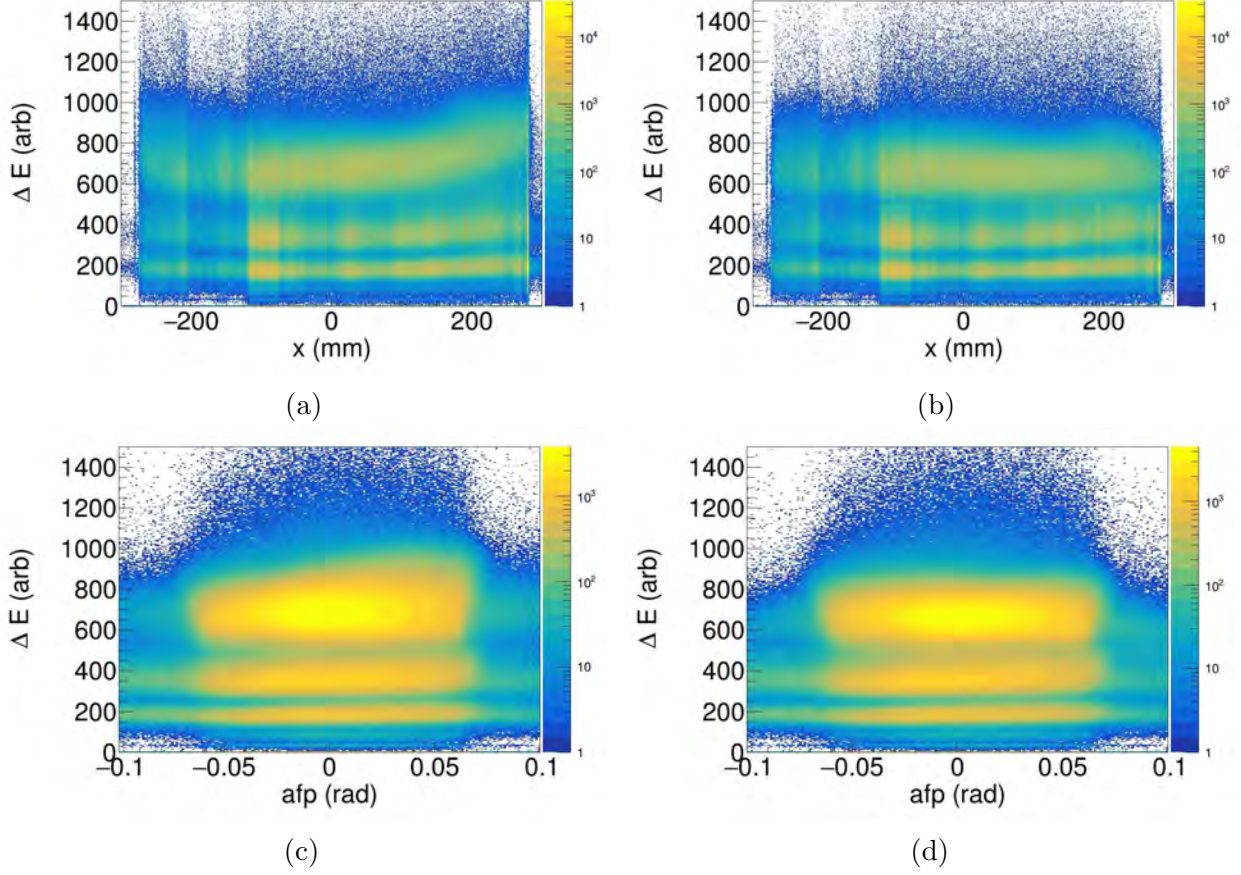


Figure 5.11: Deposited energy, ΔE , in the focal plane scintillator. (a) uncorrected ΔE vs x position, (b) uncorrected ΔE vs afp, (c) corrected ΔE vs x position, and (d) corrected ΔE vs afp.

polynomials for correction in both regions. Figure 5.11 shows ΔE vs xfp and ΔE vs afp before and after correction.

The particle identification plot following ToF and ΔE corrections are shown in Figure 5.12. The ToF and ΔE both use a width of 3σ for the ^{10}B gate. The plot provided sufficient separation of the reaction fragments to isolate the ^{10}B events of interest.

5.2.5 CRDC Efficiency Corrections

An inefficient region in CRDC 1 below pad 63 was observed during the experiment, which motivated a change in the magnetic rigidity setting of the S800 during the experiment. The

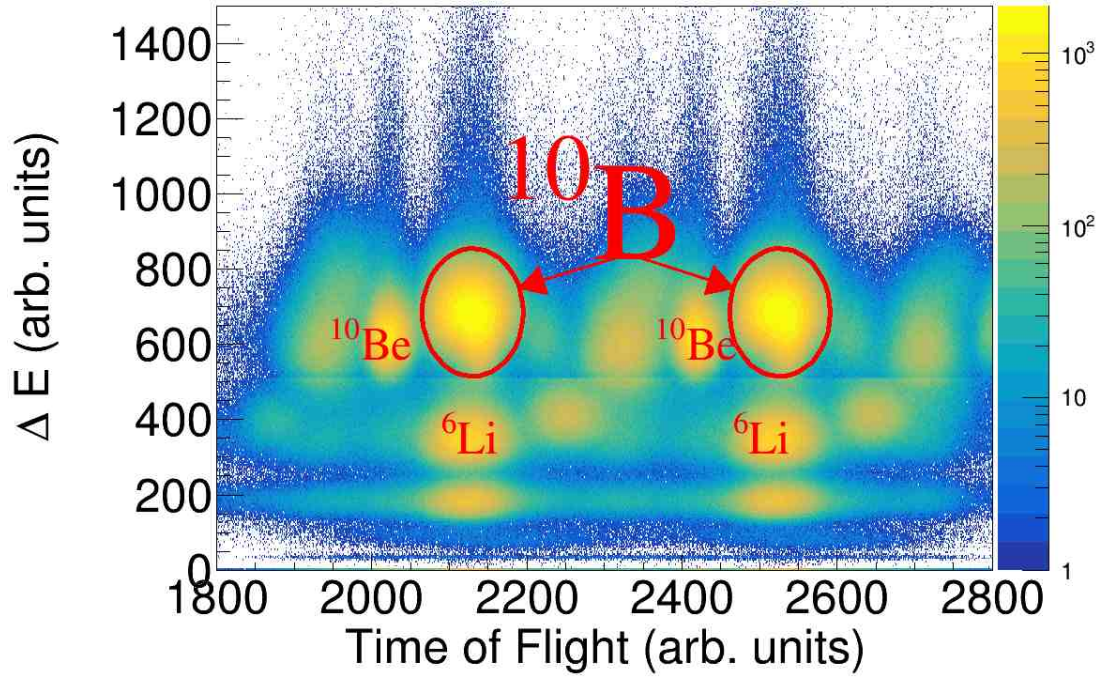


Figure 5.12: Particle identification plot used to identify ^{10}B during experiment e23009. Two timing bands are from the RF signal. It was decided not to collapse the timing signal into one timing band and make two ^{10}B gates.

inefficiency region is clearly observed in 5.3(c). The x-spectra of ^{10}B in the drift chambers before and after the rigidity shift are shown in Figure 5.13. While a relatively smooth x-distribution was expected in ^{10}B , both detectors show localized minima and maxima that are indicative of position-dependent inefficiencies in each detector. As the measured experimental resolution of the ^{90}Y excitation energy is just over 3 MeV, these local fluctuations are much narrower than expected. When a pad experiences lower detection efficiency than neighboring pads, it will result in fewer events being mapped to the impacted pad, leading to event buildup in nearby pads. Misplacing an event by even a few pads impacts the measured focal plane angle, and, therefore, the ray-traced parameters and the reconstructed excitation-energy spectrum. The issue is compounded when an event is misplaced in both detectors. The effect of the observed inefficiencies on the *ata* vs *Ex* plot in ^{90}Zr following

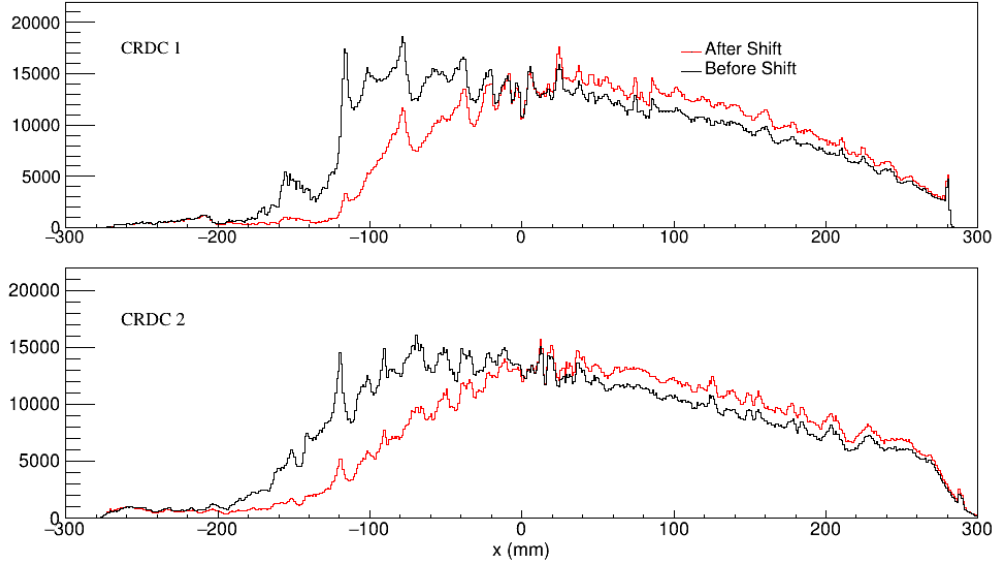


Figure 5.13: x-position of CRDC 1 (top) and CRDC 2 (bottom) gated on ^{10}B before (black) and after (red) the rigidity change.

energy reconstruction is shown in Figure 5.14(a). The bent vertical lines are due to issues in CRDC 1 while the diagonal lines are due to issues in CRDC 2.

Since "good" events necessitate signals from both CRDCs, efficiency issues in one CRDC will impact the shape of the measured distribution in the other CRDC. Therefore, separate PID plots were made gating only on events using CRDC 1 + scintillator and CRDC 2 + scintillator instead of CRDC 1 + CRDC 2. The reaction setting could not be used to develop this correction, however, as any correction developed using ^{10}B would need to make assumptions about the distribution shape, potentially adding artificial resonances to the analysis. Instead, ^{10}Be observed in the focal plane was chosen as the optimal choice to develop the efficiency correction, as it also produces a smooth x-distribution in both CRDCs and was present across the entire focal plane. In addition, since the proton number is only different by one, the detection efficiency would be the most similar to ^{10}B . The ^{10}Be spectrum in both CRDCs is shown in Figure 5.15. The CRDC 1 spectrum in red shows a low efficiency

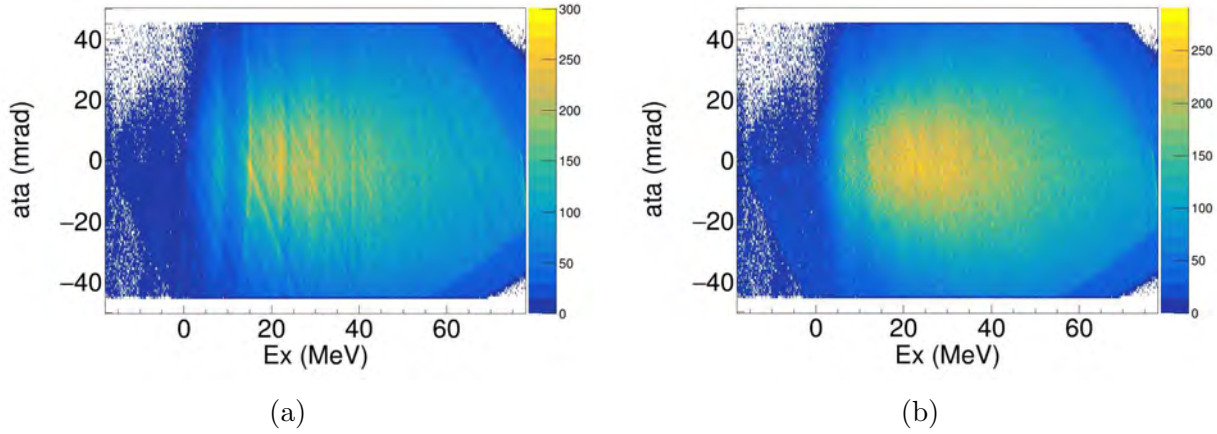


Figure 5.14: Dispersive angle (ata) as a function of excitation energy in ^{90}Y (a) before and (b) after applying the efficiency correction.

region between -205 mm and -118 mm, event buildup between -117 and -76 mm, and local variations along the whole focal plane. CRDC 2 shows local variations along the x-spectrum.

To isolate the ^{10}Be events in each CRDC, the PID plots for CRDC 1 and CRDC 2 must be corrected for position and angle in the focal plane, as was done for ^{10}B as discussed in Section 5.2.2. However, since each PID can only rely on a single CRDC, an additional x-position was required to make the dispersive angle. Instead of the second drift chamber, the position in the scintillator can be used for this purpose. The scintillator position was obtained by mapping the time difference between scintillator PMTs to the projected position in the scintillator using the relation

$$x_{scint\ projected} = x_{fp} + L_{C1 \rightarrow Scint} \times \tan(afp) \quad (5.6)$$

where $x_{scint\ projected}$ is the projected scintillator position, x_{fp} is the x-position in CRDC 1, afp is the dispersive angle, and $L_{C1 \rightarrow Scint}$ is the distance between CRDC 1 and the scintillator and is defined to be 1483.0 mm. The scintillator x-position vs PMT time difference plot is shown in Figure 5.16. The fit-line shown in the figure was used to map the measured

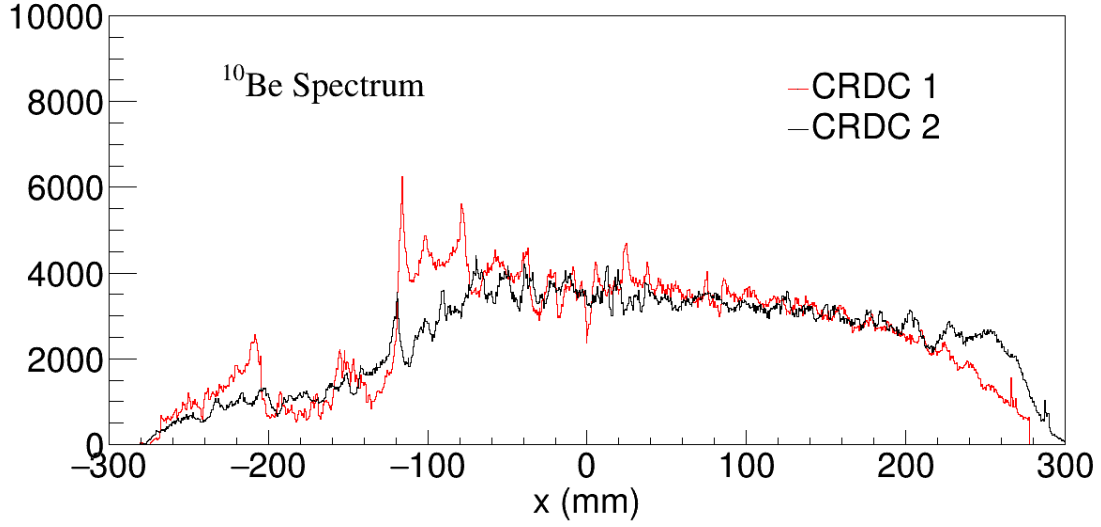


Figure 5.15: ^{10}Be spectrum for CRDC 1 (red) and CRDC 2 (black), gated on the CRDC 2 corrected PID and CRDC 1 corrected PID, respectively.

time difference to the scintillator x-position. The fit line function is

$$x_{scint}(mm) = 124650 + 1723.73 \times tdiff + 9.43378 \times tdiff^2 + 0.0256814 \times tdiff^3 + 3.48525e-05 \times tdiff^4 + 1.88546e-08 \times tdiff^5 \quad (5.7)$$

where $tdiff$ is the PMT time difference. The position resolution in the scintillator was determined to be greater than 5 cm. Although not ideal, it was adequate for this purpose.

The PID correction process discussed in Section 5.2.2 was used to remove correlations from the PID plots for each CRDC, as the x-position and angle used for each CRDC plot were observed to be correlated with the time of flight and scintillator energy. The resulting PID plots are shown in Figure 5.17. The gates used for ^{10}Be were intentionally narrowed to limit the intrusion of other fragments in the gate, as the separation in the PID plots was limited.

The efficiency correction requires two components: a global correction function to deal

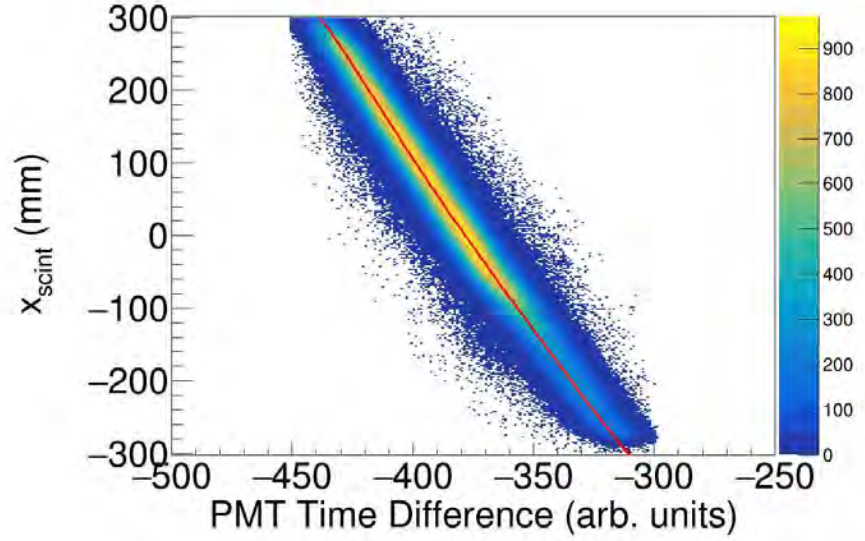


Figure 5.16: Projected scintillator position as a function of PMT time difference, gated on ^{10}Be events. The red line was used to project the time difference to x-position in the scintillator.

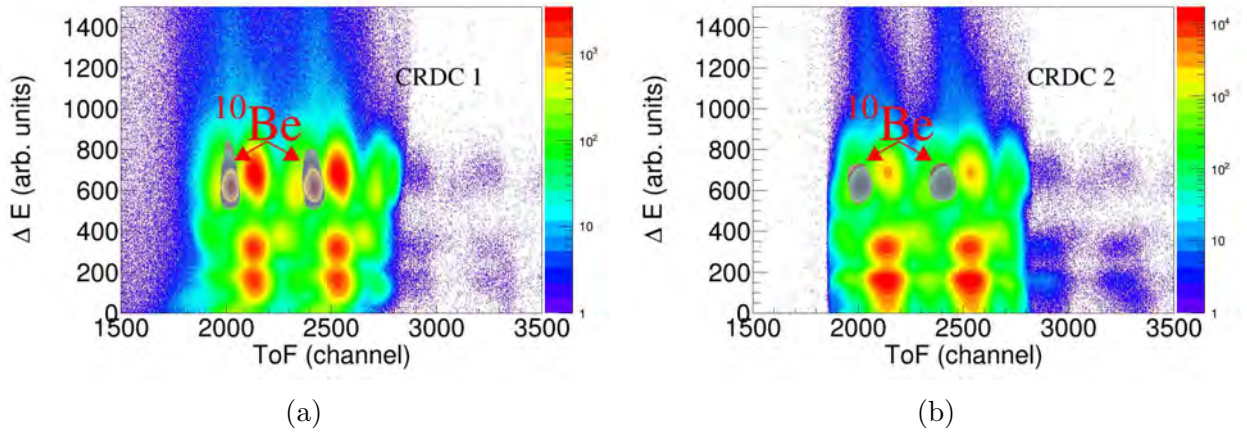


Figure 5.17: The Corrected PIDs for (a) CRDC 1 and (b) CRDC 2. The gate used for ^{10}Be in each plot is off-colored and labeled.

with the large inefficient regions along the entire detector, and a local correction focused on correcting local event buildup. The global correction function for each detector was obtained by first investigating the broad inefficiencies across each detector given by the reconstructed events. To correct CRDC 1 (CRDC 2), the PID corrected by using CRDC 2 (CRDC 1) is used, and CRDC 1 (CRDC 2) events are reconstructed using CRDC 2 (CRDC 1) and the projected scintillator position, x_{scint} , from Equation 5.7. First, the broad correction functions are made for each CRDC using the ratio

$$eff(\%, x)_{broad, C1} = \frac{N(x)_{Coinc, C1 projected}}{N(x)_{C1 all, C1 projected}} \bigg|_{C2} \quad (5.8)$$

$$eff(\%, x)_{broad, C2} = \frac{N(x)_{Coinc, C2 projected}}{N(x)_{C2 all, C2 projected}} \bigg|_{C1} \quad (5.9)$$

where the subscripts C1 and C2 represent CRDC 1 and CRDC 2, $eff(\%, x)_{broad}$ is the broad correction function, $N(x)_{Coinc, projected}$ is the reconstructed x-position for the respective detector when both CRDCs fire, and $N(x)_{all, projected}$ is the reconstructed x-position singles events. $N(x)_{Coinc, projected}$ and $N(x)_{all, projected}$ are both produced by gating on the PID using the opposite CRDC as labeled in each equation. The events for each CRDC are reconstructed using the equations

$$x_{C1 reconstructed} = x_{scint} - L_{C1 \rightarrow Scint} \times \frac{x_{scint} - x_{C2}}{L_{C2 \rightarrow Scint}} \quad (5.10)$$

$$x_{C2 reconstructed} = x_{scint} - L_{C2 \rightarrow Scint} \times \frac{x_{scint} - x_{C1}}{L_{C1 \rightarrow Scint}} \quad (5.11)$$

where the subscripts C1 and C2 represent CRDC 1 and CRDC 2, x_{scint} is the scintillator position calculated using Equation 5.7, $L_{C1 \rightarrow Scint}$ is the distance from CRDC 1 to the Scin-

tillator, $L_{C2 \rightarrow Scint}$ is the distance from CRDC 2 to the scintillator, and x is the x-position of the designated CRDC. $L_{C1 \rightarrow Scint}$ was 1483.0 mm and $L_{C2 \rightarrow Scint}$ was 410.0 mm. By taking the ratio of events reconstructed using the other CRDC and the scintillator, only the inefficiency of the detector of interest will remain. The results of the broad inefficiency functions for both CRDCs are shown in Figure 5.19 (a).

Next, since the reconstructed events have poor resolution (~ 25 mm for CRDC 2, ~ 75 mm for CRDC 1), a fine structure correction was determined that matches the broad distribution when smeared with the resolution of the reconstructed events. This was straightforward for CRDC 2, as the broad efficiency function was flat across most of the focal plane. As a result, a global efficiency of 0.94 was used for CRDC 2. To produce the "corrected" ^{10}Be x-spectrum, the CRDC 2 x-spectrum using the same gate was divided by the global efficiency, then smeared using a Gaussian function with a FWHM of 8 mm to remove local variations. There are still issues on the left hand side of CRDC 2, but only the region above about -115 mm is used during the experiment and was the focus of the correction. The global efficiency function was more difficult for CRDC 1, as the efficiency varied widely throughout the focal plane (Figure 5.19 (a)). A correction function was developed that, when smeared with the resolution, matched the broad correction function in red in Figure 5.19 (a). The efficiency function used is shown in Figure 5.19 (a) as the dotted red line, and the comparison with the broad correction function is shown in Figure 5.18. The coincident x-spectrum for CRDC 1 was divided by the efficiency function, and then smeared with the resolution of the reconstructed events. However, as CRDC 1 had large sections of poor efficiency and corresponding sections of event buildup, an additional correction step was required. The final corrected spectrum was produced by fitting the scaled and smeared spectrum with a sixth order polynomial.

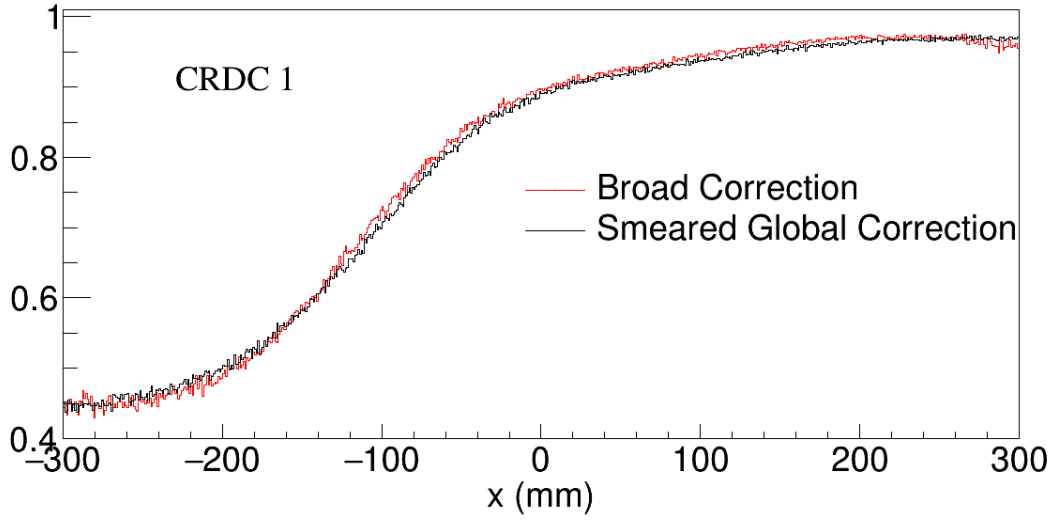


Figure 5.18: Comparison between the broad correction determined using Equation 5.8 and the smeared global correction.

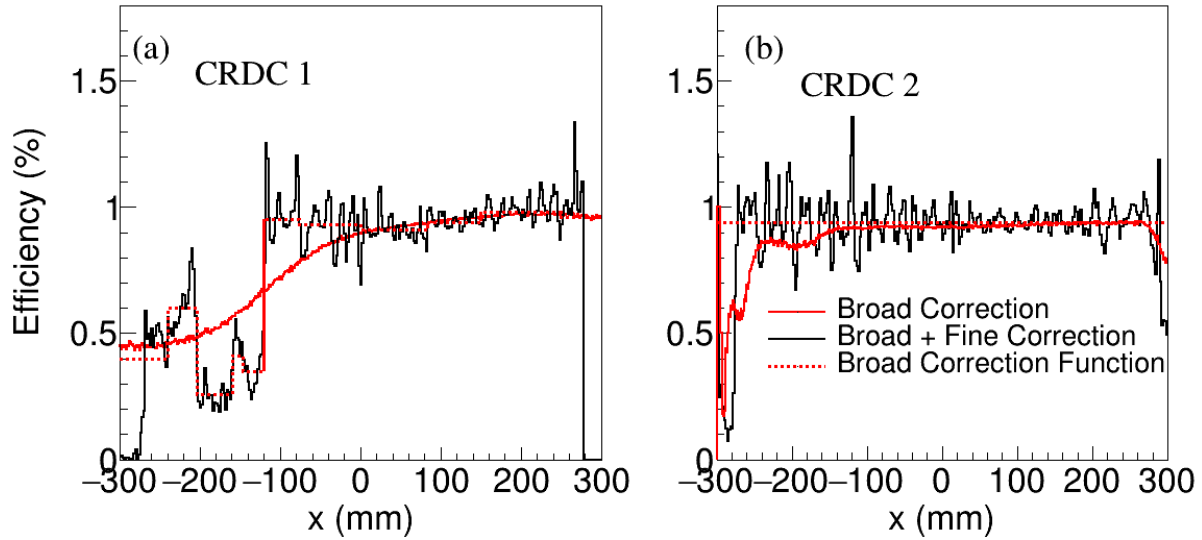


Figure 5.19: Efficiency for (a) CRDC 1 and (b) CRDC 2. The solid red line is the broad correction function, the red dotted line is the global correction, and the black is the combination of the global correction and the fine corrections.

The final position-dependent efficiency corrections were calculated by dividing the x-spectrum for each CRDC with the respective corrected spectrum (CRDC 2) or polynomial fit (CRDC 1). The resulting position-dependent efficiency corrections are shown in Figure 5.19 (b). To validate the results of the CRDC 1 efficiency correction, the CRDC 1 x-spectrum corresponding to the events in the numerator of Equation 5.8 can be corrected and smeared, and then compared to the reconstructed CRDC 1 events from the $N(x)_{C1all,C1projected}$ spectrum. By correcting the coincident spectrum for CRDC 1, all events missing from that spectrum when gating on CRDC 2 will be accounted for. Then, by smearing with the resolution of the reconstructed CRDC 1 events, the shape of the distribution should match the reconstructed spectrum for CRDC 1 using CRDC 2 and the focal plane scintillator. This comparison is shown in Figure 5.20 and shows that the correction reproduces the reconstructed spectrum well.

To incorporate the efficiency corrections for both CRDCs on an event-by-event basis, a scale factor was obtained. The scale factor was defined as

$$\epsilon_{scale\ factor} = \frac{1}{Eff_{CRDC1}(x_{C1}) * Eff_{CRDC2}(X_{C2})} \quad (5.12)$$

where $Eff_{CRDC1}(x_{C1})$ is the CRDC 1 efficiency correction for the x-position in CRDC 1 and $Eff_{CRDC2}(X_{C2})$ is the CRDC 2 efficiency correction for the x-position in CRDC 2. The result of the CRDC corrections on the ata vs Ex plot is shown in Figure 5.14(b). The results of the corrections show a significant reduction in local variations in both CRDCs, as well as the correction of the very inefficient regions that were present in CRDC 1.

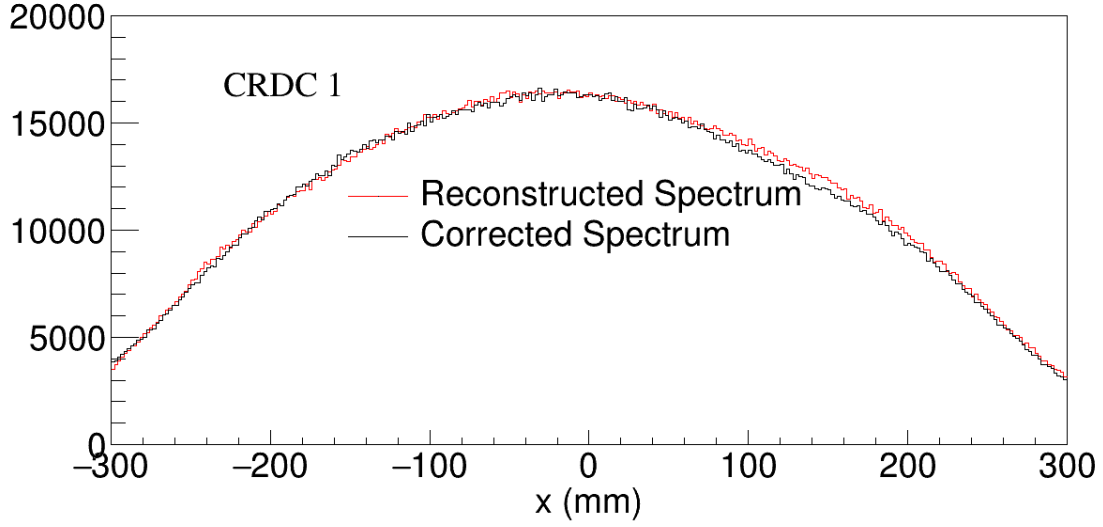


Figure 5.20: The comparison between the CRDC 1 reconstructed spectrum and the corrected and smeared x-spectrum.

5.2.6 GRETINA Corrections

GRETINA was used to tag the events of interest by detecting the γ rays from the decaying ^{10}B . The efficiency calibration for GRETINA was detailed in Section 3.3.3. As the ejectiles from the reaction are traveling at about 43% the speed of light, the lab frame energy of the γ ray is reconstructed using a Doppler correction as discussed in Section 3.3 using Equation 3.30. To perform this correction, the direction of the ejectile must be taken into account. If the beam is perfectly perpendicular to the target, no correction is necessary. However, when the averaged angle of the beam on target has a slight deviation, a correlation will be seen between the azimuthal scattering angle and the Doppler-corrected energy. To correct the correlation, the angle in Equation 3.30 between the γ ray and the emitting particle is calculated using the equation

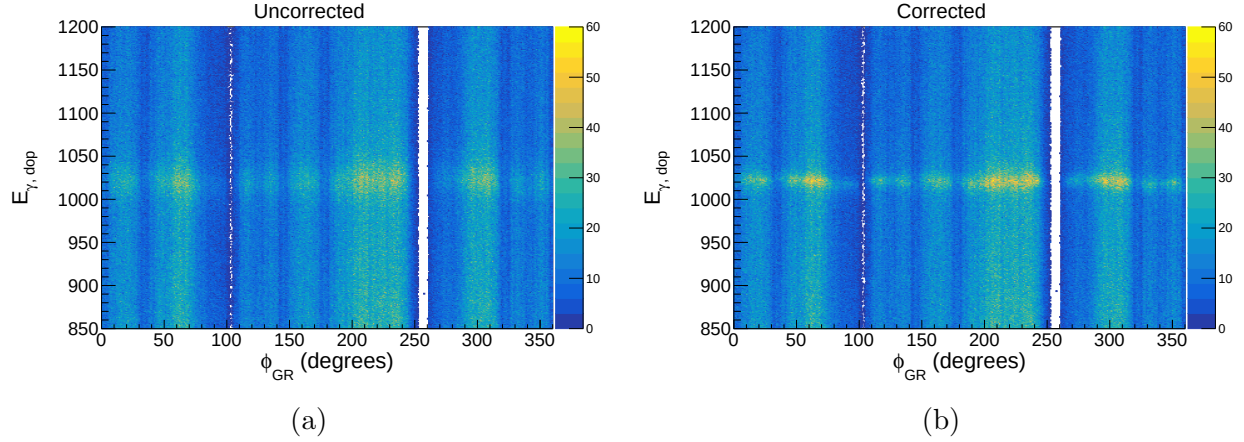


Figure 5.21: The Doppler correction as a function of azimuthal angle measured in GRETINA for (a) Doppler correction assuming beam perpendicular to target, and (b) Doppler correction after correcting the angular correlation.

$$\cos(\theta) = \sin(\theta_{GR}) \times \sin(\theta_{S800}) \times \quad (5.13)$$

$$\left(\sin(\phi_{GR}) \times \sin(\phi_{S800}) + \cos(\phi_{GR}) \times \cos(\phi_{S800}) + \sin(\theta_{GR}) \times \sin(\theta_{S800}) \right). \quad (5.14)$$

where the subscript $S800$ refers to the angle produced by ray tracing through the spectrograph and GR refers to the angle reconstructed in GRETINA. This correction is applied on an event-by-event basis during the Doppler correction. The results of the correction on the 1022 keV γ -ray peak are shown in Figure 5.21(b). By applying the correction, the resolution of the peak improves from a FWHM value of 34.6 keV before correction to a value of 19.1 keV after the correction was applied. This increase is evident when comparing 5.21(a) to 5.21(b).

As shown in Figure 5.23, the Doppler-correction needed a slight adjustment as the 1022 keV photopeak wasn't centered at the correct energy. Furthermore, a slight shift in the

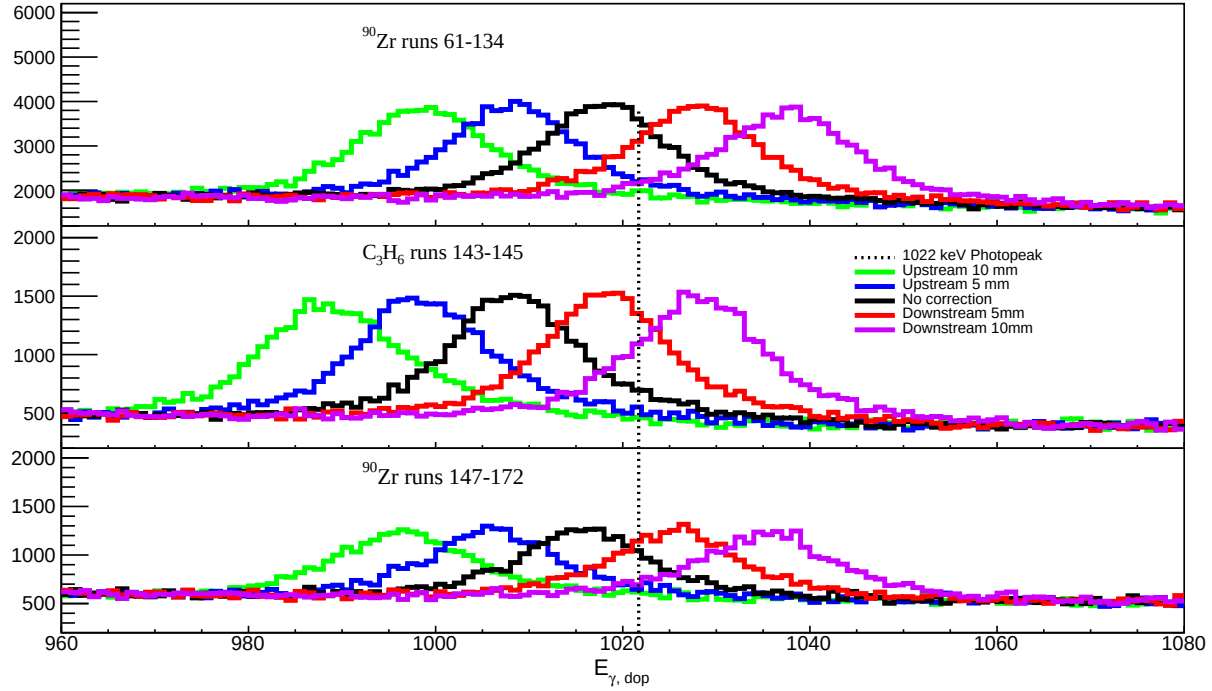


Figure 5.22: 1022 keV photopeak during runs where the target remained stationary

location of this photopeak was observed during the experiment. These shifts correspond to target changes during the experiment. Because the Doppler-corrected energy is proportional to $\cos(\theta)$ as described by 3.30, shifting the target upstream or downstream will change the scattering angle of the γ ray, resulting in the Doppler-corrected energy increasing or decreasing, respectively. To determine the z-offset of the target, the assumed target position in the analysis software was varied between -2 cm and 2 cm in 5 mm increments. The resulting Doppler-corrected energy spectra between target changes, with the position varied between -1 cm and 1 cm, are shown in Figure 5.22. The resulting 1022 keV photopeak centroid location was determined for each offset using a Gaussian fit. The centroids were plotted as a function of run number and fit with a first order polynomial. The target offset was determined by setting the offset such that the photopeak energy was 1021.7 keV. The position correction for each set of runs is given in Table 5.3

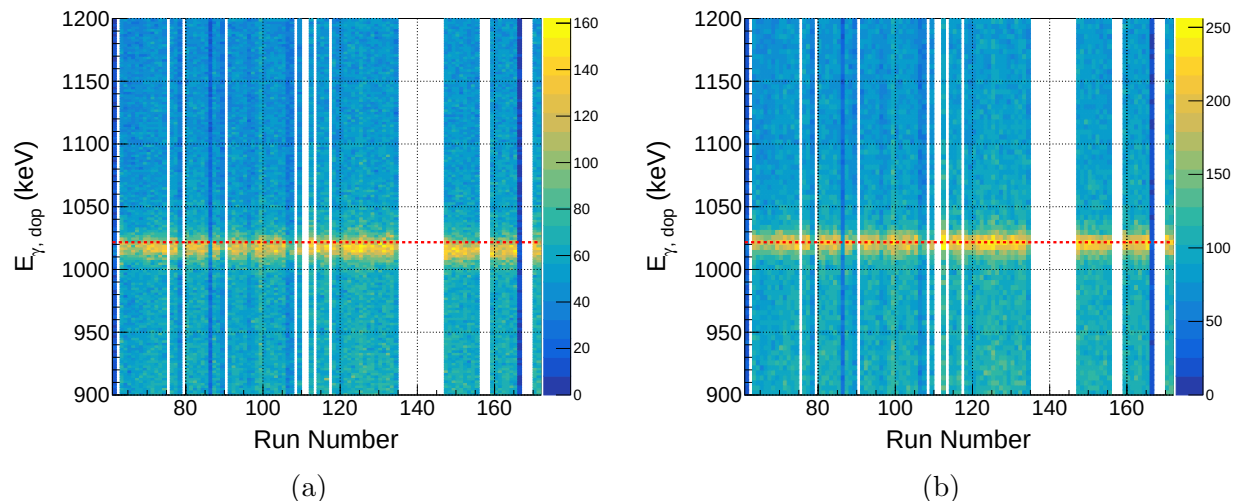


Figure 5.23: Doppler-corrected γ -ray energy spectrum of the ^{90}Zr data as a function of run number, zoomed in on the 1022 keV photopeak (a) before applying the z-position correction and (b) after applying the z-position correction. The red line through the spectra indicates the 1022 keV photopeak.

Runs	Target	Position Correction
61-134	^{90}Zr	1.8767 mm
143-145	C_3H_6	6.578 mm
147-172	^{90}Zr	2.8113 mm

Table 5.3: Position corrections along the beam axis determined for each group of runs between target changes.

5.3 Excitation Energy Reconstruction

Following calibration, the focal plane coordinates are mapped to the target coordinates using the ray-tracing procedure described in Section 3.2.2. The target coordinates are then used to reconstruct the excitation energy of ^{90}Zr using a "missing mass" calculation as described in Section 3.2.3. Correlations were observed in the data between bta and yta . A fourth order polynomial was used to correct the correlation. The bta vs yta plots before and after the correction are shown in Figure 5.24. Note that only the region between $-6 < yta < 6$ was used in the correction and for the analysis, as including larger yta values increased

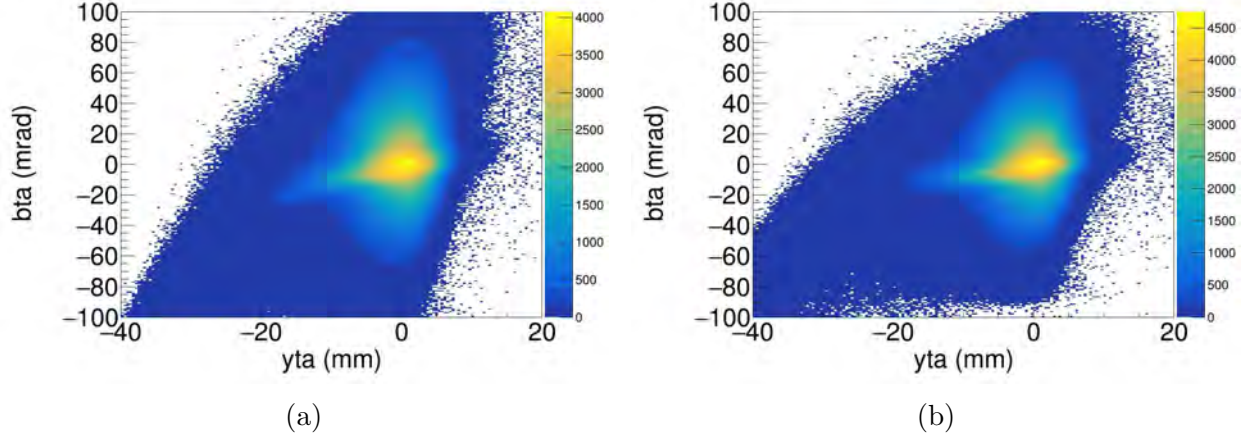


Figure 5.24: bta vs yta (a) before correction and (b) after correction. Only yta values between $-6|yta|6$ were used in the analysis and used for the correction.

the number of background events. Correlations were also observed between Ex , ata , and bta . The polypropylene data, using hydrogen kinematics, was helpful in correcting these correlations, as the $^{10}\text{Be}(p,n)$ reaction is sensitive to the scattering angle. A scale factor of 0.85 was applied to both ata and bta . The results before and after the correlation correction are shown in Figure 5.25.

The $^{12}\text{C}(\text{g.s.}) \rightarrow ^{12}\text{B}(\text{g.s.})$ transition in the polypropylene data (analyzed using ^{12}C kinematics) was found to be centered at 10.7 MeV. A shift in excitation energy can occur by assuming that $B\rho$ is fixed and correct, while the kinetic energy of the particles will vary due to reactions occurring throughout the target. The transition to $^{12}\text{B}(\text{g.s.})$ is isolated in the data by gating on events below 15 mrad, as events at higher angles are dominated by the $^{10}\text{Be}(p,n)$ interaction. As the use of two different rigidity settings throughout the experiment was necessary, an adjustment to the correction is required for the rigidity not used during the polypropylene runs. To determine this adjustment, the $E_{\gamma,lab}$ vs $E_x(^{90}\text{Y})$ plots before and after the correction were compared. Decay channels in the γ -ray spectrum of the product nucleus should open and close at the same excitation energy. The correction applied

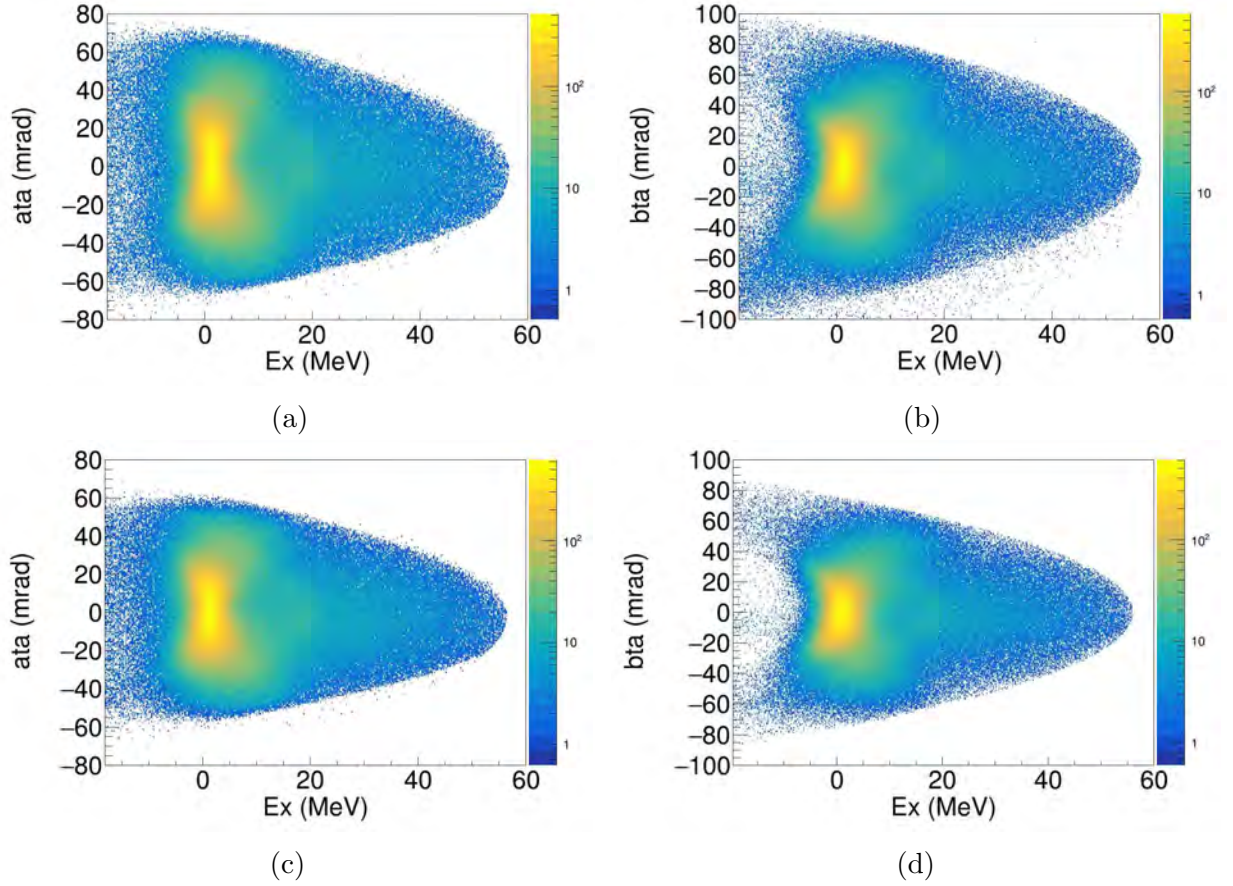


Figure 5.25: Target coordinate scattering angles vs excitation energy before and after removing correlations. (a) ata vs Ex before correction, (b) bta vs Ex before correction, (c) ata vs Ex after correction, (d) bta vs Ex after correction. The missing events near 0 MeV and 0° was due to the low efficiency section of CRDC 1.

to the data using the first rigidity setting was reduced to 9.7 MeV to align these spectra. The excitation energy spectrum for ^{90}Y was shifted down by 0.50 MeV to account for the difference in energy loss between the polypropylene target and the ^{90}Zr target. Data below an excitation energy of 15 MeV were removed from the analysis for runs before the rigidity shift as the large efficiency corrections that had to be applied have significant uncertainties. After correcting the cross section for the loss of events below 15 MeV, it was determined that the data below 4 MeV was not usable. The higher angular bins were negative after the background subtraction, which was due to low statistics in the signal regions leading to high

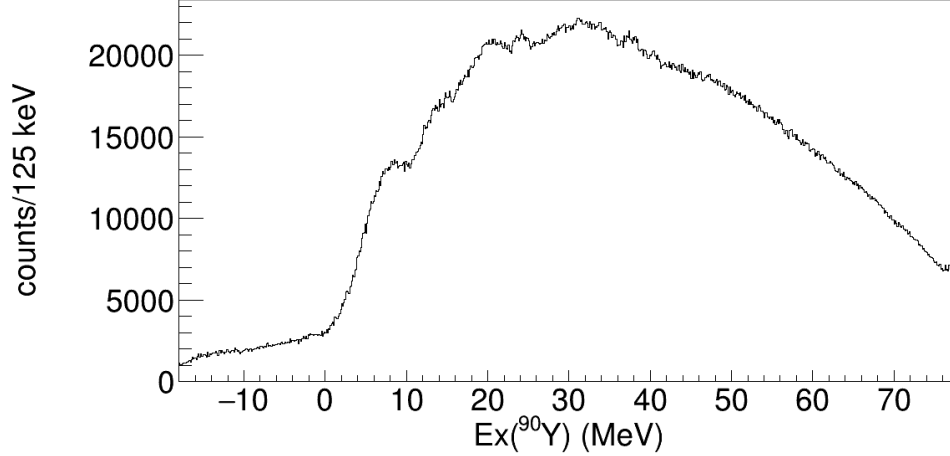


Figure 5.26: Reconstructed excitation energy for ^{90}Y . Counts below -3 MeV are due to background present in the measurement. These events are removed when gating on excited states in ^{10}B .

statistical uncertainties in the background subtraction. The excitation energy spectrum for all the ^{90}Y data is shown in Figure 5.26.

The angular resolution during the experiment was determined by measuring the unreacted ^{10}Be in the focal plane of the S800. The width was determined by fitting each *ata* and *bta* with a Gaussian function. The resolution in the dispersive and non-dispersive directions were determined to be 12.3 mrad and 13.5 mrad, respectively. The *ata* and *bta* plots are shown in the top of Figure 5.27. The resolution of the excitation energy was determined by observing the width of the ^{12}B ground state in the polypropylene data using the $^{12}\text{C}(^{10}\text{Be}, ^{10}\text{B}[1^+, 0.718\text{ MeV}])^{12}\text{B}$ reaction. The spin-transfer channel in ^{12}B is isolated using the sideband subtraction discussed in Section 4.2.1, followed by the feeding subtraction discussed in Section 4.2.2. The resulting distribution was then fit using two Gaussian functions, one for the ^{12}B ground state and one for the higher energy tail. The results of the fit are shown in the bottom of Figure 5.27.

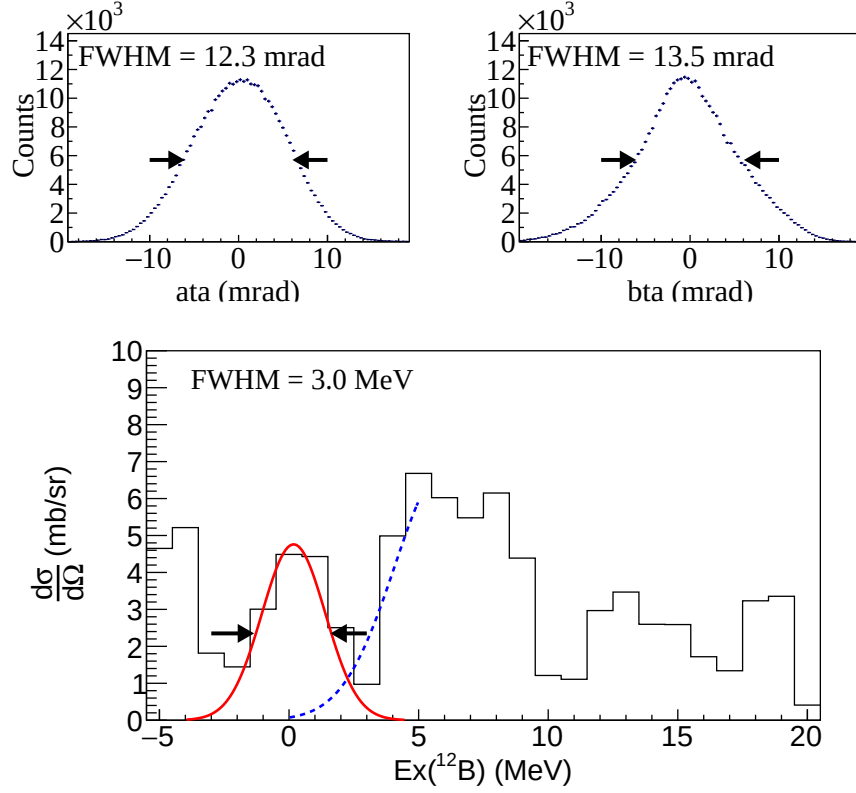


Figure 5.27: Experimental resolutions for experiment 23009. The angular resolutions were determined by measuring the unreacted ^{10}Be beam in the focal plane, while the energy resolution was determined by measuring the width of the $^{12}\text{B}(\text{g.s.})$ after isolating the spin-transfer channel.

5.4 Isolating spin and non-spin channels

To isolate the spin and non-spin-transfer channels, the sideband subtraction method, as described in Section 4.2.1, was utilized to isolate each transition. However, the background shape was observed to vary slightly as a function of scattering angle. As a result, the scale factor (Equation 3.38) for each transition was determined separately for each angular bin. The excitation energy spectrum was divided into 0.33° bins from $0^\circ \leq \theta_{CM} \leq 4^\circ$. The transitions of interest in each angular bin were then fit in a similar way to the Carbon data, discussed in Section 4.2.1. The 414 keV photopeak and the 1022 keV photopeak were

Scale Factors			
Angular Range	Photopeak		
	414 keV	718 keV	1022 keV
$\theta_{c.m.} = 0^\circ - 0.33^\circ$	0.760	1.908	0.343
$\theta_{c.m.} = 0.33^\circ - 0.66^\circ$	0.759	1.891	0.347
$\theta_{c.m.} = 0.66^\circ - 1.0^\circ$	0.758	1.895	0.346
$\theta_{c.m.} = 1.0^\circ - 1.33^\circ$	0.761	1.881	0.347
$\theta_{c.m.} = 1.33^\circ - 1.66^\circ$	0.763	1.816	0.349
$\theta_{c.m.} = 1.66^\circ - 2.0^\circ$	0.751	1.788	0.353

Table 5.4: Scale factors used in the sideband subtraction for each transition and angular bin.

each fit with a Gaussian function to model the photopeak and a second order polynomial to model the background, while the 718 keV photopeak was fit with a combination of 3 Gaussian functions for the signal and a second order polynomial for the background. Figure 5.28 shows the γ -ray spectrum and corresponding background functions at different scattering angles for the photopeaks. The scale factors determined by the fitting procedure are presented in Table 5.4. The 718 keV photopeak showed the most variation in the scale factor. As the signal region is wide and there is a significant background under the signal, it is the most sensitive to the background shape. The Doppler-corrected γ -energy spectrum indicating the gates used is shown in Figure 5.29.

Following the sideband subtraction, the spin-states are isolated by removing the feeding contributions in each of the angular bins. This is accomplished using Equation 4.1 for the non-spin-transfer channel and Equation 4.2 for the spin-transfer channel, respectively, just like with the Carbon analysis. The resulting spin-transfer and non-spin-transfer channel spectra up to $\theta_{c.m.} = 2^\circ$ are presented in Figure 5.30.

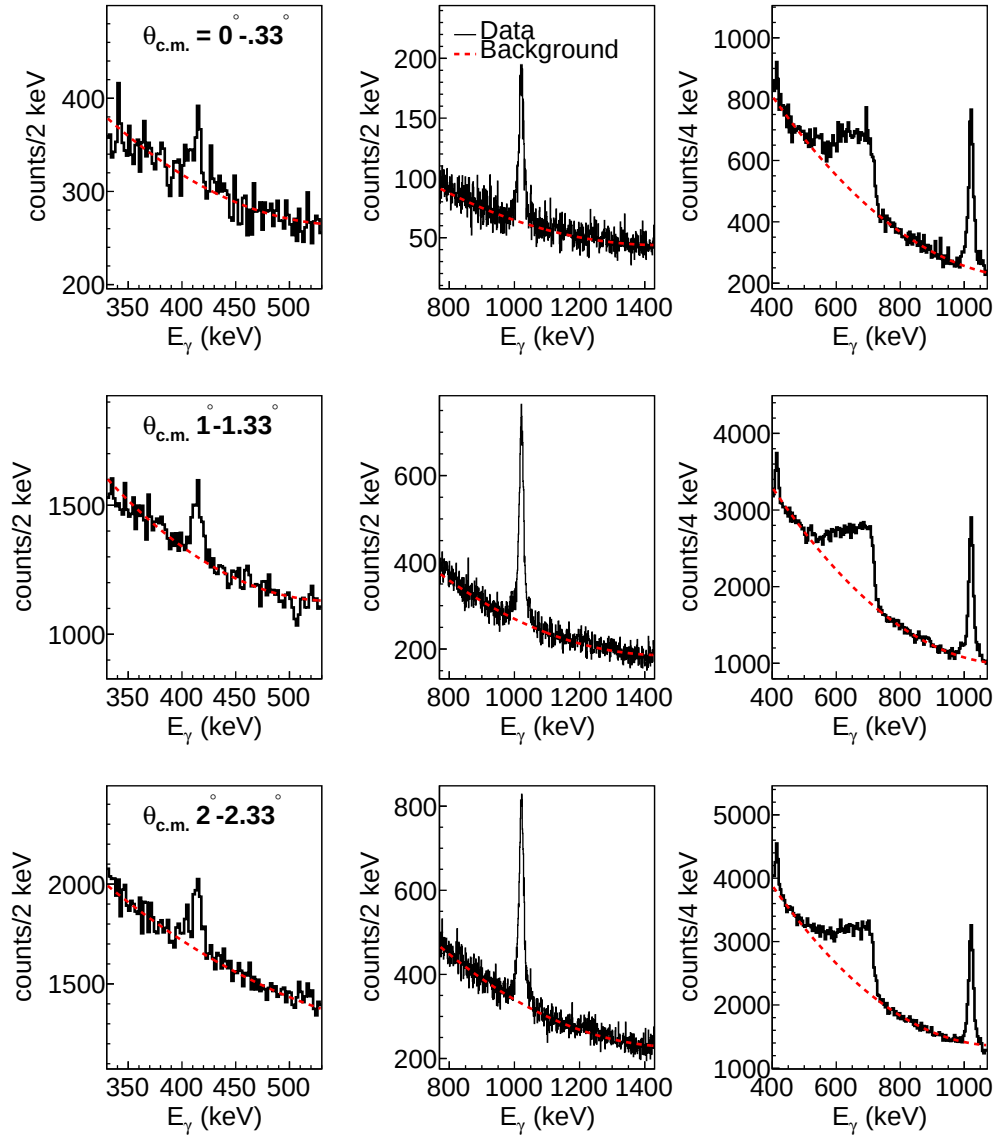


Figure 5.28: The 414 keV (left), the 1022 keV (middle), and the 718 keV (right) transitions at three different scattering angles. The data is in black and the function used to model the background is in red.

5.5 Cross Section Calculation

After the spectra are obtained, the final step before applying the MDA is to convert the counts in the ^{90}Y excitation energy spectrum to differential cross-section. The excitation energy spectra shown in Figure 5.30 are re-binned to 4 MeV wide excitation energy bins,

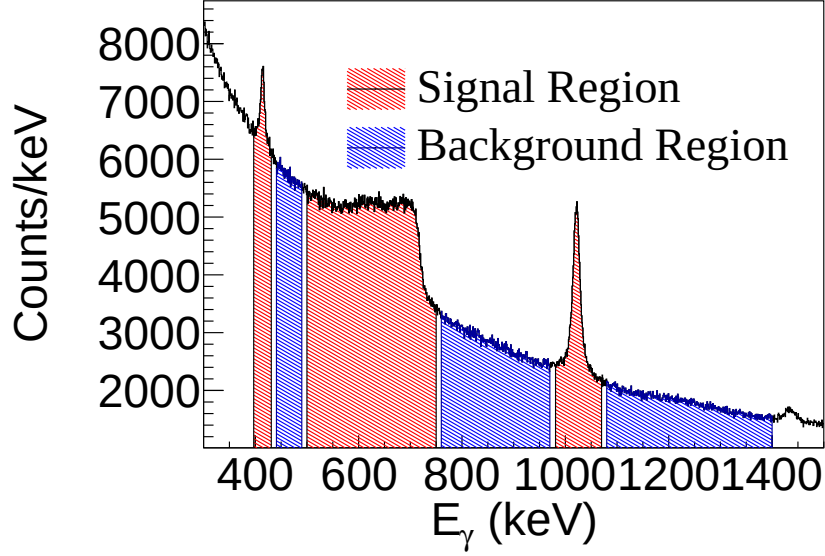


Figure 5.29: γ -ray energy-spectrum showing the signal and background gates used for the three transitions of interest.

and each bin is plotted as a function of the scattering angle in the center of mass frame (θ_{CM}). The spectra are separated into 0.33° bins to produce the angular distributions. The bin widths for excitation energy and scattering angle were chosen to reduce the impact of statistical uncertainties in the decomposition while retaining a clear separation of the monopole resonance in each channel. This was particularly important for the scattering angle, as binning near the experimental resolution did not allow for separation.

The differential cross section is defined as

$$\frac{d\sigma}{d\Omega} = \frac{N_m}{N_i N_t \mathcal{L} d\Omega_{CM} \epsilon_\gamma} \quad (5.15)$$

where N_m refers to the counts in a bin after background subtraction, N_i is the number of incident ^{10}Be ions, N_t is the number of ^{90}Zr atoms in the target, $\mathcal{L}$ is the effective run time of the data collection, $d\Omega_{CM}$ is the opening angle of the angular bin, and ϵ_γ is the efficiency of GREYINA for the coincident γ ray. Note that in Figure 5.30, ϵ_γ is already taken into

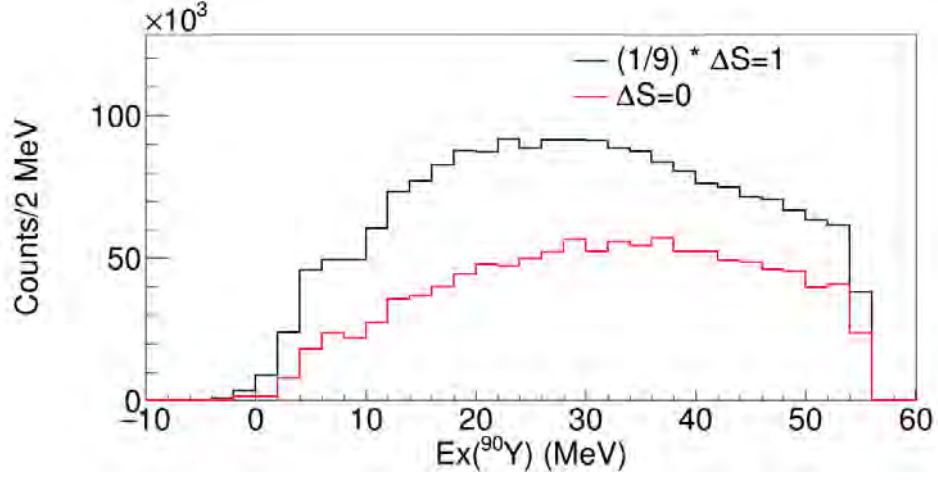


Figure 5.30: Excitation energy spectra for scattering angles $\theta_{c.m.} \leq 2^\circ$ for the spin-transfer (red) and non-spin-transfer (black) channels in ^{90}Y . The spin-transfer spectrum is scaled by 1/9 to compare spectrum shape. The counts presented in this spectrum have already been corrected for γ -ray detection efficiency.

account. A brief description of how each quantity is obtained is as follows:

- N_m : The counts at each energy and angle following the background and feeding subtraction.
- N_i : The number of incident ^{10}Be particles was determined on a run-by-run basis as described in Section 3.1.3.
- N_t : The number of ^{90}Zr atoms in the target was determined using the average target thickness of the 54.5 mg/cm^2 and 52.3 mg/cm^2 foils as shown in 5.1, as it was assumed that few interactions would occur with the outer foil. The average target thickness was determined to be 53.4 mg/cm^2 , which corresponds to $N_t = 3.57 \times 10^{20} \text{ cm}^{-2}$.
- $\mathcal{L}$: The live-time for each experimental run was determined by the data acquisition system. The average live-time, including detector dead-time, was $\sim 75\%$

Possible final state in ^{90}Y			
	$\Delta L = 0$	$\Delta L = 1$	$\Delta L = 2$
$\Delta S = 0$	$J^\pi = \mathbf{0}^+$	$J^\pi = \mathbf{1}^-$	$J^\pi = \mathbf{2}^+$
$\Delta S = 1$	$J^\pi = \mathbf{1}^+$	$J^\pi = 0^-, \mathbf{1}^-, 2^-$	$J^\pi = 1^+, \mathbf{2}^+, 3^+$

Table 5.5: Selection rules for $^{90}\text{Zr}(0^+, g_s) \rightarrow ^{90}\text{Y}$ mediated by each transition used in the MDA for ^{90}Y . The distribution shapes used are in bold.

- $d\Omega_{CM}$: The opening angle for each bin is determined as

$$d\Omega = 2\pi \int_{\theta_i}^{\theta_f} \sin\theta d\theta \quad (5.16)$$

where θ_i and θ_f are the lower and upper bin limits of the

- ϵ_γ : the γ ray efficiency is determined using the average value for the respective photo-peak as discussed in Section 3.3.3.

As the final spectrum will include multipolarity contributions from transitions associated with different angular momentum transfers, the monopole resonance is extracted in each channel by decomposing the spectrum using a multipole decomposition analysis (MDA).

5.6 MDA

The multipolarity contributions in the final spectra are disentangled using the MDA. The MDA is achieved by fitting the differential cross sections in each excitation-energy bin with a linear combination of angular distributions associated with different angular-momentum transfers using Equation 4.3. This is the same process as employed in the carbon analysis, discussed in Section 4.3.1. The angular distributions $\Delta L \leq 2$ were used in the MDA for both channels, as the inclusion of higher order terms didn't change the result of the fit.

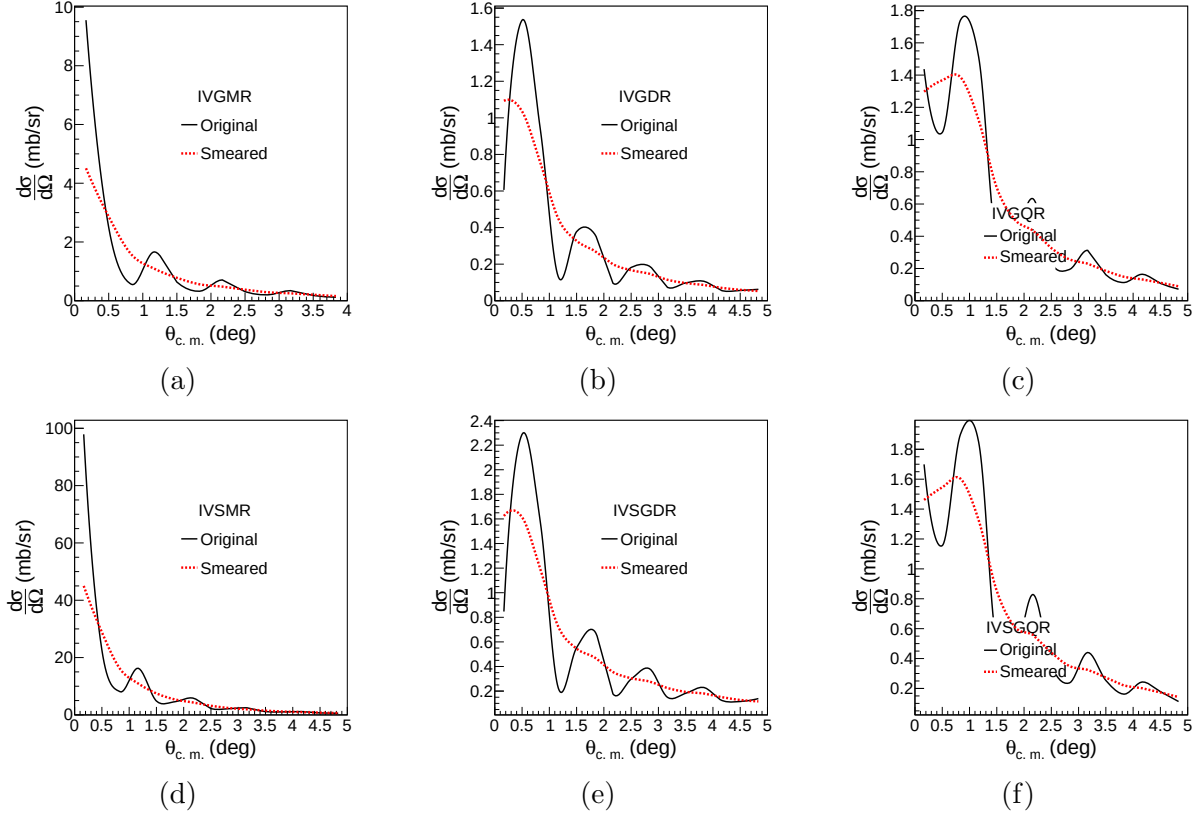


Figure 5.31: DWBA angular distributions at $E_x(^{90}\text{Y}) = 0$ MeV. The black line is the original output from the DWBA calculation, the red dotted line is the smeared distribution. a) isovector monopole resonance, b) isovector dipole resonance, c) isovector quadrupole resonance, d) isovector spin monopole resonance, e) isovector spin dipole resonance, f) isovector spin quadrupole resonance.

The theoretical distributions were calculated in excitation-energy steps of 1.0 MeV and in angular steps of 0.1° from $0.0^\circ < \theta_{c.m.} < 6.0^\circ$.

Before the MDA is applied, the theoretical distributions were smeared with the angular resolution, which was $\sim 1.05^\circ$ (see Chapter 3). This smearing process is the same process that was applied during the carbon analysis and is discussed in Section 4.3. The distributions before and after smearing at $E_x(^{90}\text{Y}) = 0$ MeV are shown in Figure 5.31. Due to the poor angular resolution, the shape of the smeared distributions for the different angular momentum transfers were very similar above $\sim 2^\circ$. As a result, only the angular distribution between $0^\circ < \theta_{c.m.} < 2^\circ$ are used in the MDA.

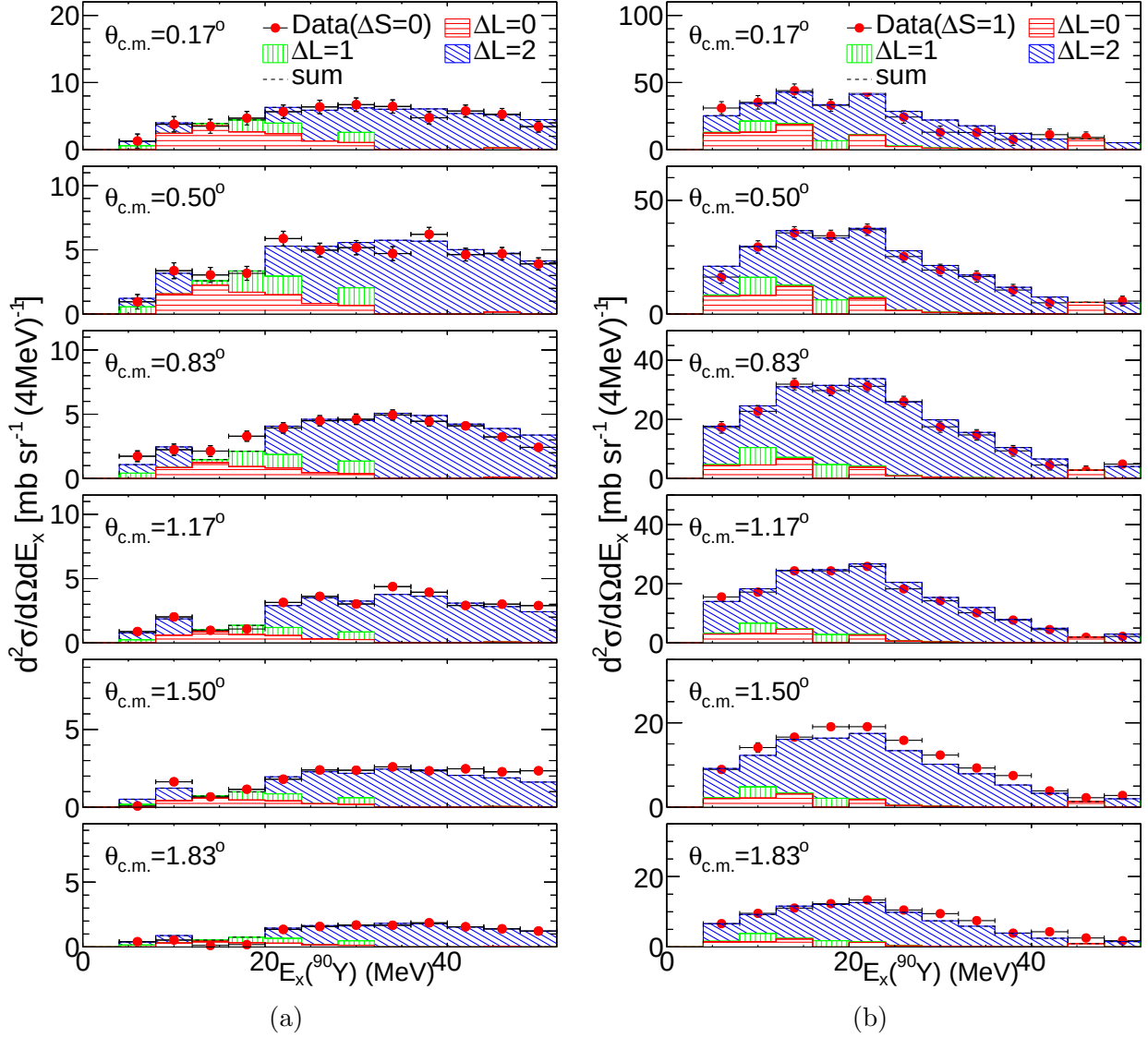


Figure 5.32: Decomposed double differential cross sections binned in 0.33° bins up to 2° for a) the $\Delta S = 0$ channel and b) the $\Delta S = 1$ channel.

5.6.1 Results

The resulting double differential cross section for each scattering angle bin is shown in Figure 5.32. The cross section data are labeled by the red points. The MDA results show the contributions from the $\Delta L = 0$ (red), $\Delta L = 1$ (green), and $\Delta L = 2$ (blue) components. The monopole contribution peaks at 0° , while the dipole contribution peaks around 0.5° , with the quadrupole dominating at higher scattering angles. In both channels, significant

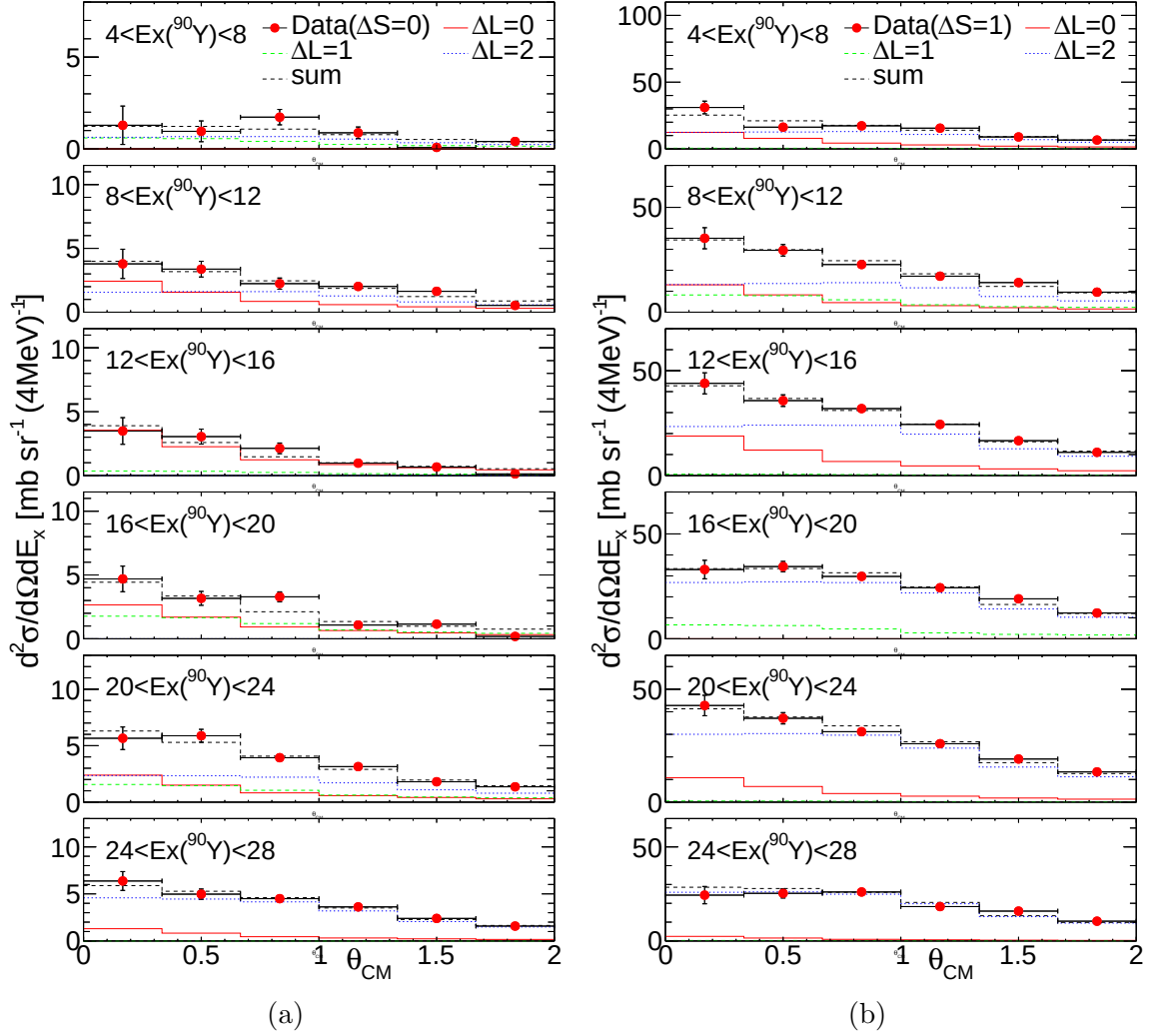


Figure 5.33: Results of fits in 4 MeV bins for a) the $\Delta S = 0$ channel and b) the $\Delta S = 1$ channel.

$\Delta L = 0$ contributions are observed at excitation energies below about 30 MeV. In the $\Delta S = 1$ channel, displayed in Figure 5.32(b), a significant amount of $\Delta L = 0$ contributions are observed at excitation energies below 8 MeV, whereas this is not the case in the $\Delta S = 0$ channel (Figure 5.32(b)). This has been observed previously in ^{90}Zr and has been attributed to Gamow Teller strength up to ~ 10 MeV [18–20, 108, 110, 111]. The results of the fitting between 4 MeV and 28 MeV for the non-spin-flip channel (a) and the spin-flip channel (b) are shown in Figure 5.33. The relatively poor angular resolution during the experiment resulted

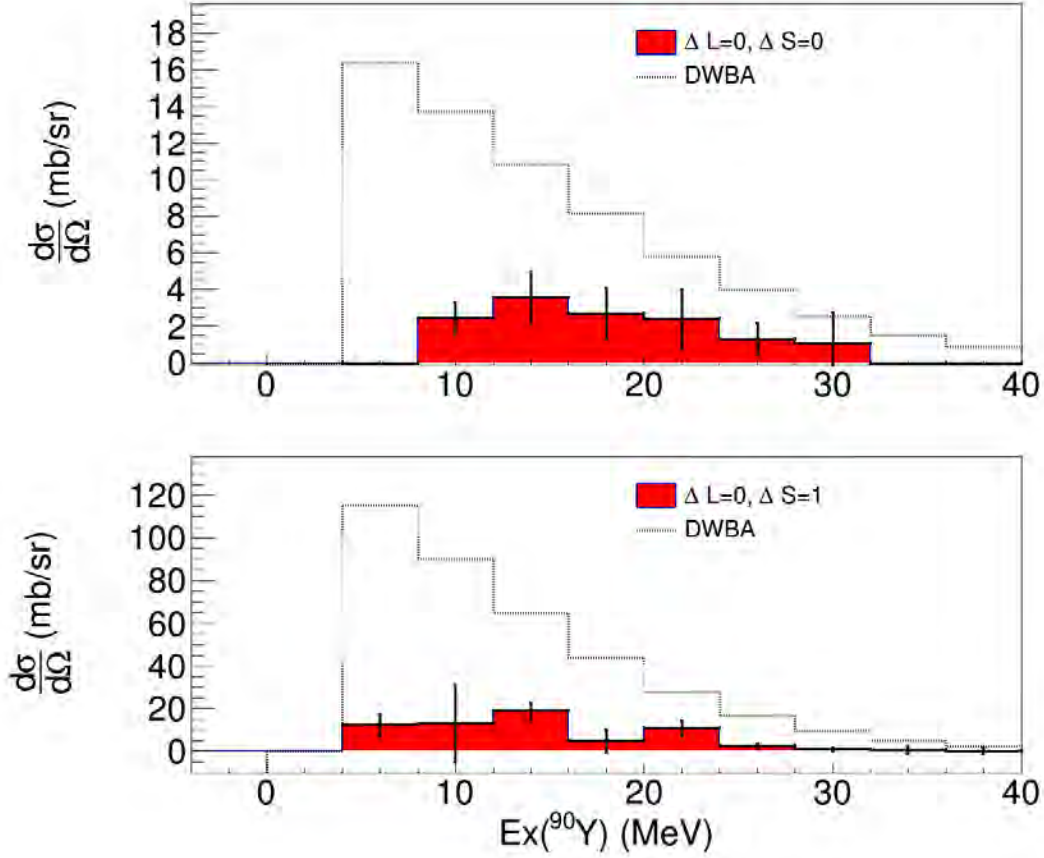


Figure 5.34: The extracted $\Delta L = 0$ cross section at $\theta_{CM} = 0^\circ$ as a function of excitation energy (red) and the calculated DWBA cross section at $\theta_{CM} = 0^\circ$.

in large fit uncertainties, but the multipolarities were still separable.

5.6.2 Comparison to Theoretical Calculations

The results of the MDA were interpreted using comparisons to theoretical calculations. The extracted monopole strength distributions were compared to proton-neutron Relativistic Quasiparticle Time Blocking Approximation (pn-RQTBA) calculations [91], which are discussed in Chapter 2. The RQTBA fragments strength into realistic distributions and offers a robust model for calculating giant resonance strength. The calculation was smeared with a gaussian function to match the experimental resolution. The monopole strength is also com-

Monopole Strength (fm ⁴)		
	pn-RQTBA	NORMOD
IVGMR	2426	2982
IVSGMR	10720	8947

Table 5.6: Calculated monopole strength using pn-RQTBA and DWBA formalisms.

pared to the DWBA cross-sections calculated in the normal-modes formalism as discussed in Chapter 2, which is used to determine the percent of the Non-Energy Weighted Sum Rule (NEWSR) observed. The calculated monopole strength using both the NORMOD code and the RQTBA is presented in Table 5.6. The determined strengths are similar in both channels, with the NORMOD calculation being slightly higher for the IVGMR and slightly smaller for the IVSGMR.

The DWBA cross sections using the NORMOD inputs assume that the NEWSR is fully exhausted at every point. The calculated cross sections were corrected for the $^{10}\text{Be} \rightarrow ^{10}\text{B}(1^+, g.s.)$ transition being 21% lower than the shell-model calculations, and were also scaled by a factor of 1.95 due to the extracted $^{12}\text{C}(0^+, g.s.) \rightarrow ^{12}\text{B}(1^+, g.s.)$ cross section from Ref [15] being larger than the DWBA calculations. The corrected DWBA cross section at $\theta_{CM} = 0^\circ$ for the IVGMR (top) and IVSGMR (bottom) are presented as the dotted black lines in Figure 5.34. The corresponding $\Delta L = 0$ cross section for the respective channel is presented in red. The percent of the NEWSR exhausted by the monopole resonance in each energy bin is calculated by dividing the the cross section of the extracted $\Delta L = 0$ channel by the theoretical DWBA cross section at $\theta_{CM} = 0^\circ$. The total strength exhausted is then calculated by multiplying the percent of the NEWSR used by the total strength from Table 5.6, which is calculated using the code NORMOD. The strength calculation is described mathematically as

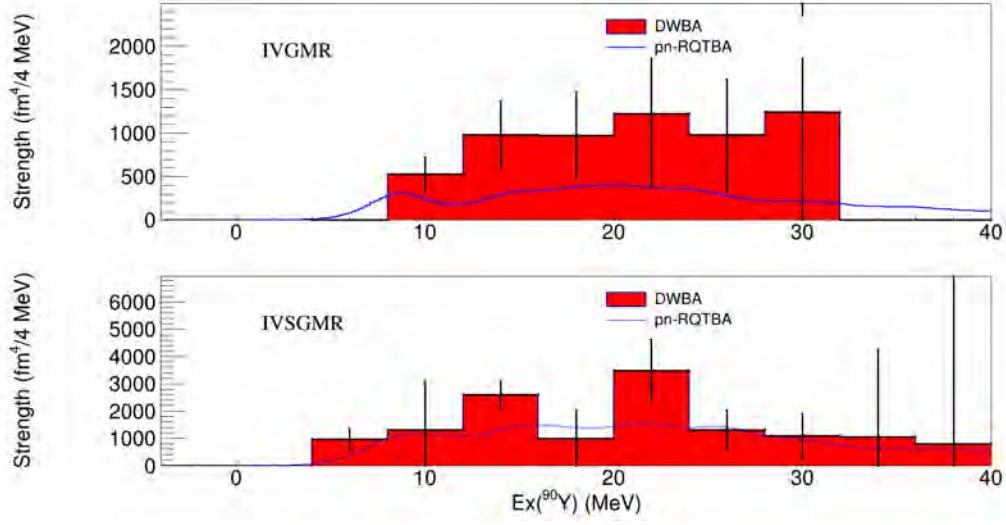


Figure 5.35: Comparison of the monopole strength as a function of excitation energy using the DWBA calculation in red and the RTBA in blue. The strength in red is determined using equation 5.17. The DWBA strength is enhanced compared to the RQTBA calculation due to the used optical potential as discussed in the text.

$$Strength = \frac{\frac{d\sigma}{s\Omega}Exp(\theta = 0^\circ)}{\frac{d\sigma}{d\Omega}DWBA(\theta = 0^\circ)} \times S_{NORMOD} \quad (5.17)$$

$$= \%(NEWSR) \times S_{NORMOD} \quad (5.18)$$

where $\frac{d\sigma}{s\Omega}Exp(\theta = 0^\circ)$ is the extracted $\Delta L = 0$ cross section at $\theta = 0^\circ$, $\frac{d\sigma}{d\Omega}DWBA(\theta = 0^\circ)$ is the $\Delta L = 0$ cross section calculated using the DWBA formalism at $\theta = 0^\circ$, and S_{NORMOD} is the transition strength calculated using the NORMOD code.

The comparison of the strength functions is shown in Figure 5.35, with the RQTB calculation in blue and the DWBA in red. The RQTBA calculation reproduces the shape of both channels well. For the $\Delta S = 0$ channel, the RQTBA calculation shows a peak around 9 MeV, which is due to the $(\pi) 3p_{1/2} \rightarrow (\nu) 2p_{1/2}$ and $(\pi) 3p_{3/2} \rightarrow (\nu) 2p_{3/2}$ particle-hole excitations. This peak is not clearly observed in the data, but this could be due to

NEWSR Strength (%)	
IVGMR	199 ± 81 (stat) ± 80 (syst)
IVSGMR	121 ± 47 (stat) ± 48 (syst)

Table 5.7: Exhaustion of the normal-modes NEWSR strength dbased on the comparison between the experimental cross section and calculated DWBA cross sections with normal-modes transition densities. The uncertainties are labeled as statistical and systematic. The systematic uncertainties come from the determined uncertainty in the optical potential.

the significant uncertainties. For the $\Delta S = 1$ channel, the calculation doesn't predict any strength below ~ 8 MeV. The strength in that region is therefore attributed to Gamow Teller strength, which is investigated below. The choice of the optical potential plays a role, as the DWBA calculation uses the distortion of the incoming and outgoing waves after interacting with the optical potential to produce the transition strength and interaction cross section, as discussed in Chapter 2. As elastic scattering data for ^{10}Be on ^{90}Zr at a comparable energy isn't available, an optical potential calculated using the method described in Chapter 2 was used. This method was compared to a calculation in which an optical potential produced from a fit to elastic scattering data for ^{16}O on ^{90}Zr from Ref. [87] (see Table 2.2. For the IVGMR, the cross section calculated at $E_x = 0$ MeV using the first optical potential is ~ 30 mb/sr, while the fitted optical potential gave a cross section of 18 mb/sr. This suggests a systematic uncertainty of 40% based on the choice of optical potential. The summed NEWSR strengths using the DWBA calculations up to 35 MeV are presented in Table 5.7. The statistical uncertainties are included in the fit uncertainties, which are labeled as statistical uncertainties. The uncertainties from the choice of optical potential are labeled as systematic uncertainties. Although the total strengths extracted from the data are higher than the theoretical prediction, within statistical and systematical uncertainties, the theory and experiment are consistent.

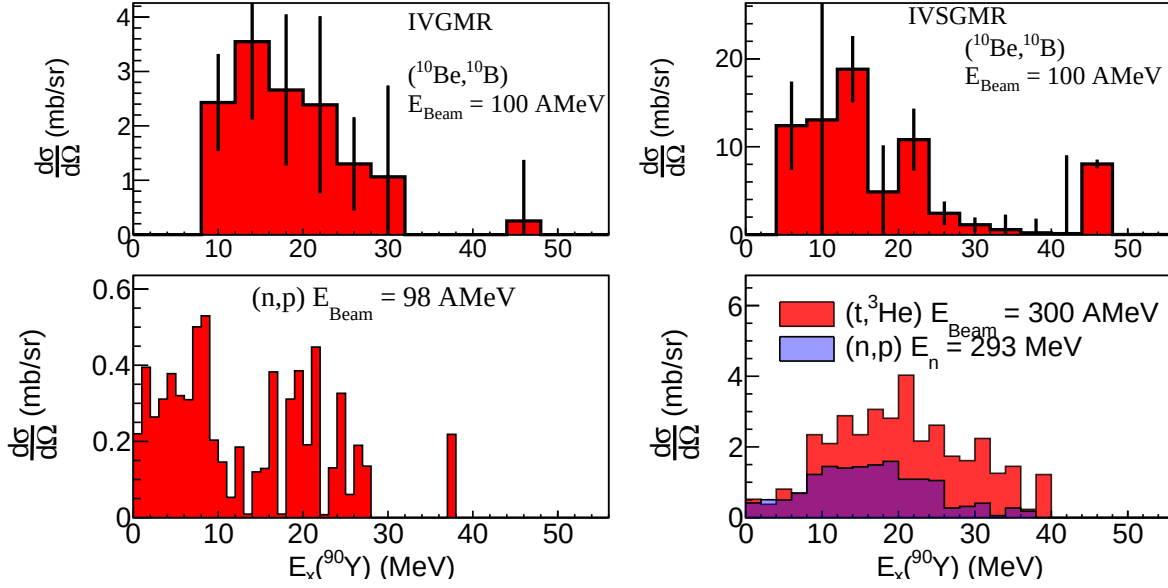


Figure 5.36: The $\Delta L = 0$ cross section extracted for the IVGMR (top-left) and the IVSGMR (top-right), compared with the extracted cross section from experiments featuring similar spin-selectivity (bottom). The (n,p) data shown in the bottom-left panel is from Ref. [18]. The (t, ^3He) and (n,p) data shown in the bottom-right panel are from Refs. [19, 20]. For details, see the text.

5.6.3 Comparison with Previous Work

Previous measurements of the isovector monopole resonances in ^{90}Y include both $\Delta S = 0$ and $\Delta S = 1$ channels. As shown in Figure 1.6 the strength of the central component of the isovector non-spin-transfer interaction (J_τ^2) is almost equal to that of the spin-transfer interaction ($J_{\sigma\tau}^2$) at $E = 50$ MeV. The ratio of the $J_\tau^2/J_{\sigma\tau}^2$ drops rapidly as E increases. For $E = 200\text{-}300$ MeV, the $J_{\sigma\tau}^2$ strength is about 10 times higher.

As mentioned in Chapter 1, composite probes such as (t, ^3He) are a good option to study the monopole resonances, as the probe will be absorbed at the nuclear surface. A good comparison for the IVSGMR in ^{90}Y using a compound probe and a nucleonic probe comes from Ref. [19]. In that work, the (t, ^3He) probe at 300 AMeV and the (n,p) probe at $E_n = 293$ MeV from Ref. [20] on ^{90}Zr and ^{208}Pb were compared. The $\Delta S = 0$ channel is highly

suppressed at these beam energies, so the $\Delta S = 1$ channel can be safely assumed to be the dominant transition. As shown in the bottom right of Figure 5.36, the cross sections of the $\Delta L = 0$ response for the $(t, {}^3\text{He})$ and (n, p) reactions are about the same up to an excitation energy of about 8 MeV. At higher excitation energies, the $\Delta L = 0$ cross section for the $(t, {}^3\text{He})$ reaction displays a significant enhancement. This comparison indicates that below $E_x = 8$ MeV, the monopole strength is dominated by Gamow-Teller transitions, as the response is expected to be similar for the $(t, {}^3\text{He})$ and (n, p) reactions. At higher excitation energies, much more monopole strength is found in the $(t, {}^3\text{He})$ reaction than in the (n, p) reaction because of the difference in absorption. A similar effect is observed in the ${}^{90}\text{Zr}(n, p)$ reaction at 98 MeV [18], shown in the bottom left panel of Figure 5.36. A relatively strong monopole response below 10 MeV, primarily due to Gamow-Teller excitations, is accompanied by relatively little strength at higher excitation energies, in this case due to a mixture of the IVGMR and IVSGMR.

As shown in the top left panel of Figure 5.36, the $\Delta L = 0, \Delta S = 0$ cross section from the $({}^{10}\text{Be}, {}^{10}\text{B})$ reaction shows no low-lying $\Delta L = 0$ contributions, as there is no equivalent of the Gamow-Teller excitation for $\Delta S = 0$. There is significant $\Delta L = 0$ strength between 8 MeV and 32 MeV, which is attributed to the IVGMR. The centroid of the IVGMR strength distribution (Figure 5.35) from this work is around $E_x = 21$ MeV with a width of $\Gamma = 9$ MeV.

In the $\Delta S = 1$ cross section, low-energy $\Delta L = 0$ strength is found up to about 8 MeV, which is attributed mostly to the GT transition based on the above comparison between the $(t, {}^3\text{He})$ and (n, p) reactions. If it is assumed to be entirely GT strength, it gives a GT strength of $B(\text{GT}) = 2 \pm 0.8$. This value is on the high end of previously measured values using the (n, p) reaction, with Ref. [18] reporting a strength of 1.7 ± 0.2 up to 10 MeV (E_{beam}

$= 98$ MeV), Ref. [111] reporting strength of 1.0 ± 0.3 up to 8 MeV ($E_{beam} = 198$ MeV), and Ref. [20] reporting a strength of 0.7 ± 0.1 (stat) ± 0.1 ($\hat{\sigma}_{GT}$) ($E_{beam} = 300$ MeV). We note that further GT strength could reside below 4 MeV, but as discussed in Section 5.3, these data were not usable in this experiment. Given the experimental resolution of 3 MeV, it is also likely that some $\Delta L = 0$ strength at higher E_x is also observed below 8 MeV. There is significant $\Delta L = 0$ strength above $E_x = 8$ MeV, which is attributed to the IVSGMR. The centroid of the IVSGMR was observed to be at $E_x = 20 \pm 6$ MeV with a width of $\Gamma = 10$ MeV. The centroid is close to agreement with the centroid presented in [19], which measured the IVSGMR centroid to be $E_x = 23.97 \pm 0.5$ MeV. Overall, we find that the results from the presnet experiment are consistent with previous data. The relatively large uncertainties compromise a detailed comparison.

Chapter 6. Conclusion and Future Work

Through the pioneering experiments on ^{28}Si and ^{12}C , the $(^{10}\text{Be}, ^{10}\text{B} + \gamma)$ reaction has been shown to be a powerful tool to simultaneously measure the IVGMR and IVSGMR in a single experiment. This is particularly useful because the resonances have been historically difficult to isolate and study, as the IVSGMR tends to dominate the response. The simultaneous measurement is significant as well because it reduces the systematic uncertainties that arise when comparing results from different measurements. Together with the complimentary $(^{10}\text{C}, ^{10}\text{B} + \gamma)$ reaction, the IVGMR and IVSGMR can be simultaneously studied in the (n,p) and (p,n) directions.

In this thesis the IVGMR and the IVSGMR have been measured in a single measurement in ^{90}Y using the $(^{10}\text{Be}, ^{10}\text{B} + \gamma)$ reaction at 100 AMeV. In addition, previous data on ^{12}C were used to demonstrate the isolation of the $\Delta S = 0$ and $\Delta S = 1$ response in a single measurement. The measurements were performed at the National Superconducting Cyclotron Laboratory (NSCL, ^{12}C) and at the Facility for Rare Isotope Beams (FRIB, ^{90}Y) using a coincident measurement between the GRETINA array and the S800 Spectrograph. By using the γ ray to tag the excited states in ^{10}B , spin filters are produced and the $\Delta S = 0$ and $\Delta S = 1$ responses can be isolated and studied separately. The excitation energy spectra and reaction scattering angle were reconstructed using the S800 spectrograph. Using the reconstructed scattering angles, angular distributions at each excitation energy are obtained and decomposed into contributions associated with the transfer of different units of angular momentum transfer using fits with theoretical angular distributions calculated using a distorted wave Born approximation. The $\Delta L = 0$ response in the $\Delta S = 0$ and $\Delta S = 1$ channels were extracted for $4 < E_x(^{90}\text{Y}) < 55$ MeV.

The resulting $\Delta L = 0$ response in each channel was compared to theoretical calculations and to previous measurements. Both spin channels agree within uncertainties with the pn-RQTBA calculation. The $\Delta L = 0, \Delta S = 1$ channel shows low energy monopole strength that is not present in the pn-RQTBA calculation. This strength is attributed mostly to Gamow Teller strength, which is observed in both (n,p) and (t, ^3He) experiments. The measured IVGMR and IVSGMR distributions were compared to the predicted strengths calculated in the normal-modes formalism to determine the percent exhaustion of the non-energy weighted sum rule (NEWSR). The strength exhaustion for the IVGMR was $199 \pm 81(\text{stat}) \pm 80(\text{syst})$, and for the IVSGMR it was $121 \pm 47(\text{stat}) \pm 48(\text{syst})$.

6.1 Future Work

The ($^{10}\text{Be}, ^{10}\text{B} + \gamma$) reaction has been shown to be a powerful tool for the simultaneous measurement of isovector monopole resonances. However, the large uncertainty in the extracted spectra compromised detailed comparison of the monopole strength with previous work and theory. To reduce uncertainties in the extracted data, improvements in the angular resolution and improved statistics are necessary. Improving the angular resolution can be accomplished by restricting the ^{10}B beams angular spread using slits or by developing ion-optical transport that minimizes the angular spread on the target. At the beam intensities necessary, it is not possible to track beam particles on an event-by-event basis. Higher ^{10}Be beam intensity will improve the statistics and will be crucial for future studies. As FRIB ramps up to full power, higher intensity beams will be available and will allow for the study of heavy nuclei, and will eventually allow for the study of the isovector monopole resonances in e.g., ^{208}Pb . Improving the γ -ray detection efficiency would also improve the statistical

uncertainties. Therefore, performing these experiments with GRETA, which has more modules than GRETINA, will be helpful. Employing the $(^{10}\text{C}, ^{10}\text{B} + \gamma)$ reaction to measure the isovector monopole resonances in the $\Delta T_z = -1$ direction is the next experimental step, providing complimentary information to that obtained using the $(^{10}\text{Be}, ^{10}\text{B} + \gamma)$ reaction. As this work is an important step in a systematic study of the IVGMR and IVSGMR throughout the nuclear chart, conducting a thorough study using both reactions will provide a complete picture of the isovector monopole resonances with impacts of our understanding of the bulk properties of nuclear matter.

APPENDIX A

WSAW Input Files

```
1 0.1      20.      1 150  0
2 10BE10B
3 9.       4.      60.     .65    1.25    1.25    7.0
4 21.8     1.      0.      0.     0.     0.5     .5
5 9.       4.      60.     .65    1.25    1.25    7.0
6 9.0      1.      1.      0.     0.     1.5     .5
7 9.       4.      60.     .65    1.25    1.25    7.0
8 3.5      1.      1.      0.     0.     0.5     .5
9 9.       4.      60.     .65    1.25    1.25    7.0
10 1.0      1.      2.      0.     0.     2.5     .5
11 9.       4.      60.     .65    1.25    1.25    7.0
12 1.0      1.      2.      0.     0.     1.5     .5
13 9.       4.      60.     .65    1.25    1.25    7.0
14 1.0      1.      0.      1.     0.     0.5     .5
15 9.       4.      60.     .65    1.25    1.25    7.0
16 1.0      1.      3.      0.     0.     3.5     .5
17 9.       4.      60.     .65    1.25    1.25    7.0
18 1.0      1.      3.      0.     0.     2.5     .5
19 9.       4.      60.     .65    1.25    1.25    7.0
20 1.0      1.      1.      1.     0.     1.5     .5
21 9.       4.      60.     .65    1.25    1.25    7.0
22 23.4     1.      0.      0.     1.     0.5     .5
23 9.       4.      60.     .65    1.25    1.25    7.0
24 9.9      1.      1.      0.     1.     1.5     .5
25 9.       4.      60.     .65    1.25    1.25    7.0
26 4.1      1.      1.      0.     1.     0.5     .5
27 9.       4.      60.     .65    1.25    1.25    7.0
28 1.0      1.      2.      0.     1.     2.5     .5
29 9.       4.      60.     .65    1.25    1.25    7.0
30 1.0      1.      2.      0.     1.     1.5     .5
31 9.       4.      60.     .65    1.25    1.25    7.0
32 1.0      1.      0.      1.     1.     0.5     .5
33 9.       4.      60.     .65    1.25    1.25    7.0
34 1.0      1.      3.      0.     1.     3.5     .5
35 9.       4.      60.     .65    1.25    1.25    7.0
36 1.0      1.      3.      0.     1.     2.5     .5
37 9.       4.      60.     .65    1.25    1.25    7.0
38 1.0      1.      1.      1.     1.     1.5     .5
39 -1.
40
```

Figure A.1: WSAS input file for the ^{10}Be , ^{10}B two-body system.

This appendix has the input files used in the WSAW code.

```

1  0.1      20.      1  150    0
2  90ZR90Y
3  89.      39.      60.      .65      1.25      1.25      7.0
4  11.00    1.       4.       0.       0.       4.5       .5
5  89.      39.      60.      .65      1.25      1.25      7.0
6  4.29     1.       4.       0.       0.       3.5       .5
7  89.      39.      60.      .65      1.25      1.25      7.0
8  6.48     1.       2.       1.       0.       2.5       .5
9  89.      39.      60.      .65      1.25      1.25      7.0
10 4.30     1.       2.       1.       0.       1.5       .5
11 89.      39.      60.      .65      1.25      1.25      7.0
12 5.09     1.       0.       2.       0.       0.5       .5
13 89.      39.      60.      .65      1.25      1.25      7.0
14 2.22     1.       5.       0.       0.       5.5       .5
15 89.      39.      60.      .65      1.25      1.25      7.0
16 4.00     1.       5.       0.       0.       4.5       .5
17 89.      39.      60.      .65      1.25      1.25      7.0
18 4.00     1.       3.       1.       0.       3.5       .5
19 89.      39.      60.      .65      1.25      1.25      7.0
20 4.00     1.       3.       1.       0.       2.5       .5
21 89.      39.      60.      .65      1.25      1.25      7.0
22 4.00     1.       1.       2.       0.       1.5       .5
23 89.      39.      60.      .65      1.25      1.25      7.0
24 4.00     1.       1.       2.       0.       0.5       .5
25 89.      39.      60.      .65      1.25      1.25      7.0
26 4.00     1.       6.       0.       0.       6.5       .5
27 89.      39.      60.      .65      1.25      1.25      7.0
28 4.00     1.       6.       0.       0.       5.5       .5
29 89.      39.      60.      .65      1.25      1.25      7.0
30 4.00     1.       4.       1.       0.       4.5       .5
31 89.      39.      60.      .65      1.25      1.25      7.0
32 4.00     1.       2.       2.       0.       2.5       .5
33 89.      39.      60.      .65      1.25      1.25      7.0
34 4.00     1.       0.       3.       0.       0.5       .5
35 89.      39.      60.      .65      1.25      1.25      7.0
36 4.00     1.       2.       2.       0.       1.5       .5
37 89.      39.      60.      .65      1.25      1.25      7.0
38 4.00     1.       7.       0.       0.       7.5       .5
39 89.      39.      60.      .65      1.25      1.25      7.0
40 34.4     1.       0.       0.       1.       0.5       .5
41 89.      39.      60.      .65      1.25      1.25      7.0
42 28.9     1.       1.       0.       1.       1.5       .5
43 89.      39.      60.      .65      1.25      1.25      7.0
44 27.6     1.       1.       0.       1.       0.5       .5
45 89.      39.      60.      .65      1.25      1.25      7.0
46 22.3     1.       2.       0.       1.       2.5       .5
47 89.      39.      60.      .65      1.25      1.25      7.0
48 19.3     1.       2.       0.       1.       1.5       .5
49 89.      39.      60.      .65      1.25      1.25      7.0
50 17.4     1.       0.       1.       1.       0.5       .5
51 89.      39.      60.      .65      1.25      1.25      7.0
52 14.6     1.       3.       0.       1.       3.5       .5
53 89.      39.      60.      .65      1.25      1.25      7.0
54 9.6      1.       3.       0.       1.       2.5       .5
55 89.      39.      60.      .65      1.25      1.25      7.0
56 8.5      1.       1.       1.       1.       1.5       .5
57 89.      39.      60.      .65      1.25      1.25      7.0
58 7.0      1.       1.       1.       1.       0.5       .5
59 89.      39.      60.      .65      1.25      1.25      7.0
60 6.1      1.       4.       0.       1.       4.5       .5
61 -1.
62
63

```

Figure A.2: WSAS input file for the ^{90}Zr , ^{90}Y two-body system.

APPENDIX B

FOLD Input Files

This appendix includes the FOLD input files for each of the transitions used in the Multipole Decomposition Analysis (MDA) for the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B})^{90}\text{Y}$ reaction.

```
1      1      1BEZRGDR
2      600 0.03      1000.      10.      1      1      1
3      0.0+      0.0+
4      1.0      +0.0      1.0      +1.0
5      3      3      0.000
6      2      2      0      0.0      0.26612
7      3      3      0      0.0      0.51885
8      -1      -1
9      10BE10B
10     1.0-      0.0+
11     6.0      +6.0      5.0      5.0
12     3      3      0.000
13     15     10     1      0.00000      -0.5019
14     13     10     1      0.00000      -0.2078
15     13     8      1      0.00000      -0.3253
16     13     6      1      0.00000      -0.0465
17     14     10     1      0.00000      0.0848
18     14     9      1      0.00000      -0.4408
19     12     8      1      0.00000      0.1084
20     12     9      1      0.00000      -0.1739
21     12     7      1      0.00000      -0.1714
22     11     8      1      0.00000      -0.1833
23     11     7      1      0.00000      -0.0916
24     21     15     1      0.00000      -0.1944
25     19     15     1      0.00000      -0.0748
26     20     15     1      0.00000      0.0265
27     -1      -1
28     90ZR90Y
29     0.923      2.23      1.000      franey_100
30     1
31     1      0      1      -1
32     1.00      1.00      1.00      1.00      1.00      1.00      1.00
33     1.00      1.00      1.00      1.00      1.00      1.00      1.00
34
```

Figure B.1: FOLD input file for the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B})^{90}\text{Y}$ isovector giant dipole resonance.

```

1      1      1BEZRGQR
2      600 0.03      1000.      10.      1      1      1
3          0.0+      0.0+
4      1.0      +0.0      1.0      +1.0
5          3      3      0.000
6          2      2      0      0.0      0.26612
7          3      3      0      0.0      0.51885
8          -1      -1
9      10BE10B
10         2.0+      0.0+
11        6.0      +6.0      5.0      5.0
12          3      3      0.000
13         15      6      2      0.00000      -0.3077
14         13      4      2      0.00000      -0.1486
15         13      6      2      0.00000      -0.1005
16         13      5      2      0.00000      -0.0502
17         14      6      2      0.00000      0.0870
18         14      5      2      0.00000      -0.2611
19         12      4      2      0.00000      0.1214
20         12      6      2      0.00000      0.0502
21         12      5      2      0.00000      -0.0768
22         11      6      2      0.00000      -0.0711
23         11      5      2      0.00000      -0.0580
24         21      10      2      0.00000      -0.4352
25         19      10      2      0.00000      -0.1343
26         19      8      2      0.00000      -0.2611
27         19      9      2      0.00000      -0.0465
28         20      10      2      0.00000      0.0950
29         20      9      2      0.00000      -0.3857
30         18      10      2      0.00000      0.0465
31         18      8      2      0.00000      0.1066
32         18      9      2      0.00000      -0.1140
33         18      7      2      0.00000      -0.1410
34         17      10      2      0.00000      -0.0930
35         17      8      2      0.00000      -0.1085
36         17      9      2      0.00000      -0.0380
37         17      7      2      0.00000      -0.0768
38         16      8      2      0.00000      0.1085
39         16      9      2      0.00000      -0.0711
40         28      15      2      0.00000      -0.1820
41         27      15      2      0.00000      0.0324
42         26      15      2      0.00000      -0.0530
43         25      15      2      0.00000      -0.0142
44         24      15      2      0.00000      -0.0347
45         -1      -1
46      90ZR90Y
47      0.923      2.23      1.000      franey_100
48          1
49          2      0      2      -1
50      1.00      1.00      1.00      1.00      1.00      1.00      1.00
51      1.00      1.00      1.00      1.00      1.00      1.00      1.00
--

```

Figure B.2: FOLD input file for the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B})^{90}\text{Y}$ isovector giant quadrupole resonance.

```

1      1      1BEZRIVSM
2      600 0.03      1000.      10.      1      1      1
3      1.0+      0.0+
4      1.0      +0.0      1.0      +1.0
5      3      3      0.000
6      2      2      1      0.0      0.06463
7      3      3      1      0.0      0.18072
8      2      3      1      0.0      0.51116
9      3      2      1      0.0      -0.23584
10     -1      -1
11     10BE10B
12     1.0+      0.0+
13     6.0      +6.0      5.0      5.0
14     3      3      0.000
15     13      6      1      0.00000      0.2336
16     13      5      1      0.00000      -0.2498
17     12      6      1      0.00000      0.2498
18     12      5      1      0.00000      -0.1249
19     11      4      1      0.00000      0.2360
20     19      10      1      0.00000      0.2931
21     19      9      1      0.00000      -0.3385
22     18      9      1      0.00000      -0.1892
23     18      10      1      0.00000      0.3385
24     16      7      1      0.00000      -0.0658
25     16      8      1      0.00000      0.2633
26     17      8      1      0.00000      0.2943
27     17      7      1      0.00000      -0.1862
28     26      15      1      0.00000      0.1117
29     25      15      1      0.00000      0.1347
30     -1      -1
31     90ZR90Y
32     0.923      2.23      1.000      franey_100
33     1
34     0      1      1      -1
35     1.00      1.00      1.00      1.00      1.00      1.00      1.00
36     1.00      1.00      1.00      1.00      1.00      1.00      1.00

```

Figure B.3: FOLD input file for the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B})^{90}\text{Y}$ isovector spin giant monopole resonance.

```

1      1      1BEZRSDR1
2      600 0.03      1000.      10.      1      1      1
3      1.0+      0.0+
4      1.0      +0.0      1.0      +1.0
5      3      3      0.000
6      2      2      1 0.0      0.06463
7      3      3      1 0.0      0.18072
8      2      3      1 0.0      0.51116
9      3      2      1 0.0      -0.23584
10     -1     -1
11     10BE10B
12     1.0-      0.0+
13     6.0      +6.0      5.0      5.0
14     3      3      0.000
15     15     10      1 0.00000 0.3422
16     13     10      1 0.00000 -0.1417
17     13      8      1 0.00000 0.2218
18     13      6      1 0.00000 0.1901
19     14     10      1 0.00000 0.4627
20     14      9      1 0.00000 -0.3006
21     12      8      1 0.00000 0.2957
22     12      9      1 0.00000 0.1185
23     12      7      1 0.00000 -0.1169
24     11      8      1 0.00000 -0.1250
25     11      7      1 0.00000 0.1250
26     21     15      1 0.00000 0.1325
27     19     15      1 0.00000 -0.0510
28     20     15      1 0.00000 0.1804
29     -1     -1
30     90ZR90Y
31     0.923      2.23      1.000      franey_100
32     1
33     1      1      1      -1
34     1.00      1.00      1.00      1.00      1.00      1.00      1.00
35     1.00      1.00      1.00      1.00      1.00      1.00      1.00
36

```

Figure B.4: FOLD input file for the $^{90}\text{Zr}(^{10}\text{Be},^{10}\text{B})^{90}\text{Y}$ isovector spin giant dipole resonance.

```

1      1      1BEZRSQR2
2      600 0.03      1000.      10.      1      1      1
3      1.0+      0.0+
4      1.0      +0.0      1.0      +1.0
5      3      3      0.000
6      2      2      1      0.0      0.06463
7      3      3      1      0.0      0.18072
8      2      3      1      0.0      0.51116
9      3      2      1      0.0      -0.23584
10     -1      -1
11     10BE10B
12     2.0+      0.0+
13     6.0      +6.0      5.0      5.0
14     3      3      0.000
15     15     6      2      0.00000      0.2452
16     13     4      2      0.00000      0.1185
17     13     5      2      0.00000      0.1001
18     14     6      2      0.00000      0.2428
19     14     5      2      0.00000      -0.2081
20     12     4      2      0.00000      0.1451
21     12     6      2      0.00000      0.1001
22     11     6      2      0.00000      -0.0566
23     11     5      2      0.00000      0.0694
24     21     10     2      0.00000      0.3468
25     19     8      2      0.00000      0.2081
26     19     9      2      0.00000      0.1298
27     20     10     2      0.00000      0.3406
28     20     9      2      0.00000      -0.3074
29     18     10     2      0.00000      0.1298
30     18     8      2      0.00000      0.2124
31     18     7      2      0.00000      -0.1124
32     17     10     2      0.00000      -0.0742
33     17     9      2      0.00000      0.0757
34     17     7      2      0.00000      0.0918
35     16     8      2      0.00000      0.1298
36     16     9      2      0.00000      0.0566
37     28     15     2      0.00000      0.1451
38     27     15     2      0.00000      0.1422
39     25     15     2      0.00000      0.0508
40     24     15     2      0.00000      -0.0276
41     -1      -1
42     90ZR90Y
43     0.923      2.23      1.000      franey_100
44     1
45     2      1      2      -1
46     1.00      1.00      1.00      1.00      1.00      1.00      1.00
47     1.00      1.00      1.00      1.00      1.00      1.00      1.00
48

```

Figure B.5: FOLD input file for the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B})^{90}\text{Y}$ isovector spin giant quadrupole resonance.

APPENDIX C

DWHI Input Files

This appendix includes the DWHI input files for each of the transitions used in the Multipole Decomposition Analysis (MDA) for the $^{90}\text{Zr}(^{10}\text{Be},^{10}\text{B})^{90}\text{Y}$ reaction at Q_{CE} , which is -1.77 MeV.

```
1 12100000410000000 MG26(C,B) STATE 1 ROUSSEL-CHOMAZ (O+SI) POTL
2 BEZRIVM
3 61. 0. 0.1
4 300 1 0 0 0 0
5 0.03 600
6 1000. 10. 4. 90. 40. 1.30 3. 0.
7 1. -127. 1.491 0.533 0. -101. 1.491 0.533 0. 0.
8 0.
9 -1.77 10. 5. 90. 39. 1.30 3. 0.
10 1. -147. 1.449 0.560 0. -118. 1.449 0.560 0. 0.
11 0.
12 0 0 0
13 0. 0. 0. 1.
14 ivgmr.plot
15
```

Figure C.1: DWHI input file for the $^{90}\text{Zr}(^{10}\text{Be},^{10}\text{B})^{90}\text{Y}$ isovector giant monopole resonance at $E_x = Q$.

```

1  1210000041000000      MG26(C,B) STATE 1 ROUSSEL-CHOMAZ (O+SI) POTL
2  BEZRGQR
3      61.      0.      0.1
4  300  1  0  0  0  4
5      0.03      600
6  1000.      10.      4.      90.      40.      1.30      3.      0.
7  1.      -127.      1.491      0.533      0.      -101.      1.491      0.533      0.      0.
8  0.
9  -1.77      10.      5.      90.      39.      1.30      3.      0.
10 1.      -147.      1.449      0.560      0.      -118.      1.449      0.560      0.      0.
11 0.
12  2  0  4
13  0.      0.      0.      1.
14  ivgqr.plot
15

```

Figure C.3: DWHI input file for the $^{90}\text{Zr}(^{10}\text{Be},^{10}\text{B})^{90}\text{Y}$ isovector giant quadrupole resonance at $E_x = Q$.

```

1  1210000041000000      MG26(C,B) STATE 1 ROUSSEL-CHOMAZ (O+SI) POTL
2  BEZRGDR
3      61.      0.      0.1
4  300  1  0  0  0  2
5      0.03      600
6  1000.      10.      4.      90.      40.      1.30      3.      0.
7  1.      -127.      1.491      0.533      0.      -101.      1.491      0.533      0.      0.
8  0.
9  -1.77      10.      5.      90.      39.      1.30      3.      0.
10 1.      -147.      1.449      0.560      0.      -118.      1.449      0.560      0.      0.
11 0.
12  1  0  2
13  0.      0.      0.      1.
14  ivgdr.plot
15

```

Figure C.2: DWHI input file for the $^{90}\text{Zr}(^{10}\text{Be},^{10}\text{B})^{90}\text{Y}$ isovector giant dipole resonance at $E_x = Q$.

```

1  1210000041000000    MG26(C,B) STATE 1 ROUSSEL-CHOMAZ (O+SI) POTL
2  BEZRSM
3    61.    0.    0.1
4  300 1  0 2  0 2
5    0.03    600
6  1000.   10.   4.    90.   40.   1.30   3.    0.
7    1.    -127.  1.491  0.533  0.    -101.  1.491  0.533   0.    0.
8    0.
9   -1.77   10.   5.    90.   39.   1.30   3.    0.
10   1.    -147.  1.449  0.560  0.    -118.  1.449  0.560   0.    0.
11   0.
12    0  2  2
13    0.    0.    0.    1.
14  ivsmr.plot
15

```

Figure C.4: DWHI input file for the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B})^{90}\text{Y}$ isovector spin giant monopole resonance at $E_x = Q$.

```

1  1210000041000000    MG26(C,B) STATE 1 ROUSSEL-CHOMAZ (O+SI) POTL
2  BEZRSDR1
3    61.    0.    0.1
4  300 1  0 2  0 2
5    0.03    600
6  1000.   10.   4.    90.   40.   1.30   3.    0.
7    1.    -127.  1.491  0.533  0.    -101.  1.491  0.533   0.    0.
8    0.
9   -1.77   10.   5.    90.   39.   1.30   3.    0.
10   1.    -147.  1.449  0.560  0.    -118.  1.449  0.560   0.    0.
11   0.
12    1  2  2
13    0.    0.    0.    1.
14  ivsdr1.plot
15

```

Figure C.5: DWHI input file for the $^{90}\text{Zr}(^{10}\text{Be}, ^{10}\text{B})^{90}\text{Y}$ isovector spin giant dipole resonance at $E_x = Q$.

```

1  1210000041000000      MG26(C,B) STATE 1 ROUSSEL-CHOMAZ (O+SI) POTL
2  BEZRSQR2
3      61.      0.      0.1
4  300  1  0  2  0  4
5      0.03      600
6  1000.      10.      4.      90.      40.      1.30      3.      0.
7  1.      -127.      1.491      0.533      0.      -101.      1.491      0.533      0.      0.
8  0.
9  -1.77      10.      5.      90.      39.      1.30      3.      0.
10 1.      -147.      1.449      0.560      0.      -118.      1.449      0.560      0.      0.
11 0.
12 2  2  4
13 0.      0.      0.      1.
14 ivsqr2.plot
15

```

Figure C.6: DWHI input file for the $^{90}\text{Zr}(^{10}\text{Be},^{10}\text{B})^{90}\text{Y}$ isovector spin giant quadrupole resonance at $E_x = Q$.

BIBLIOGRAPHY

- [1] M. Harakeh and A. van der Woude, *Giant Resonances: Fundamental High-Frequency Modes of Nuclear Excitation*. Oxford University Press, 2001.
- [2] D. H. Youngblood, H. L. Clark, and Y.-W. Lui, “Compression mode giant resonances,” *RIKEN Rev*, vol. 23, p. 159, 1999.
- [3] A. Bohr and B. R. Mottelson, *Nuclear structure. Volume II. Nuclear deformations*. Addison-Wesley/W. A. Benjamin, Inc., Reading, MA, 01 1975.
- [4] D. H. Youngblood, H. L. Clark, and Y.-W. Lui, “Incompressibility of nuclear matter from the giant monopole resonance,” *Phys. Rev. Lett.*, vol. 82, pp. 691–694, Jan 1999.
- [5] A. Erell, J. Alster, J. Lichtenstadt, M. A. Moinester, J. D. Bowman, M. D. Cooper, F. Irom, H. S. Matis, E. Piasezky, and U. Sennhauser, “Measurements on isovector giant resonances in pion charge exchange,” *Phys. Rev. C*, vol. 34, pp. 1822–1844, Nov 1986.
- [6] F. Irom, J. D. Bowman, G. O. Bolme, E. Piasezky, U. Sennhauser, J. Alster, J. Lichtenstadt, M. Moinester, J. N. Knudson, S. H. Rokni, and E. R. Siciliano, “Excitation of isovector giant resonances in pion single-charge exchange at 120, 165, and 230 mev,” *Phys. Rev. C*, vol. 34, pp. 2231–2239, Dec 1986.
- [7] M. Scott, *Search for the Isovector Giant Monopole Resonance via the $^{28}\text{Si}(^{10}\text{Be}, ^{10}\text{B} + \gamma)$ Reaction at 100 MeV*. PhD thesis, Michigan State University, 2015.
- [8] M. A. Franey and W. G. Love, “Nucleon-nucleon t-matrix interaction for scattering at intermediate energies,” *Phys. Rev. C*, vol. 31, pp. 488–498, Feb 1985.
- [9] H. Lenske, H. H. Wolter, and H. G. Bohlen, “Reaction mechanism of heavy-ion charge-exchange scattering at intermediate energies,” *Phys. Rev. Lett.*, vol. 62, pp. 1457–1460, Mar 1989.
- [10] M. Leitner, B. Bird, F. Casagrande, S. Chouhan, C. Compton, J. Crisp, K. Elliott, A. Facco, A. Fox, M. Hodek, M. Johnson, G. Kiupel, I. Malloch, D. Miller, S. Miller, D. Morris, D. Norton, R. Oweiss, J. Ozelis, and S. Zhao, “The frib project at msu,” in *Proceedings of the 16th International Conference on RF Superconductivity*, 06 2013.
- [11] M. Hausmann, A. Aaron, A. Amthor, M. Avilov, L. Bandura, R. Bennett, G. Bollen, T. Borden, T. Burgess, S. Chouhan, V. Graves, W. Mittig, D. Morrissey, F. Pellemoine, M. Portillo, R. Ronningen, M. Schein, B. Sherrill, and A. Zeller, “Design of the advanced rare isotope separator aris at frib,” *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 317,

- pp. 349–353, 2013. XVIth International Conference on ElectroMagnetic Isotope Separators and Techniques Related to their Applications, December 27, 2012 at Matsue, Japan.
- [12] J. Pereira, “The nscl s800 spectrograph..” <https://wikihost.nscl.msu.edu/S800Doc/doku.php>. September 2025.
 - [13] S. Paschalis, I. Lee, A. Macchiavelli, C. Campbell, M. Cromaz, S. Gros, J. Pavan, J. Qian, R. Clark, H. Crawford, D. Doering, P. Fallon, C. Lionberger, T. Loew, M. Petri, T. Stezelberger, S. Zimmermann, D. Radford, K. Lagergren, D. Weisshaar, R. Winkler, T. Glasmacher, J. Anderson, and C. Beausang, “The performance of the gamma-ray energy tracking in-beam nuclear array gretina,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 709, pp. 44–55, 2013.
 - [14] S. Gillespie. private communication.
 - [15] S. M. Ali, C. Maher, R. G. T. Zegers, M. Scott, D. Bazin, M. Bowry, B. A. Brown, C. M. Campbell, A. Gade, S. Galès, U. Garg, M. N. Harakeh, E. Kwan, C. Langer, C. Loelius, C. Morse, S. Noji, T. Redpath, H. Sakai, M. Sasano, C. Sullivan, and D. Weisshaar, “Extraction of the non-spin- and spin-transfer isovector responses via the $^{12}\text{C}(^{10}\text{Be}, ^{10}\text{B} + \gamma)^{12}\text{B}$ reaction,” *Phys. Rev. C*, vol. 112, p. 024602, Aug 2025.
 - [16] J. Ahrens, H. Borchert, K. H. Czock, H. B. Eppler, H. Gimm, H. Gundrum, M. Kröning, P. Riehn, G. Sita Ram, A. Zieger, and B. Ziegler, “Total nuclear photon absorption cross sections for some light elements,” *Nucl. Phys. A*, vol. 251, no. 3, pp. 479–492, 1975.
 - [17] H. Okamura, S. Ishida, N. Sakamoto, H. Otsu, T. Uesaka, T. Wakasa, Y. Satoh, T. Fujita, H. Sakai, T. Niizeki, K. Katoh, T. Yamamoto, T. Yamashita, Y. Hara, H. Ohnuma, T. Ichihara, and K. Hatanaka, “Study of the spin-dipole state via the $(\vec{d}, ^2\text{He})$ reaction at 270 MeV,” *Nucl. Phys. A*, vol. 577, no. 1, pp. 89–92, 1994.
 - [18] H. Cond, N. Olsson, E. Ramström, T. Rönqvist, R. Zorro, J. Blomgren, A. Hkansson, G. Tibell, O. Jonsson, L. Nilsson, P.-U. Renberg, M. sterlund, W. Unkelbach, J. Wambach, S. van der Werf, J. Ullmann, and S. Wender, “The $^{90}\text{Zr}(n, p)^{90}\text{Y}$ reaction at $E_n=98$ mev,” *Nuclear Physics A*, vol. 545, no. 4, pp. 785–821, 1992.
 - [19] K. Miki, H. Sakai, T. Uesaka, H. Baba, C. L. Bai, G. P. A. Berg, N. Fukuda, D. Kameda, T. Kawabata, S. Kawase, T. Kubo, S. Michimasa, H. Miya, S. Noji, T. Ohnishi, S. Ota, A. Saito, Y. Sasamoto, H. Sagawa, M. Sasano, S. Shimoura, H. Takeda, H. Tokieda, K. Yako, Y. Yanagisawa, and R. G. T. Zegers, “Identification of the β^+ isovector spin monopole resonance via the ^{208}Pb and $^{90}\text{Zr}(t, ^3\text{He})$ reactions at 300 MeV/u,” *Phys. Rev. Lett.*, vol. 108, p. 262503, Jun 2012.

- [20] K. Yako, H. Sakai, M. Greenfield, K. Hatanaka, M. Hatano, J. Kamiya, H. Kato, Y. Kitamura, Y. Maeda, C. Morris, H. Okamura, J. Rapaport, T. Saito, Y. Sakemi, K. Sekiguchi, Y. Shimizu, K. Suda, A. Tamii, N. Uchigashima, and T. Wakasa, “Determination of the gamowteller quenching factor from charge exchange reactions on ^{90}Zr ,” *Physics Letters B*, vol. 615, no. 3, pp. 193–199, 2005.
- [21] W. Bothe and W. Gentner, “Atomumwandlungen durch r-strahlen,” *Zeitschrift fr Physik*, vol. 106, pp. 236–248, 1937.
- [22] A. M. Migdal, “Quadrupole and dipole γ -radiation of nuclei,” *J. Phys. USSR*, p. 8:331, 1944.
- [23] G. C. Baldwin and G. S. Klaiber, “Photo-fission in heavy elements,” *Phys. Rev.*, vol. 71, pp. 3–10, Jan 1947.
- [24] M. Goldhaber and E. Teller, “On nuclear dipole vibrations,” *Phys. Rev.*, vol. 74, pp. 1046–1049, Nov 1948.
- [25] H. Steinwedel, J. H. D. Jensen, and P. Jensen, “Nuclear dipole vibrations,” *Phys. Rev.*, vol. 79, p. 1019, Sep 1950.
- [26] B. L. Berman and S. C. Fultz, “Measurements of the giant dipole resonance with monoenergetic photons,” *Rev. Mod. Phys.*, vol. 47, pp. 713–761, Jul 1975.
- [27] B. S. Ishkhanov and I. M. Kapitonov, “Giant dipole resonance of atomic nuclei. prediction, discovery, and research,” *Physics-Uspekhi*, vol. 64, p. 141, may 2021.
- [28] K. Goeke and J. Speth, “Theory of giant resonances,” *Annual Review of Nuclear and Particle Science*, vol. 32, no. Volume 32, 1982, pp. 65–115, 1982.
- [29] R. Pitthan and T. Walcher, “Inelastic electron scattering in the giant resonance region of la, ce and pr,” *Physics Letters B*, vol. 36, no. 6, pp. 563–564, 1971.
- [30] S. Fukuda and Y. Torizuka, “Giant multipole resonances in ^{90}Zr observed by inelastic electron scattering,” *Phys. Rev. Lett.*, vol. 29, pp. 1109–1111, Oct 1972.
- [31] M. Lewis and F. Bertrand, “Evidence from inelastic proton scattering for a giant quadrupole vibration in spherical nuclei,” *Nuclear Physics A*, vol. 196, no. 2, pp. 337–346, 1972.
- [32] D. H. Youngblood, J. M. Moss, C. M. Rozsa, J. D. Bronson, A. D. Bacher, and D. R. Brown, “Giant resonances observed in the scattering of 96- and 115-mev alpha particles,” *Phys. Rev. C*, vol. 13, pp. 994–1008, Mar 1976.

- [33] M. N. Harakeh, K. van der Borg, T. Ishimatsu, H. P. Morsch, A. van der Woude, and F. E. Bertrand, “Direct evidence for a new giant resonance at $80A^{-\frac{1}{3}}$ mev in the lead region,” *Phys. Rev. Lett.*, vol. 38, pp. 676–679, Mar 1977.
- [34] J. M. Lattimer, “Constraints on nuclear symmetry energy parameters,” *Particles*, vol. 6, no. 1, pp. 30–56, 2023.
- [35] P. Danielewicz, P. Singh, and J. Lee, “Symmetry energy iii: Isovector skins,” *Nuclear Physics A*, vol. 958, pp. 147–186, 2017.
- [36] B. G. Todd-Rutel and J. Piekarewicz, “Neutron-rich nuclei and neutron stars: A new accurately calibrated interaction for the study of neutron-rich matter,” *Phys. Rev. Lett.*, vol. 95, p. 122501, Sep 2005.
- [37] B. Alex Brown, “Neutron radii in nuclei and the neutron equation of state,” *Phys. Rev. Lett.*, vol. 85, pp. 5296–5299, Dec 2000.
- [38] S. Fracasso and G. Colò, “Fully self-consistent charge-exchange quasiparticle random-phase approximation and its application to isobaric analog resonances,” *Phys. Rev. C*, vol. 72, p. 064310, Dec 2005.
- [39] N. Auerbach and A. Klein, “A microscopic theory of giant electric isovector resonances,” *Nuclear Physics A*, vol. 395, no. 1, pp. 77–118, 1983.
- [40] K. Langanke and G. Martínez-Pinedo, “Nuclear weak-interaction processes in stars,” *Rev. Mod. Phys.*, vol. 75, pp. 819–862, 2003.
- [41] T. Marketin, G. Martínez-Pinedo, N. Paar, and D. Vretenar, “Role of momentum transfer in the quenching of gamow-teller strength,” *Phys. Rev. C*, vol. 85, p. 054313, May 2012.
- [42] J. Speth, ed., *Electric and Magnetic Giant Resonances in Nuclei*, vol. 7 of *International Review of Nuclear Physics*. Singapore: World Scientific, 1991.
- [43] S. Shlomo and D. H. Youngblood, “Nuclear matter compressibility from isoscalar giant monopole resonance,” *Phys. Rev. C*, vol. 47, pp. 529–536, Feb 1993.
- [44] U. Garg, *Isoscalar Giant Resonances: Experimental Studies*, pp. 631–673. Singapore: Springer Nature Singapore, 2023.
- [45] H. Steinwedel and J. D.Jensen, “Hydrodynamik von kerndipolschwingungen,” *Zeitschrift fr Naturforschung A*, vol. 5, no. 8, pp. 413–420, 1950.
- [46] J. Bowman, E. Lipparini, and S. Stringari, “Isovector monopole excitation energies,” *Physics Letters B*, vol. 197, no. 4, pp. 497–499, 1987.

- [47] F. Osterfeld, “Nuclear spin and isospin excitations,” *Rev. Mod. Phys.*, vol. 64, pp. 491–557, Apr 1992.
- [48] A. Bohr and B. Mottelson, *Nuclear Structure: Volume Ii (nuclear Deformations)*. Nuclear Structure, Basic Books, 1969.
- [49] S. Fallieros and B. Goulard, “Isovector excitations in nuclei,” *Nuclear Physics A*, vol. 147, no. 3, pp. 593–600, 1970.
- [50] M. Ichimura, H. Sakai, and T. Wakasa, “Spinisospin responses via (p,n) and (n,p) reactions,” *Progress in Particle and Nuclear Physics*, vol. 56, no. 2, pp. 446–531, 2006.
- [51] Y. Fujita, B. Rubio, and W. Gelletly, “Spinisospin excitations probed by strong, weak and electro-magnetic interactions,” *Progress in Particle and Nuclear Physics*, vol. 66, no. 3, pp. 549–606, 2011.
- [52] R. G. T. Zegers, *Excitation of Isovector Giant Resonances Through Charge-Exchange Reactions*, pp. 739–773. Singapore: Springer Nature Singapore, 2023.
- [53] R. G. T. Zegers, A. M. van den Berg, S. Brandenburg, F. R. R. Fleurot, M. Fujiwara, J. Guillot, V. M. Hannen, M. N. Harakeh, H. Laurent, K. van der Schaaf, S. Y. van der Werf, A. Willis, and H. W. Wilschut, “Search for isovector giant monopole resonances via the $\text{Pb}(^3\text{He}, tp)$ reaction,” *Phys. Rev. Lett.*, vol. 84, pp. 3779–3782, Apr 2000.
- [54] R. G. T. Zegers, S. Brandenburg, M. N. Harakeh, S. Y. van der Werf, J. Jänecke, T. O’Donnell, D. A. Roberts, S. Shaheen, G. P. A. Berg, C. C. Foster, T. Rinckel, and E. J. Stephenson, “Search for isovector giant monopole resonances via the $^{124}\text{Sn}(^3\text{He}, tn)$ reaction,” *Phys. Rev. C*, vol. 61, p. 054602, Mar 2000.
- [55] I. Lhenry, “Decay of the isovector giant resonances excited in charge exchange reactions,” *Nuclear Physics A*, vol. 599, no. 1, pp. 245–258, 1996. Proceedings of the Groningnen Conference on Giant Resonances.
- [56] C. Brat, M. Buner, J. Hostachy, P. Martin, J. Barrette, B. Berthier, B. Fernandez, A. Miczaka, A. Villari, H. Bohlen, S. Kubono, E. Stiliaris, and W. von Oertzen, “Electric isovector nuclear response from ^{13}C induced charge-exchange reactions,” *Nuclear Physics A*, vol. 555, no. 2, pp. 455–476, 1993.
- [57] T. Ichihara, M. Ishihara, H. Ohnuma, T. Niizeki, Y. Satou, H. Okamura, S. Kubono, M. H. Tanaka, and Y. Fuchi, “Isovector quadrupole resonance observed in the $^{60}\text{Ni}(^{13}\text{C}, ^{13}\text{N})^{60}\text{Co}$ reaction at $E/A = 100$ MeV,” *Phys. Rev. Lett.*, vol. 89, p. 142501, Sep 2002.
- [58] S. Nakayama, T. Yamagata, M. Tanaka, M. Inoue, K. Yuasa, T. Itahashi, H. Ogata, N. Koori, and K. Shima, “Relative strength $(\Delta S = 1)/[(\Delta S = 0) + (\Delta S = 1)]$ of

- isovector spin excitations in the high-lying resonance region of ^{12}C ,” *Phys. Rev. Lett.*, vol. 67, pp. 1082–1085, Aug 1991.
- [59] J. S. Winfield, D. Beaumel, S. Galès, H. Laurent, I. Lhenry, J. M. Maison, G. M. Crawley, S. Danczyk, S. E. Hirzebruch, J. C. Stasusko, and T. Suomijärvi, “The ($^7\text{Li}, ^7\text{Be}\gamma$) reaction and isovector spin strength in ^{40}Ca ,” *Phys. Rev. C*, vol. 54, no. 1, pp. 125–131, 1996.
 - [60] S. Nakayama, H. Akimune, Y. Arimoto, I. Daito, H. Fujimura, Y. Fujita, M. Fujiwara, K. Fushimi, H. Kohri, N. Koori, K. Takahisa, T. Takeuchi, A. Tamii, M. Tanaka, T. Yamagata, Y. Yamamoto, K. Yonehara, and H. Yoshida, “Isovector electric monopole resonance in ^{60}Ni ,” *Phys. Rev. Lett.*, vol. 83, pp. 690–693, Jul 1999.
 - [61] R. G. T. Zegers, R. Meharchand, Y. Shimbara, S. M. Austin, D. Bazin, B. A. Brown, C. A. Diget, A. Gade, C. J. Guess, M. Hausmann, G. W. Hitt, M. E. Howard, M. King, D. Miller, S. Noji, A. Signoracci, K. Starosta, C. Tur, C. Vaman, P. Voss, D. Weisshaar, and J. Yurkon, “ $^{34}\text{P}(^7\text{Li}, ^7\text{Be} + \gamma)$ reaction at 100A MeV in inverse kinematics,” *Phys. Rev. Lett.*, vol. 104, p. 212504, May 2010.
 - [62] R. Meharchand, R. G. T. Zegers, B. A. Brown, S. M. Austin, T. Baugher, D. Bazin, J. Deaven, A. Gade, G. F. Grinyer, C. J. Guess, M. E. Howard, H. Iwasaki, S. McDaniel, K. Meierbachtol, G. Perdikakis, J. Pereira, A. M. Prinke, A. Ratkiewicz, A. Signoracci, S. Stroberg, L. Valdez, P. Voss, K. A. Walsh, D. Weisshaar, and R. Winkler, “Probing configuration mixing in ^{12}Be with gamow-teller transition strengths,” *Phys. Rev. Lett.*, vol. 108, p. 122501, Mar 2012.
 - [63] N. Anantaraman, J. S. Winfield, Sam M. Austin, J. A. Carr, C. Djalali, A. Gillibert, W. Mittig, J. A. Nolen, and Z. W. Long, “($^{12}\text{C}, ^{12}\text{B}$) and ($^{12}\text{C}, ^{12}\text{N}$) reactions at $E/A = 70$ MeV as spin probes: Calibration and application to 1^+ states in ^{56}Mn ,” *Phys. Rev. C*, vol. 44, pp. 398–414, Jul 1991.
 - [64] Y. Sasamoto, T. Uesaka, S. Shimoura, S. Michimasa, S. Ota, H. Tokieda, H. Miya, S. Kawase, Y. Kikuchi, K. Kisamori, M. Takaki, M. Dozono, H. Mathubara, K. Yako, S. Noji, K. Miki, H. Sakai, T. Kubo, Y. Yanagisawa, H. Takeda, K. Yoshida, T. Ohnishi, N. Fukuda, D. Kameda, N. Inabe, N. Aoi, S. Takeuchi, T. Ichihara, H. Baba, S. Sakaguchi, P. Doornenbal, H. Wang, R. Chen, Y. Shimizu, T. Kawahara, T. Kawabata, N. Yokota, Y. Maeda, H. Miyasako, and G. P. A. Berg, *The super-allowed Fermi type charge exchange reaction for studies of isovector non-spin-flip monopole resonance*, pp. 148–151. World Scientific, 2012.
 - [65] Y. Sasamoto, *Study of the isovector non-spin-flip monopole resonance via the super-allowed Fermi type charge exchange ($^{10}\text{C}, ^{10}\text{B}\gamma$) reaction*. PhD thesis, University of Tokyo, 2012.

- [66] T. Uesaka, H. Matsubara, K. Miki, S. Noji, H. Sakai, Y. Sasamoto, S. Shimoura, M. Takaki, and K. Yako, “New experimental studies of nuclear spin-isospin responses,” *Progress of Theoretical Physics Supplement*, vol. 196, pp. 150–157, 10 2012.
- [67] H. Ueno, Y. Fujita, H. Fujita, T. Shinada, Y. Kanzaki, M. Yosoi, A. Tamii, K. Takahisa, F. Ihara, H. Kohri, T. Yamagata, and K. Katori, “(${}^6\text{Li}, {}^6\text{He}$) reaction at 100 MeV/nucleon as a probe of spin-excitation strengths,” *Phys. Lett. B*, vol. 465, no. 1, pp. 67–73, 1999.
- [68] T. Ichihara, M. Ishihara, H. Ohnuma, T. Niizeki, T. Yamamoto, K. Katoh, T. Yamashita, Y. Fuchi, S. Kubono, M. Tanaka, H. Okamura, S. Ishida, and T. Uesaka, “Excitation of spin-dipole states by the ${}^{12}\text{C}({}^{12}\text{C}, {}^{12}\text{N}){}^{12}\text{B}$ reaction at $E/A = 135$ MeV,” *Nucl. Phys. A*, vol. 577, no. 1, pp. 93–98, 1994.
- [69] T. Ichihara, M. Ishihara, H. Ohnuma, T. Niizeki, Y. Tajima, T. Yamamoto, Y. Fuchi, S. Kubono, M. Tanaka, H. Okamura, S. Ishida, S. Miyamoto, and H. Toyokawa, “Charge-exchange reaction ${}^{12}\text{C}({}^{12}\text{C}, {}^{12}\text{N}){}^{12}\text{B}$ at $E/A = 135$ MeV,” *Phys. Lett. B*, vol. 323, no. 3, pp. 278–283, 1994.
- [70] T. Ichihara, M. Ishihara, H. Ohnuma, T. Niizeki, T. Yamamoto, K. Katoh, T. Yamashita, Y. Hara, Y. Fuchi, S. Kubono, M. H. Tanaka, H. Okamura, S. Ishida, T. Uesaka, and Y. Satou, “Spin-flip and non-spin-flip isovector excitations observed in the $({}^{12}\text{C}, {}^{12}\text{N})$ reactions at $E/A = 135$ MeV and the $({}^{13}\text{C}, {}^{13}\text{N})$ reactions at $E/A = 100$ MeV,” *Nucl. Phys. A*, vol. 583, pp. 109–114, 1995.
- [71] S. Noji, H. Sakai, N. Aoi, H. Baba, G. P. A. Berg, P. Doornenbal, M. Dozono, N. Fukuda, N. Inabe, D. Kameda, T. Kawabata, S. Kawase, Y. Kikuchi, K. Kisamori, T. Kubo, Y. Maeda, H. Matsubara, S. Michimasa, K. Miki, H. Miya, H. Miyasako, S. Sakaguchi, Y. Sasamoto, S. Shimoura, M. Takaki, H. Takeda, S. Takeuchi, H. Tokieda, T. Ohnishi, S. Ota, T. Uesaka, H. Wang, K. Yako, Y. Yanagisawa, N. Yokota, K. Yoshida, and R. G. T. Zegers, “Excitation of the isovector spin monopole resonance via the exothermic ${}^{90}\text{Zr}({}^{12}\text{N}, {}^{12}\text{C})$ reaction at 175 MeV/ u ,” *Phys. Rev. Lett.*, vol. 120, p. 172501, Apr 2018.
- [72] M. Scott, R. G. T. Zegers, R. Almus, Sam M. Austin, D. Bazin, B. A. Brown, C. Campbell, A. Gade, M. Bowry, S. Galès, U. Garg, M. N. Harakeh, E. Kwan, C. Langer, C. Loelius, S. Lipschutz, E. Litvinova, E. Lunderberg, C. Morse, S. Noji, G. Perdikakis, T. Redpath, C. Robin, H. Sakai, Y. Sasamoto, M. Sasano, C. Sullivan, J. A. Tostevin, T. Uesaka, and D. Weisshaar, “Observation of the isovector giant monopole resonance via the ${}^{28}\text{Si}({}^{10}\text{Be}, {}^{10}\text{B}^*[1.74\text{ MeV}])$ reaction at 100A MeV,” *Phys. Rev. Lett.*, vol. 118, p. 172501, Apr 2017.
- [73] J. Cook, K. W. Kemper, P. V. Drumm, L. K. Fifield, M. A. C. Hotchkis, T. R. Ophel, and C. L. Woods, “ ${}^{16}\text{O}({}^7\text{Li}, {}^7\text{Be}){}^{16}\text{N}$ reaction at 50 MeV,” *Phys. Rev. C*, vol. 30, pp. 1538–1544, Nov 1984.

- [74] M. Hofstee, S. van der Werf, A. van den Berg, N. Blasi, J. Bordewijk, W. Borghols, R. De Leo, G. Emery, S. Fortier, S. Gals, M. Harakeh, P. den Heijer, C. de Jager, H. Langevin-Joliot, S. Micheletti, M. Morlet, M. Pignanelli, J. Schippers, H. de Vries, A. Willis, and A. van der Woude, “Localized 1 particle-hole strength in nuclei,” *Nuclear Physics A*, vol. 588, no. 3, pp. 729–766, 1995.
- [75] S. van der Werf, “Normod.” unpublished.
- [76] T. Marketin, E. Litvinova, D. Vretenar, and P. Ring, “Fragmentation of spin-dipole strength in 90zr and 208pb,” *Physics Letters B*, vol. 706, no. 4, pp. 477–481, 2012.
- [77] I. Thompson and F. Nunes, *Nuclear Reactions for Astrophysics: Principles, Calculation and Applications of Low-Energy Reactions*. Nuclear Reactions for Astrophysics: Principles, Calculation and Applications of Low-energy Reactions, Cambridge University Press, 2009.
- [78] D. Jackson, *Nuclear Reactions*. Science paperbacks, Methuen, 1970.
- [79] V. Madsen, “A formalism for direct inelastic scattering and charge exchange,” *Nuclear Physics*, vol. 80, no. 1, pp. 177–197, 1966.
- [80] R. G. T. Zegers, *Search for isovector giant monopole resonances*. PhD thesis, University of Groningen, 1999.
- [81] B. Brown and W. Rae, “The shell-model code nushellx@msu,” *Nuclear Data Sheets*, vol. 120, pp. 115–118, 2014.
- [82] B. Alex Brown, “New skyrme interaction for normal and exotic nuclei,” *Phys. Rev. C*, vol. 58, pp. 220–231, Jul 1998.
- [83] W. G. Love and M. A. Franey, “Effective nucleon-nucleon interaction for scattering at intermediate energies,” *Phys. Rev. C*, vol. 24, pp. 1073–1094, Sep 1981.
- [84] M. A. Franey and W. G. Love, “Nucleon-nucleon t -matrix interaction for scattering at intermediate energies,” *Phys. Rev. C*, vol. 31, pp. 488–498, Feb 1985.
- [85] J. A. Tostevin and B. A. Brown, “Diffraction dissociation contributions to two-nucleon knockout reactions and the suppression of shell-model strength,” *Phys. Rev. C*, vol. 74, p. 064604, Dec 2006.
- [86] B. Alex Brown, “New skyrme interaction for normal and exotic nuclei,” *Phys. Rev. C*, vol. 58, pp. 220–231, Jul 1998.
- [87] N. Anantaraman, J. S. Winfield, S. M. Austin, J. A. Carr, C. Djalali, A. Gillibert, W. Mittig, J. A. Nolen, and Z. W. Long, “($^{12}\text{C}, ^{12}\text{B}$) and ($^{12}\text{C}, ^{12}\text{N}$) reactions at $e/a=70$

- mev as spin probes: Calibration and application to 1^+ states in ^{56}Mn ,” *Phys. Rev. C*, vol. 44, pp. 398–414, Jul 1991.
- [88] J. Engel, P. Vogel, and M. R. Zirnbauer, “Nuclear structure effects in double-beta decay,” *Phys. Rev. C*, vol. 37, pp. 731–746, Feb 1988.
 - [89] J. Suhonen, *From Nucleons to Nucleus: Concepts of Microscopic Nuclear Theory*. Theoretical and Mathematical Physics, Berlin, Germany: Springer, 2007.
 - [90] P. Ring and P. Schuck, *The Nuclear Many-Body Problem*. Physics and astronomy online library, Springer, 2004.
 - [91] E. Litvinova, B. Brown, D.-L. Fang, T. Marketin, and R. Zegers, “Benchmarking nuclear models for gamowteller response,” *Physics Letters B*, vol. 730, pp. 307–313, 2014.
 - [92] C. Robin and E. Litvinova, “Nuclear response theory for spin-isospin excitations in a relativistic quasiparticle-phonon coupling framework,” *The European Physical Journal A*, vol. 52, p. 205, 2016.
 - [93] H. Liang and E. Litvinova, *Model for Collective Vibration*, pp. 2143–2177. Singapore: Springer Nature Singapore, 2023.
 - [94] D. Morrissey and NSCL staff, “A new high-resolution separator for high-intensity secondary beams,” *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 126, no. 1, pp. 316–319, 1997. International Conference on Electromagnetic Isotope Separators and Techniques Related to Their Applications.
 - [95] G. F. Knoll, *Radiation Detection and Measurement*, vol.3. John Wiley and Sons, 2010.
 - [96] D. Bazin, J. Caggiano, B. Sherrill, J. Yurkon, and A. Zeller, “The s800 spectrograph,” *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 204, pp. 629–633, 2003. 14th International Conference on Electromagnetic Isotope Separators and Techniques Related to their Applications.
 - [97] J. Yurkon, D. Bazin, W. Benenson, D. Morrissey, B. Sherrill, D. Swan, and R. Swanson, “Focal plane detector for the s800 high-resolution spectrometer,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 422, no. 1, pp. 291–295, 1999.
 - [98] D. Weisshaar, D. Bazin, P. Bender, C. Campbell, F. Recchia, V. Bader, T. Baugher, J. Belarge, M. Carpenter, H. Crawford, M. Cromaz, B. Elman, P. Fallon, A. Forney, A. Gade, J. Harker, N. Kobayashi, C. Langer, T. Lauritsen, I. Lee, A. Lemasson,

- B. Longfellow, E. Lunderberg, A. Macchiavelli, K. Miki, S. Momiyama, S. Noji, D. Radford, M. Scott, J. Sethi, S. Stroberg, C. Sullivan, R. Titus, A. Wiens, S. Williams, K. Wimmer, and S. Zhu, “The performance of the γ -ray tracking array gretina for γ -ray spectroscopy with fast beams of rare isotopes,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 847, pp. 187–198, 2017.
- [99] W. R. Leo, *Techniques for nuclear and particle physics experiments: a how-to approach*. Berlin: Springer, 1994.
- [100] D. J. Morrissey, B. M. Sherrill, M. Steiner, A. Stolz, and I. Wiedenhoever, “Commissioning the A1900 projectile fragment separator,” *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 204, pp. 90–96, 2003.
- [101] H. Fujita, Y. Fujita, G. P. A. Berg, A. D. Bacher, C. C. Foster, K. Hara, K. Hatanaka, T. Kawabata, T. Noro, H. Sakaguchi, Y. Shimbara, T. Shinada, E. J. Stephenson, H. Ueno, and M. Yosoi, “Realization of matching conditions for high-resolution spectrometers,” *Nucl. Instr. Methods Phys. Res., Sect. A*, vol. 484, no. 1, pp. 17–26, 2002.
- [102] B. Bonin, N. Alamanos, B. Berthier, G. Bruge, H. Faraggi, D. Legrand, J. C. Lugol, W. Mittig, L. Papineau, A. I. Yavin, D. K. Scott, M. Levine, J. Arvieux, L. Farvacque, and M. Buenerd, “Response functions of ^{58}Ni , ^{116}Sn and ^{208}Pb to the excitation of intermediate-energy α -particles,” *Nucl. Phys. A*, vol. 430, no. 2, pp. 349–396, 1984.
- [103] M. Ichimura, H. Sakai, and T. Wakasa, “Spinisospin responses via (p, n) and (n, p) reactions,” *Prog. Part. Nucl. Phys.*, vol. 56, no. 2, pp. 446–531, 2006.
- [104] J. Kelley, J. Purcell, and C. Sheu, “Energy levels of light nuclei $a=12$,” *Nuclear Physics A*, vol. 968, pp. 71–253, 2017.
- [105] X. Yang, L. Wang, J. Rapaport, C. D. Goodman, C. Foster, Y. Wang, W. Unkelbach, E. Sugarbaker, D. Marchlinski, S. de Lucia, B. Luther, J. L. Ullmann, A. G. Ling, B. K. Park, D. S. Sorenson, L. Rybarczyk, T. N. Taddeucci, C. R. Howell, and W. Tornow, “Dipole and spin-dipole resonances in charge-exchange reactions on ^{12}C ,” *Phys. Rev. C*, vol. 48, pp. 1158–1171, Sep 1993.
- [106] N. Olsson, H. Condé, E. Ramström, T. Rönqvist, R. Zorro, J. Blomgren, A. Håkansson, G. Tibell, O. Jonsson, L. Nilsson, P.-U. Renberg, A. Brockstedt, P. Ekström, M. Österlund, S. Y. van der Werf, D. J. Millener, G. Szefflinska, and Z. Szefflinski, “The $^{12}\text{C}(n, p)^{12}\text{B}$ reaction at $E_n = 98$ MeV,” *Nucl. Phys. A*, vol. 559, no. 3, pp. 368–400, 1993.
- [107] S. Nakayama, H. Akimune, I. Daito, H. Fujimura, Y. Fujita, M. Fujiwara, K. Fushimi, T. Inomata, K. Ishibashi, H. Kohri, N. Koori, K. Takahisa, A. Tamii, M. Tanaka, H. Toyokawa, and T. Yamagata, “The $(^7\text{Li}, ^7\text{Be})$ reaction as a spin-probe for isovector

- excitations,” *Nucl. Instr. Methods Phys. Res., Sect. A*, vol. 402, no. 2, pp. 367–370, 1998.
- [108] T. Annakkage, J. Jänecke, J. S. Winfield, G. P. A. Berg, J. A. Brown, G. Crawley, S. Danczyk, M. Fujiwara, D. J. Mercer, K. Pham, D. A. Roberts, J. Stasko, and G. H. Yoo, “Isovector giant resonances in ${}^6\text{He}$, ${}^{12}\text{B}$, ${}^{90}\text{Y}$, ${}^{120}\text{In}$, and ${}^{208}\text{Tl}$ observed in the (${}^7\text{Li}, {}^7\text{Be}$) charge-exchange reaction,” *Nucl. Phys. A*, vol. 648, no. 1, pp. 3–44, 1999.
- [109] E. Lunderberg, *SUBBARRIER COULOMB EXCITATION AT REA3 COMMISSIONING OF THE SEGA-JANUS EXPERIMENTAL SETUP*. PhD thesis, Michigan State University, 2017.
- [110] S. Yen, B. Spicer, M. Moinester, K. Raywood, R. Abegg, W. Alford, A. Celler, T. Drake, D. Frekers, O. Husser, R. Helmer, R. Henderson, K. Hicks, K. Jackson, R. Jeppesen, J. King, N. King, K. Lin, S. Long, C. Miller, V. Officer, R. Schubank, G. Shute, M. Vetterli, and A. Yavin, “Gamow-teller strength and giant resonances in ${}^{90}\text{Zr}(\text{n,p})$ at 198 mev,” *Physics Letters B*, vol. 206, no. 4, pp. 597–600, 1988.
- [111] K. J. Raywood, B. M. Spicer, S. Yen, S. A. Long, M. A. Moinester, R. Abegg, W. P. Alford, A. Celler, T. E. Drake, D. Frekers, P. E. Green, O. Häusser, R. L. Helmer, R. S. Henderson, K. H. Hicks, K. P. Jackson, R. G. Jeppesen, J. D. King, N. S. P. King, C. A. Miller, V. C. Officer, R. Schubank, G. G. Shute, M. Vetterli, J. Watson, and A. I. Yavin, “Spin-flip isovector giant resonances from the ${}^{90}\text{Zr}(\text{n,p}){}^{90}\text{Y}$ reaction at 198 mev,” *Phys. Rev. C*, vol. 41, pp. 2836–2851, Jun 1990.