

PROPERTIES OF NEUTRON-RICH PREFRAGMENTS IN PROJECTILE FRAGMENTATION
REACTIONS

By

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ABSTRACT

Projectile fragmentation is one of the primary methods used to produce exotic nuclei at rare-isotope beam facilities. As experiments continue to push toward the limits of nuclear existence, accurate projectile fragmentation reaction models are essential for reliably predicting fragment production rates and planning future experiments. At present, these models are evaluated primarily through comparisons with inclusive fragment production cross sections. This dissertation investigates whether exclusive measurements of fast neutrons emitted in coincidence with charged reaction products are sensitive to the projectile fragmentation reaction mechanism and can therefore provide more rigorous tests of the models used to describe these reactions.

An extended analysis was performed on data from the fragmentation of an 83 MeV/u ^{32}Mg beam incident on a 235 mg/cm² beryllium target, measured with the MoNA-Sweeper setup at the National Superconducting Cyclotron Laboratory. Various neutron observables were reconstructed such as the neutron kinetic energy, angular distributions, interaction multiplicities, and coincidences-to-total ratios in coincidence with the final fragments. The measurements probed isotopic chains of $^{23-31}\text{Na}$, $^{21-29}\text{Ne}$, $^{19-24}\text{F}$ and $^{17-21}\text{O}$. The results were compared to the predictions of the Abrasion and INCL++ models using detailed GEANT4 (version 10.7) simulations of the full experimental setup. Both reaction models qualitatively reproduced the measured neutron observables, but neither model fully reproduced the complete experimental dataset. Differences between the model predictions and measured data were attributed primarily to the properties of the excited prefragments formed during the fast step of the reaction.

Fast neutrons measured in coincidence with charged reaction products were found to provide a sensitive probe of the underlying projectile fragmentation reaction mechanism. The results of this work demonstrate that such observables provide valuable complementary information to traditional production cross-section measurements and offer a new approach for evaluating and improving projectile fragmentation reaction models.

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To my family

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CHAPTER 1

INTRODUCTION

The exploration of the atomic nucleus has revealed a remarkably diverse landscape of isotopes, extending from the stable nuclei found in nature to increasingly short-lived systems that exist only under extreme laboratory conditions. Presently, over 3,300 isotopes have been discovered [1], out of the 7,000 or so that are predicted to exist [2], leaving much of the nuclear chart unexplored. Understanding where the limits of nuclear existence lie and what new features emerge as those limits are approached and surpassed are among the central scientific challenges identified in the 2023 Nuclear Science Advisory Committee (NSAC) Long Range Plan [3]. Answering these questions is essential for understanding the evolution of nuclear structure far from stability, the synthesis of heavy elements in astrophysical environments, and the fundamental interactions that govern atomic nuclei.

Progress toward these goals depends on the ability to produce and study increasingly exotic nuclei, many of which exist for less than 100 milliseconds before decaying. Among the available production mechanisms, projectile fragmentation has become the primary method for producing exotic nuclei, particularly in the neutron-rich region of the nuclear chart [4]. Since projectile fragmentation was first established as a method to produce new isotopes in the latter half of the twentieth century, hundreds of previously unknown isotopes have been discovered. Today, this reaction continues to be the main workhorse in driving exploration toward the limits of nuclear existence. As experimental facilities push farther from stability, accurate descriptions of projectile fragmentation become increasingly important for predicting fragment production cross sections. Consequently, continued progress toward answering the fundamental questions that drive the field of nuclear physics relies not only on advances in experimental capability, but also on continued improvements in our understanding of the projectile fragmentation reaction mechanism.

1.1 Background

An isotope is a nucleus with a fixed number of protons and a varying number of neutrons. As the number of neutrons changes, nuclear properties evolve, particularly as nuclei become increasingly

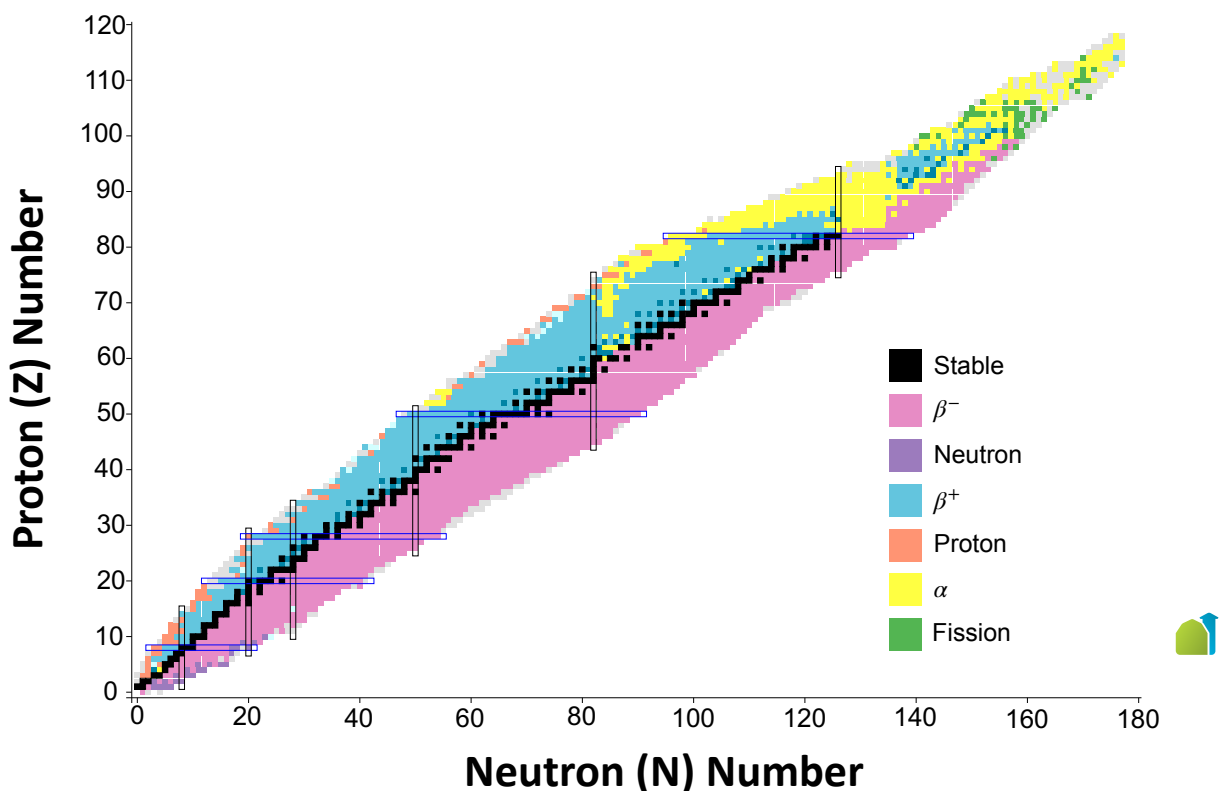


Figure 1.1: The chart of nuclides, organized by proton (Z) number on the vertical axis and neutron (N) number on the horizontal axis. The black squares represent the stable nuclides, while the other colors denote the various decay modes of the radioactive nuclides. Figure from [5].

neutron-rich (or neutron-deficient) and approach the limits of nuclear existence. A convenient way to visualize the nuclear landscape is through the chart of nuclides, which organizes all nuclei according to their proton number (Z) and neutron number (N). Similarly to how the periodic table displays patterns in chemical properties, the chart of nuclides reveals how nuclear properties evolve with neutron number. A chart of nuclides containing all presently known isotopes is shown in Figure 1.1.

Stable nuclei (shown as the black squares in Figure 1.1) occupy a relatively narrow region of the chart known as the "valley of stability," while the vast majority of known nuclei are unstable and undergo radioactive decay toward this region. Unstable nuclei are considered neutron-rich if they are to the right of the valley of stability, and neutron-deficient (proton-rich) if they are to the left of the valley of stability. The remainder of this dissertation will be focused on neutron-rich

nuclei, but note that many characteristics of neutron-rich nuclei also apply to the neutron-deficient nuclei. Eventually, the limits of nuclear binding are reached when the addition of one more neutron produces a nucleus that is unstable to neutron emission. In other words, the additional neutron is not bound to the nucleus and is emitted essentially immediately. Such nuclei are referred to as neutron-unbound nuclei, and the boundary separating neutron-bound and neutron-unbound nuclei is known as the neutron dripline. Although the neutron dripline has been experimentally established for the lightest elements (up to neon, $Z = 10$ [6, 7]), it remains unknown for much of the nuclear landscape. Extending the chart of nuclides toward these limits therefore requires experimental techniques capable of producing increasingly exotic nuclei.

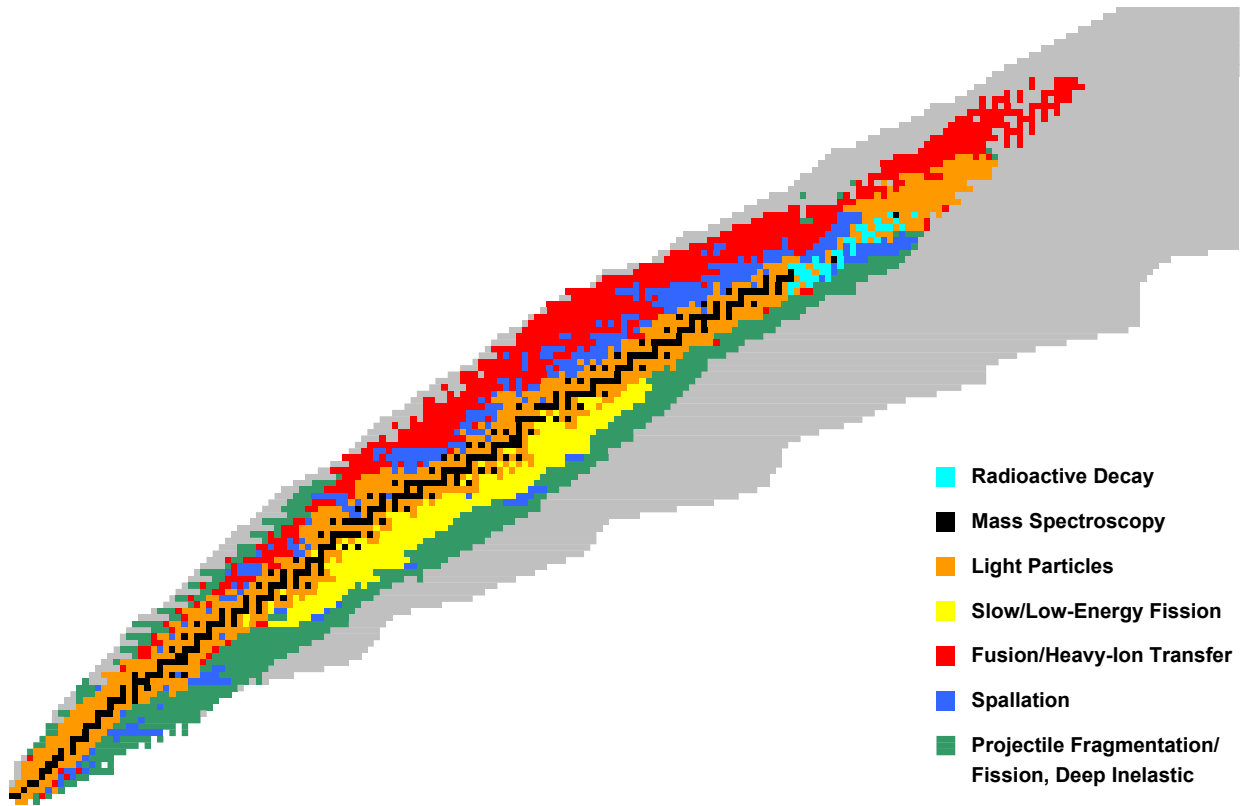


Figure 1.2: Chart of nuclides, organized in the same manner as in Figure 1.1, except the colors represent the different methods used to discover each nuclide. In particular, the nuclides in green are those which were discovered using the projectile fragmentation technique. The gray nuclides indicate those that have not been measured but are predicted to exist. Figure from [1].

The discovery of new isotopes has closely followed advances in technology: a summary depicting the different techniques used to discover the presently known nuclides is presented in Figure 1.2, with each technique displayed in a different color. Early accelerator experiments utilized reactions between stable beams and stable targets, which enabled the exploration of nuclei near the valley of stability (orange). As beam energies increased and heavy-ion accelerators became available, additional reaction mechanisms capable of producing nuclei farther from stability emerged, such as low-energy fission and fusion-evaporation reactions (yellow and red, respectively). In the present day, with heavy-ion beam energies reaching and exceeding hundreds of MeV/u, projectile fragmentation (green), combined with in-flight fragment separators, has become the primary method for producing and identifying neutron-rich nuclei far from stability. Notably, this method has been utilized in the discovery of more than 80% of all the new isotopes since 2010 [8].

The pioneering experiments studying the projectile fragmentation reaction were performed in the early 1970s using the Bevatron at Lawrence Berkeley Laboratory (LBL) in California. The results from the fragmentation of ^{14}N at 2.1 GeV/u by Heckman et al. [9] showed that the heavy reaction products produced from peripheral interactions between the projectile and target traveled with approximately the velocity of the beam¹. These observations led physicists to recognize that the forward-focused fragments could be isolated and measured or used in secondary reactions, while also motivating the development of theoretical descriptions of the reaction.

Despite the variety of theoretical descriptions that have since been developed, projectile fragmentation is generally understood as a two-step process, first described by Serber for spallation reactions [11]. Projectile fragmentation is a peripheral collision between a fast heavy-ion projectile and a relatively light target nucleus. A cartoon schematic of the reaction and its steps are shown in Figure 1.3. In the first step, the two nuclei interact, causing nucleons from the projectile to be stripped away by the target. This grazing collision creates a projectile-like "prefragment" in a highly excited state, moving with approximately the beam velocity. This first step is very fast,

¹Some of the earliest observations of heavy reaction fragments retaining velocities close to that of the incident projectile came in the 1950s from studies of relativistic heavy ion cosmic-rays using the nuclear emulsion technique [10].

occurring on the time scale it takes for the two nuclei to pass one another, on the order of 10^{-22} seconds or so. Following this, the second step occurs, where the prefragment undergoes a statistical de-excitation process, emitting various light charged particles, nucleons, and eventually γ -rays. The second step occurs on a slower time scale on the order of $10^{-21} - 10^{-18}$ seconds. After the de-excitation, the final fragment continues traveling approximately along the initial beam axis in the laboratory frame, where it can be observed experimentally.

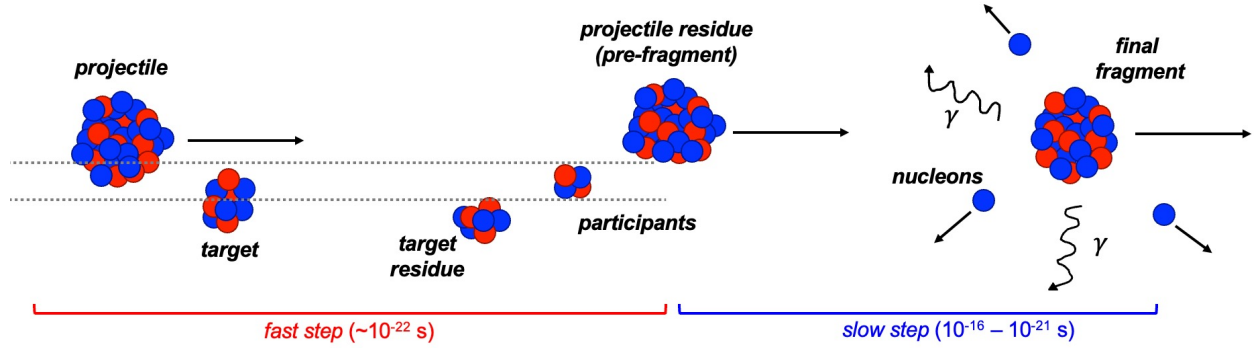


Figure 1.3: A cartoon schematic of the projectile fragmentation process. A projectile peripherally interacts with a target, forming an excited "prefragment" in the fast step. In the subsequent slow step, the prefragment de-excites by emitting various light particles and γ -rays.

Although the general two-step description of projectile fragmentation is widely accepted, a variety of theoretical approaches have been developed to describe the reaction. One class of approaches consists of empirical parameterizations such as EPAX [12] and FRACS [13], which predict isotope production rates through a fit of various spallation and fragmentation cross sections. Such semi-empirical parameterizations have the advantage of computing production cross sections without much computational strain. However, because the parameterizations are primarily based on data from stable beam experiments, these models are less reliable at extrapolating to exotic nuclei. Other, more physically motivated approaches include macroscopic abrasion-ablation models [14], which model the fast step as the geometric removal of nucleons from the projectile, and microscopic models such as the Liège Intranuclear Cascade model (INCL++) [15, 16], which describe the fast step as a cascade of individual nucleon-nucleon collisions within the interacting nuclei. These models, although they require more computational resources than semiempirical parameterizations, provide detailed descriptions of the fast step of the reaction and the properties of the resulting

intermediate prefragment.

1.2 Motivation

As experimental demands extend further from the valley of stability, the reactions that produce these nuclei involve increasingly exotic intermediate systems. Because the cross sections for producing such rare nuclei are so small [17], accurate reaction models are increasingly important for the proper planning of future experiments. Even discrepancies of a factor of two in the predicted production cross sections can substantially affect the expected beam rates, making the difference between a feasible and an infeasible experiment. Consequently, considerable effort has been devoted to developing physically motivated descriptions of the projectile fragmentation reaction.

The existence of multiple descriptions of projectile fragmentation raises an important question: how can the underlying reaction mechanism be experimentally validated? While these models share the same two-step picture and are capable of reproducing fragment production cross sections, they differ in their descriptions of the fast step of the reaction. This ambiguity becomes particularly important when the models are extrapolated to regions where little or no experimental information is available. These different fast-step descriptions lead to the formation of different prefragment properties, such as mass, excitation energy, and angular momentum. Because the prefragment formed during the fast step of the reaction undergoes de-excitation effectively immediately upon formation, direct measurements of the prefragment are impossible. Therefore, information about the reaction mechanism must be inferred from observables associated with the final reaction products.

One such experimental observable is the production cross section of the final fragments. Morrissey et al. performed calculations of a reaction between an ^{40}Ar projectile incident upon a ^{12}C target at an energy of 213 MeV/u using both a macroscopic abrasion model and a microscopic intranuclear cascade (INC) model [18]. The results of the calculations, shown in Figure 1.4, revealed the macroscopic and microscopic models to produce very different primary fragment (prefragment) distributions from one another while simultaneously predicting similar distributions of final fragments. This suggested that the de-excitation process reduces the sensitivity of the final fragment distributions to differences in the prefragment properties established during the fast step

of the reaction. Both models also reproduced general trends in the experimental cross sections for the oxygen, fluorine, and neon isotopes that were produced in the reaction (shown in Figure 1.5), but discrepancies sometimes exceeding a factor of two occurred for some isotopes. This study provided some of the earliest evidence that different reaction models could reproduce similar fragment production cross sections despite predicting substantially different prefragment distributions.

Although the comparison by Morrissey et al. was performed nearly five decades ago, inclusive fragment production cross sections remain the primary benchmark used to constrain projectile fragmentation models. Recent measurements continue to compare calculated and experimental production cross sections to further improve the reaction models [19, 20, 21, 22]. While these

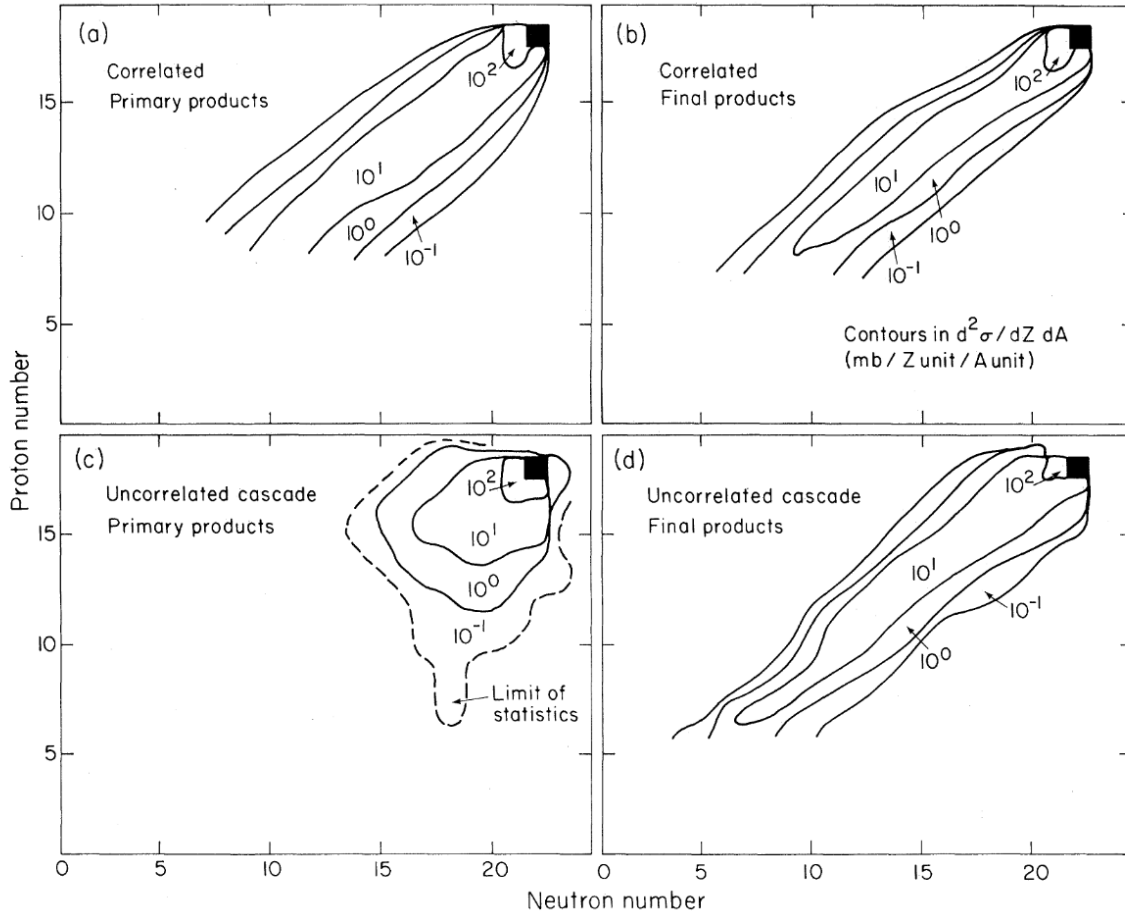


Figure 1.4: Calculations of a reaction between $^{40}\text{Ar} + ^{12}\text{C}$ at 213 MeV/u. The primary and final fragment distributions from the macroscopic abrasion model are shown in panels (a) and (b), respectively, and the same for the microscopic INC model in panels (c) and (d), respectively. Figure from [18].

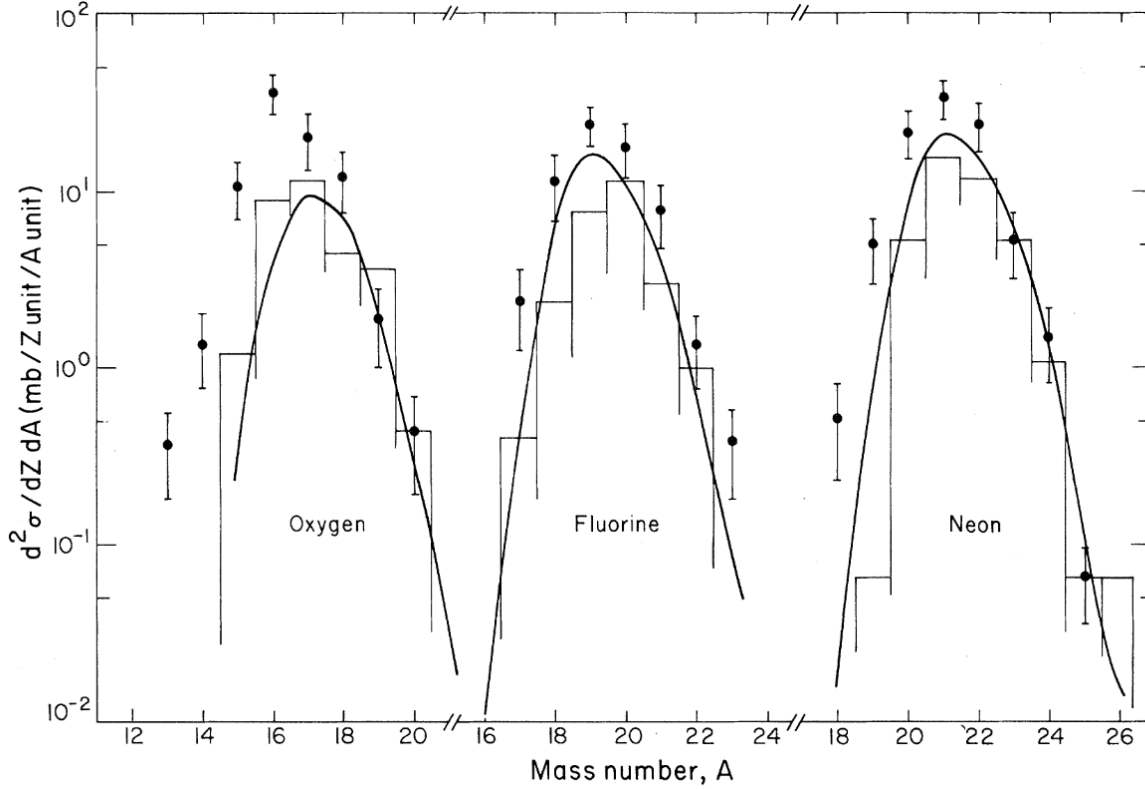


Figure 1.5: Oxygen, fluorine, and neon isotopic cross sections from a reaction between $^{40}\text{Ar} + ^{12}\text{C}$ at 213 MeV/u. The experimental results are shown as the data points, the histograms represent the INC model results, and the solid lines represent the Abrasion model results. Figure from [18].

measurements provide an essential benchmark for reaction models, they place only limited constraints on the underlying reaction mechanism. This has motivated the investigation of additional experimental observables capable of providing complementary constraints on the fast step of the reaction.

1.3 Prior Work

Previous studies have explored a variety of observables that are sensitive to different aspects of the projectile fragmentation reaction mechanism. For example, the SOFIA Collaboration at GSI performed measurements of fission observables resulting from fragmentation-induced fission of ^{236}U at 650 AMeV to constrain parameterizations describing the prefragment angular momentum [23]. The experimental fission yields were compared with those predicted by the Liège Intranuclear Cascade model (INCL++) and the Abrasion model. The results showed that the Abrasion model under-predicted the yield of the light fission fragments as compared to the experimental data, while

INCL++ agreed with the experimental data much more closely. The Abrasion model's inability to reproduce the light fission fragment yields was attributed to the prefragment angular momentum being too small. When comparing the prefragment angular momentum predictions from both the Abrasion model and INCL++, it was found that INCL++ predicted prefragment angular momenta approximately four times larger than those predicted by Abrasion for the prefragments that led to fission events.

Another example of a study to further probe the fragmentation reaction mechanism was performed using data from a fragmentation reaction of a 90-94 A MeV ^{40}Ar beam at RIKEN [24]. In this study, the longitudinal momentum distributions of the fragmentation reaction products were measured for a very wide range of fragment masses. The high-momentum side of the measured momentum distributions closely agreed with the Goldhaber model [25] for the fragment angular momentum, which is consistent with projectile fragmentation being the dominant reaction mechanism. The low momentum tail of the distribution, however, was not consistent with the "pure" fragmentation description of the reaction, and instead was attributed to an additional reaction mechanism where the projectile picks up a nucleon from the target during the interaction. In addition, fragments with more neutrons and/or protons than the projectile were observed, which provided additional evidence that other reaction mechanisms aside from the pure abrasion-ablation picture contribute at intermediate energies.

Studies like the examples presented above demonstrate the potential of complementary observables to probe the different aspects of the reaction mechanism. In addition to measuring various properties of the final fragments, it is also possible and desirable to measure the light particles emitted from the prefragment during the slow step in coincidence with the final fragment [26]. Since nucleons and light charged particles are emitted nearly isotropically in the rest frame of the prefragment, which continues to move with nearly the projectile velocity following the reaction, their emission is strongly forward focused in the laboratory frame. This forward focusing provides a significant experimental advantage, allowing detectors positioned near 0° to efficiently measure the emitted particles. In contrast, nucleons removed during the fast step of the reaction remain

centered around the target, making their efficient detection considerably more challenging. Since reactions with neutron-rich nuclei are of particular interest for this work, the main type of particle that is expected to be emitted from a neutron-rich prefragment is a neutron due to the relatively small neutron separation energies in this region. Since the neutron emission required to de-excite a prefragment to the final fragment inherently carries information about the prefragment and the underlying reaction pathway, an experiment which performs the exclusive measurement of the final fragment and the coincident neutrons could provide valuable insights to the reaction mechanism.

Such an experiment was performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. A fragmentation reaction between a neutron-rich ^{32}Mg beam and ^9Be target was performed at intermediate energies, and the subsequent neutrons emitted from the projectile-like prefragment were detected in coincidence with the final charged reaction products [27, 28] using the Modular Neutron Array (MoNA) [29] and Sweeper magnet [30] experimental setup. The primary results from the initial analysis of this experiment were the neutron interaction multiplicities in coincidence with each observed final fragment. An analysis was performed by comparing these experimental interaction multiplicities to the simulation of the de-excitation of each possible prefragment at every excitation energy in 1 MeV steps. In this analysis, only prefragments of the same element as the final fragment (meaning that only neutron emission is possible in the de-excitation) were considered. An example of an experimental interaction multiplicity being compared with different prefragments is shown in Figure 1.6. Each of the simulated interaction multiplicities were compared to the experimental distributions using a χ^2_ν statistical analysis, which allowed for the determination of a best-fit prefragment and excitation energy combination. The best-fit prefragment mass and excitation energy were compared to predictions from Abrasion models [31, 14] and the intranuclear cascade model ISABEL [32]. This comparison is presented in Figure 1.7. The best-fit prefragments to the experimental data were found to reveal a wide range of excitation energies at relatively small overall mass losses, which is more consistent with the predictions of ISABEL. This analysis of the data highlighted the promise of this experimental method to provide valuable information on the reaction mechanism.

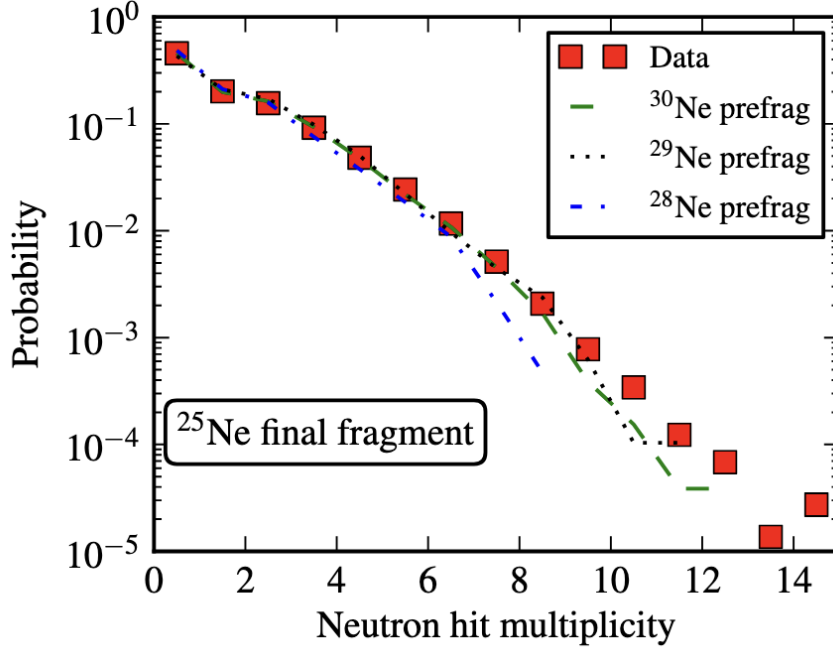


Figure 1.6: Comparison of the experimental neutron interaction, or hit, multiplicity (red squares) with the results of the simulation for ^{25}Ne final fragments. The interaction multiplicity distributions from the $^{30,29,28}\text{Ne}$ prefragments (green, black, and blue lines, respectively) at the best-fit excitation energies of 43, 23, and 14 MeV respectively, are shown. Figure from [27].

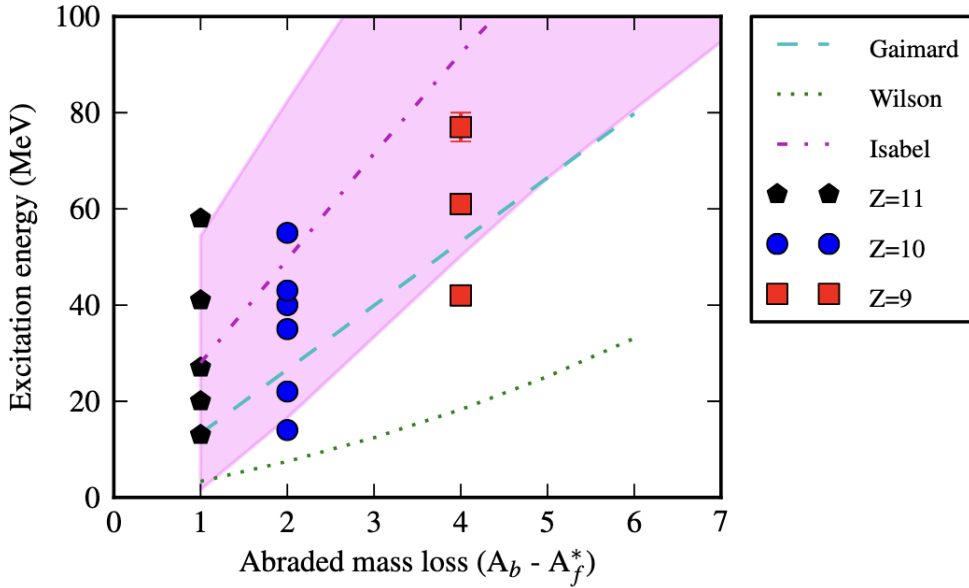


Figure 1.7: Prefragment excitation energy versus abraded mass loss (fast-step mass loss). The best-fit values from experiment are shown for $Z = 11, 10, 9$ isotopes (black pentagons, blue circles, and red squares, respectively) and compared with the predictions from the two Abrasion models [31, 14] and ISABEL [32] (green dotted, teal dashed, and pink dot-dashed lines, respectively). Figure from [27].

The work presented in this dissertation builds upon that analysis [27, 28] through a systematic investigation of neutron observables measured in coincidence with neutron-rich projectile fragments produced in the fragmentation of ^{32}Mg . The analysis is extended across multiple isotopic chains and includes comparisons of neutron kinetic energy, angular distributions, and interaction multiplicities. These observables are compared with predictions obtained using the GEANT4 [33, 34] implementation of two fundamentally different descriptions of the fast step of the reaction: the Abrasion model [14] and the Liège Intranuclear Cascade model (INCL++) [16], each coupled to the de-excitation code ABLA++ [35]. Implementing both reaction models alongside the MoNA detector geometry and response within the common GEANT4 simulation framework ensures that differences in the predicted observables arise from the reaction descriptions rather than from differences in detector modeling or the de-excitation process. Furthermore, the simulations provide direct access to the predicted prefragment properties, enabling the relationship between the reaction mechanism, the resulting prefragment characteristics, and the measured neutron observables to be investigated.

1.4 Dissertation Overview

The work presented in this dissertation investigates whether exclusive measurements of neutrons in coincidence with projectile fragmentation products provide a sensitive probe of the projectile fragmentation reaction mechanism. Because the neutron emission required to de-excite an excited prefragment to a given final fragment carries information about the underlying reaction pathway, the measured neutron observables are expected to reflect differences in the prefragment properties predicted by different reaction models. By comparing experimental neutron observables with predictions from the Abrasion and Liège Intranuclear Cascade (INCL++) reaction models, this work evaluates the sensitivity of neutron coincidence measurements to different descriptions of the fast step of the projectile fragmentation reaction.

The remainder of this dissertation is organized as follows. Chapter 2 introduces the theoretical framework of projectile fragmentation and describes the Abrasion and INCL++ reaction models, the ABLA++ de-excitation model, and their implementations within GEANT4. Chapter 3 describes the

experimental setup, including the production of the secondary beam and the Modular Neutron Array (MoNA)-Sweeper setup. Chapter 4 presents the analysis of both the experimental and simulated data, while Chapter 5 compares the measured neutron observables with the model predictions and discusses the implications of the results. Final conclusions and a future outlook are given in Chapter 6.

CHAPTER 2

FRAGMENTATION REACTION MODELS

Projectile fragmentation is commonly described as a two-step process consisting of a fast reaction step followed by the statistical de-excitation of an excited projectile-like prefragment. While many reaction models successfully reproduce inclusive observables such as fragment production cross sections, they often utilize fundamentally different descriptions of the fast step of the reaction. These different descriptions lead to different predictions for the properties of the prefragment, including its mass, excitation energy, and angular momentum, which in turn influence the subsequent de-excitation process. Since the primary objective of this work is to determine whether the exclusive measurement of neutrons in coincidence with final fragments is sensitive to these differences, it is necessary to understand how the reaction models generate the prefragment.

This chapter summarizes the two fragmentation models used in the present work: the Abrasion model and the Liège Intranuclear Cascade model. Although both models ultimately produce an excited prefragment that is passed to the same statistical de-excitation model, they differ substantially in their treatment of the fast step of the reaction. The following sections describe how each model forms the prefragment and determines its properties before introducing the ABLA++ de-excitation model and each model's implementation within GEANT4.

2.1 Abrasion-Ablation Model

One of the first models to describe the fragmentation of heavy-ion beams at relativistic energies, referred to as the geometric Abrasion-Ablation or "fireball" model, was developed in 1973 at Lawrence Berkeley Laboratory (LBL) by Bowman, Swiatecki, and Tsang [36]. This model describes these reactions in a macroscopic sense, where the projectile and target nuclei are assumed to be hard spheres. As the projectile and target nuclei overlap, a piece of the projectile (and target) nucleus gets cleanly "sheared" off, resulting in some amount of mass loss of the projectile (and target). The number of nucleons within this overlap region can be estimated as a function of the impact parameter by calculating the geometric overlap between a hard sphere (target) and a cylinder (projectile). The number of nucleons removed, N_{abr} , from a projectile with mass A_P and radius R_P

striking a target with mass A_T and radius R_T at an impact parameter b was presented by Gosset et al. [37] as

$$N_{\text{abr}} = A_P F(\nu, \beta, \mu). \quad (2.1)$$

Where $F(\nu, \beta, \mu)$ is an expression that depends on the relative sizes of the projectile and target nuclei:

$$\nu = \frac{R_P}{R_P + R_T} \quad (2.2)$$

$$\beta = \frac{b}{R_P + R_T} \quad (2.3)$$

$$\mu = \frac{R_T}{R_P} \quad (2.4)$$

and whether the collision is central or peripheral. In this model a peripheral collision is defined such that impact parameter is restricted to $R_P - R_T \leq b \leq R_P + R_T$. A central collision, then, is where $b < R_P - R_T$. In the case of peripheral collisions where $R_P > R_T$, which are the focus of the present work, the expression for $F(\nu, \beta, \mu)$ is given as:

$$F(\nu, \beta, \mu) = \frac{3}{4} (1 - \nu)^{1/2} \left(\frac{1 - \beta}{\nu} \right)^2 - \frac{1}{8} \left\{ \frac{3(1 - \beta)^{1/2}}{\nu} - \frac{[1 - (1 - \mu^2)^{3/2}][1 - (1 - \mu)^2]^{1/2}}{\mu^3} \right\} \left(\frac{1 - \beta}{\nu} \right)^3. \quad (2.5)$$

This reflects a scenario where a cylindrical cut is made through the side of the projectile, A_P . Wilson et al. [31] later added an average attenuation factor to the expression for N_{abr} to account for the nuclear mean free path λ , which results in the final form

$$N_{\text{abr}} = A_P F(\nu, \beta, \mu) \left[1 - \frac{1}{2} \exp \left(\frac{-C_P}{\lambda} \right) - \frac{1}{2} \exp \left(\frac{-C_T}{\lambda} \right) \right]. \quad (2.6)$$

The nuclear mean free path is taken as $\lambda = 16.6/E^{0.26}$, which is a parameterization of the phenomenological mean free paths obtained from experimental cross section measurements [38]. The parameter E is the beam energy in MeV. The values C_P and C_T are the maximum chord lengths of the projectile and target overlap regions, respectively.

A projectile-like prefragment can then be formed with a mass of $A_{\text{PF}} = A_P - N_{\text{abr}}$. Up to this point, only a formulation of the mass removal from the projectile has been presented. The change in charge, or the number of removed protons, has not yet been discussed. In the version of the Abrasion model used in this work, the hypergeometrical distribution is used to determine which fraction of the abraded nucleons are protons. This method assumes that each nucleon has the same probability of being removed from the nucleus, regardless of whether it is a proton or neutron. As such, the probability $P(N_{\text{PF}}, Z_{\text{PF}})$ of the reaction resulting in a prefragment with N_{PF} neutrons and Z_{PF} protons is

$$P(N_{\text{PF}}, Z_{\text{PF}}) = \frac{\binom{Z_P}{Z_P - Z_{\text{PF}}} \binom{N_P}{N_P - N_{\text{PF}}}}{\binom{A_P}{A_P - Z_{\text{PF}} - N_{\text{PF}}}}, \quad (2.7)$$

where the quantities inside the parentheses are binomial coefficients.

This hypergeometrical model corresponds to the situation where there is no correlation at all between the nucleons during the abrasion process. There are other methods which have been used to determine the proton-to-neutron ratio of the prefragment, which will only be mentioned briefly here. One method, which is used in Ref. [39], assumes that the proton-to-neutron ratio of the prefragment will be the same as that of the projectile, meaning that the removed neutrons and protons are fully correlated. Another method was proposed by Morrissey et al. [40], which falls somewhere between the first two methods. It states that the zero-point oscillation of the giant dipole resonance (GDR) determines the fluctuation of the proton-to-neutron ratio of the prefragment. Though the distribution of prefragments look quite different based on the approach taken, they can still lead to very similar distributions of final fragments after proceeding through the de-excitation step [18, 41].

2.1.1 Prefragment Excitation Energy

The prefragment, as it now contains a concave cylindrical gauge, is not in the shape of a ground-state nucleus. Rather, it has extra surface energy that must be dissipated by the emission of light particles (e.g. neutrons, protons, α , etc.). This extra surface energy was parameterized by

Gosset et al. [37] to calculate the difference in surface area between the misshapen sphere and a perfect sphere of equal volume. Oliveira et al. [41] later found that the surface excitation energy alone was too small, resulting in cross sections that were too small for light fragments far from the projectile, so they proposed an additional excitation energy contribution from a frictional spectator interaction, which overall increased the average excitation energy of the prefragments and improved results. Later, Wilson et al. [31] formulated a simpler approximation for this additional excitation energy term, which parameterizes the transfer of kinetic energy of the nucleons which are at the intersecting boundary between the projectile and target nuclei. The final form of the excitation proposed by Wilson et al. was the sum of the surface excitation energy and spectator interaction components.

A few years later, an alternative approach to calculating the excitation energy was proposed by Gaimard and Schmidt [14]. They chose to conceptualize the reaction as a diabatic model, meaning that as nucleons are removed from the projectile, the wavefunctions of its remaining nucleons are mostly undisturbed. This leaves a number of vacated single-particle levels, creating holes within the potential well. The excitation energy of the resulting prefragment is given by the sum of the single particle hole energies with respect to the Fermi surface.

Quantitatively, they take a Woods-Saxon potential with an average depth of -47.4 MeV for both neutrons and protons and assume a Fermi energy of -7.4 MeV. Assuming that the probability of removing a nucleon is the same for each level, then the level density inside the well $g(\epsilon)$ is assumed to be proportional to the single particle energy ϵ [42]. This means that the number of levels is highest near the Fermi surface and decreases toward the bottom of the well, resulting in an overall distribution,

$$P(\epsilon) \propto 40 - \epsilon. \quad (2.8)$$

Integrating this equation then leads to an average excitation energy of 13.3 MeV per abraded nucleon. The excitation energy distribution for the removal of N_{abr} nucleons is given by the convolution of N_{abr} of the linear distributions described above. The excitation energy distributions

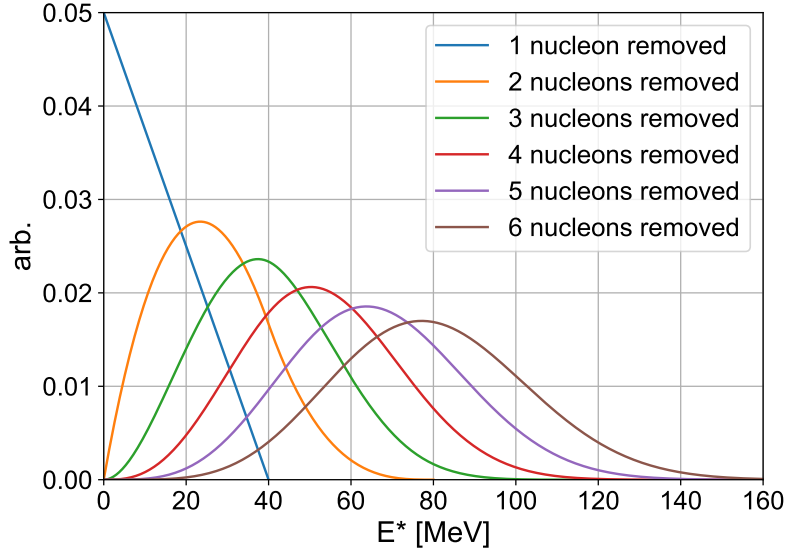


Figure 2.1: Prefragment excitation energy distributions calculated using the Gaimard and Schmidt formalism. Multiple distributions are shown in different colors representing different numbers of nucleons being removed from the projectile.

associated with the removal of multiple nucleons following this description are demonstrated in Figure 2.1.

This model assumes a diabatic abrasion process in which the remaining nucleons do not rearrange during nucleon removal. Gaimard and Schmidt investigated the validity of this assumption by estimating the degree of thermalization during the abrasion step. They defined an intrinsic thermalization time and compared it with the characteristic abrasion time to estimate the fraction of excitation energy that becomes thermalized during the reaction. Solving the corresponding differential equation yields the fraction of excitation energy that becomes thermalized during abrasion. Gaimard and Schmidt showed that for relativistic reactions (1 GeV/u) this fraction remains small for peripheral collisions, ranging from only a few percent for the removal of two nucleons to approximately 20% for the removal of ten nucleons [14].

Because the present work considers substantially lower beam energies (83 MeV/u), the same calculation was repeated for the $^{32}\text{Mg} + ^9\text{Be}$ system. The calculated fraction of thermalized excitation energy ranges from 4% to 25% for one to six abraded nucleons (Figure 2.2), indicating that most of the excitation energy remains non-thermalized. These results support the continued

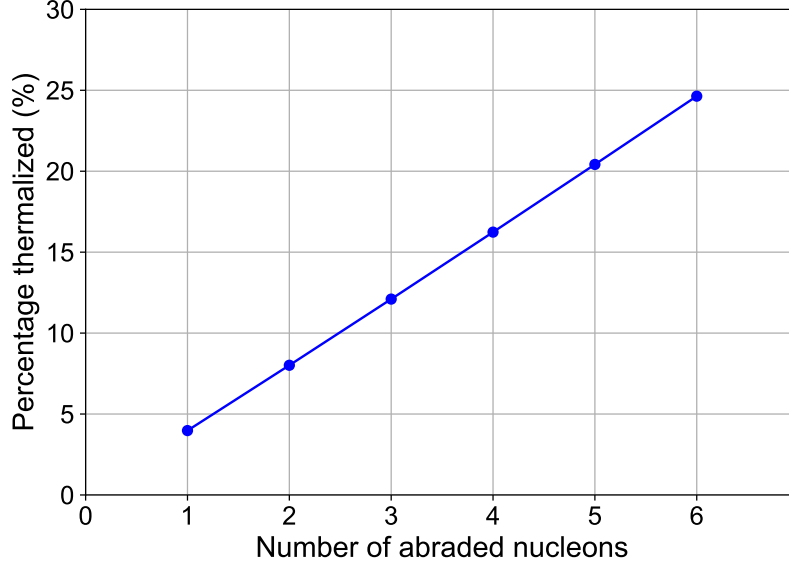


Figure 2.2: Percentage of thermalized excitation energy as a function of number of abraded nucleons. This data is for the fragmentation of $^{32}\text{Mg} + ^9\text{Be}$ at 83 MeV/u.

use of the original Gaimard-Schmidt excitation-energy prescription for the reaction discussed in this dissertation.

2.1.2 Prefragment Angular Momentum

For a more complete understanding of the fragmentation reaction mechanism, the effects of angular momentum must also be considered. Gaimard and Schmidt proposed that a statistical approach, similar to that taken by Goldhaber to describe the linear momentum of the fragmentation reaction products [25], could describe the angular momentum of the prefragment [14]. The Goldhaber formula relates the width of the fragment momentum distribution to the Fermi momenta of the removed nucleons. So, the width of the distribution of angular momenta generated during the abrasion process, referred to as the spin-cutoff parameter, can be written similarly to Goldhaber's formula [25]:

$$\sigma^2 = \langle j_z^2 \rangle \frac{A_{\text{PF}}(A_P - A_{\text{PF}})}{A_P - 1}, \quad (2.9)$$

using the mass of the projectile A_P and the prefragment A_{PF} and the average squared-value of the angular momentum projections $\langle j_z^2 \rangle$ of a nucleon in the projectile nucleus. The value of $\langle j_z^2 \rangle$ can be calculated using the nuclear shell model [43, 44]. Gaimard and Schmidt showed that this approach gives prefragments created from peripheral collisions with small angular momenta, generally less

than $10\hbar$.

In pursuit of a more general and complete description of the prefragments, de Jong et al. take into consideration all possible hole excitations of a given prefragment [45]. The probability density ρ_n for a given angular momentum J and excitation energy E^* is written as

$$\rho_n(J, E^*) \propto \frac{2J+1}{2\sigma^2(N_{\text{abr}}, E^*)} \exp \left[-\frac{J(J+1)}{2\sigma^2(N_{\text{abr}}, E^*)} \right] \quad (2.10)$$

where $\sigma^2(N_{\text{abr}}, E^*)$ is the spin-cutoff parameter, which in this case depends on the number of abraded nucleons N_{abr} and the excitation energy E^* of the prefragment. The dependence of the spin-cutoff parameter on the excitation energy for a single-hole excitation was first numerically calculated using a shell model description of the nucleus. These results were parameterized by the simple analytical expression:

$$\sigma^2(1, E^*) = 0.234 \left(1 - \frac{E^*}{\epsilon_f} \right) A_P^{2/3}. \quad (2.11)$$

It follows that the dependence of the spin-cutoff parameter on the number of abraded nucleons N_{abr} can be obtained by writing an expression analogous to the Goldhaber formula, resulting in the following expression for the spin-cutoff parameter [45]:

$$\sigma^2(N_{\text{abr}}, E^*) = 0.234 \left(1 - \frac{E^*}{N_{\text{abr}}\epsilon_f} \right) A_P^{2/3} \frac{N_{\text{abr}}(A_P - N_{\text{abr}})}{A_P - 1}. \quad (2.12)$$

Thus, Equations 2.12 and 2.10 determine the angular momentum distribution of the prefragment, from which the prefragment angular momentum J is sampled for each simulated event.

2.2 Liège Intranuclear Cascade Model (INCL++)

A separate class of models for describing fragmentation reactions, focused instead on a microscopic description of the reaction, was developed in parallel with Abrasion-Ablation models. The intranuclear cascade (INC), first proposed by Serber in 1947 [11], describes the interaction of a high-energy particle with a nucleus as a two-step process. The first step, the fast intranuclear cascade, consists of a succession of nucleon-nucleon collisions that progressively redistribute the projectile's kinetic energy among the participating target nucleons. Each participant nucleon is individually tracked as they either undergo more collisions or escape the nucleus. Following the

fast cascade, the remnant of the target nucleus releases its remaining excitation energy through the statistical emission of light particles and γ rays. This fast-slow, two-step description is conceptually similar to that adopted by Abrasion-Ablation models, although the physical description of the fast step differs substantially. While Abrasion-Ablation models treat the fast step geometrically through the sudden removal of nucleons in the overlap region of the projectile and target, INC models describe the reaction microscopically by explicitly following the dynamics of individual nucleons. The modern INC approach is based on the assumption that the incident particle possesses sufficient kinetic energy that its de Broglie wavelength is comparable to the size of a nucleon (beginning at approximately 150 MeV/u), allowing the reaction to be represented as a sequence of binary nucleon-nucleon collisions. Although the proposed low-energy limit of these models is above the energy of the reaction discussed in this dissertation (80 MeV/u), investigations have shown that the INC model used in this work perform surprisingly well at energies as low as 40 MeV/u [46, 47], supporting the use of this model in the present work.

Since Serber's original work, several INC models, including Bertini [48], ISABEL [32], and INCL++ [15], have been developed primarily for spallation reactions involving energetic light particles incident on heavy targets. The model used in the present work is the Liège Intranuclear Cascade Model (hereafter referred to as INCL++). Although the original version of INCL++ was developed for nucleon- and pion-induced reactions, the current implementation [47] has been extended to treat reactions induced by light-ion projectiles with $A \leq 18$. Because the ^{32}Mg projectile studied in this work exceeds the projectile-mass limit supported by INCL++, the calculation is performed using the accurate projectile mode introduced by Boudard et al. [47]. In this mode, the reaction is internally treated in inverse kinematics, with the light ^9Be nucleus serving as the projectile and the ^{32}Mg nucleus as the target during the cascade calculation. Following the cascade, the reaction products are transformed back into the laboratory frame before further transport.

2.2.1 Initialization

The first step of the INCL++ algorithm is the initialization of the projectile and target nuclei. Nucleons are assigned positions according to realistic proton and neutron density distributions and

momenta consistent with Fermi motion, after which they propagate within a static nuclear potential. Each of the target nucleons is assigned a position and momentum according to a Woods-Saxon distribution and a uniform Fermi sphere, respectively. The nucleon density distribution for targets with mass $A_T \geq 18$ is written as

$$\rho(r) = \begin{cases} \frac{\rho_0}{1 + \exp\left[\frac{r - R_0}{a}\right]} & r < R_{\max} \\ 0 & r \geq R_{\max} \end{cases} \quad (2.13)$$

Where $R_{\max} = R_0 + 8a$, and R_0 and a are taken from electron scattering measurements and have been parameterized as functions of the target mass number A_T [15]. The quantity ρ_0 is a normalization factor used to scale the distribution to A_T . The momentum distribution is taken as a uniform Fermi sphere with Fermi momentum p_F ,

$$p_F = \left(\frac{9\pi}{8}\right)^{1/3} \frac{\hbar}{R_0}. \quad (2.14)$$

The projectile, on the other hand, is prepared in a slightly different manner. Projectiles with mass $6 < A_P < 18$ have a density that follows the modified harmonic oscillator:

$$\rho(r) = \begin{cases} \rho_0 \frac{[1 + \alpha(r/a)^2]}{\exp[(r/a)^2]} & r < R_{\max} \\ 0 & r \geq R_{\max} \end{cases} \quad (2.15)$$

with parameters α and a taken from Ref. [49]. The momenta of the nucleons inside of the projectile are described using a Gaussian with rms momentum of $3/5 p_F$, where $p_F = 270$ MeV/c.

More recently, work was done by Rodríguez-Sánchez et al. to further improve the model agreement with experimental single nucleon removal cross sections [50]. In particular, they use Hartree-Fock-Bogoliubov calculations to better describe the proton and neutron density radii. The densities output from these calculations were fitted with the Woods-Saxon or MHO equation, based on the same mass boundaries defined above. The results from this change showed improved agreement with one nucleon removal cross-sections from proton-induced reactions on stable light, medium, and heavy targets [50].

2.2.2 Cascade

For each event, the projectile is fired at the target with a randomly sampled impact parameter, b . All nucleons within the projectile and the nucleons of the target that are within the overlap of the projectile and target nucleon densities are considered to be participants of the reaction. Nucleons in the target that are outside of the overlap region are considered spectators. As the projectile overlaps with the target nucleus, the participant nucleons are transported along classical straight-line trajectories and may undergo successive binary collisions. The probability of each interaction is determined using experimentally measured nucleon-nucleon cross sections [51], subject to Pauli blocking. The cascade continues until no further collisions are possible. In practice, the cascade is terminated once a stopping time, which is dependent on the target mass A_T , is reached [15]:

$$t_{\text{stop}} = 29.8 A_T^{0.16} \text{ fm/c}. \quad (2.16)$$

This expression was determined empirically by identifying the time at which the principal observables describing the cascade become approximately time independent. Once the stopping time is reached, the remaining nuclei are identified as excited projectile-like and target-like prefragments, whose masses, charges, momenta, excitation energies, and intrinsic angular momenta are then passed to the de-excitation model. Since for the present scenario, where the ^{32}Mg nucleus of interest is treated as the target nucleus, the following sections will focus on the target-like prefragment.

2.2.2.1 Prefragment Excitation energy and Angular Momentum

The excitation energy of the prefragment that is formed from the cascade is taken as presented by Boudard et al. [15]

$$E^* = \sum_i^{A_{\text{PF}}} T_i^{\text{PF}} - \left[\sum_i^{A_T} T_i^T - (A_T - A_{\text{PF}}) T_F \right] \quad (2.17)$$

Where the first sum iterates over the kinetic energy T of each nucleon in the prefragment, and the second sum iterates over the target (remember in this case, ^{32}Mg) nucleons in the initial state. The quantity $(A_T - A_{\text{PF}}) T_F$, where T_F is the Fermi kinetic energy, represents the minimum energy

required to remove $A_T - A_{\text{PF}}$ nucleons from the target nucleus. The excitation energy is checked at the time of each N-N collision to ensure the value remains non-negative.

The internal angular momentum of the prefragment is calculated similarly by taking the difference between the initial and final angular momenta:

$$\vec{\ell}_{\text{PF}}^* = \vec{\ell} - \left(\vec{\ell}_{\text{ej}} + \vec{\ell}_{\pi} + \vec{\ell}_{\text{PF}} \right) \quad (2.18)$$

where $\vec{\ell}$ is the angular momentum of the incident particle, $\vec{\ell}_{\text{ej}}$ is the angular momentum of the nucleons ejected from the nucleus during the cascade, $\vec{\ell}_{\pi}$ is the angular momentum of the pions, and $\vec{\ell}_{\text{PF}} = \vec{R}_{\text{PF}} \times \vec{p}_{\text{PF}}$ is the angular momentum of the prefragment's center of mass.

2.3 Comparison of Models

Although both the Abrasion and INCL++ models describe the fast step of projectile fragmentation, they are based on fundamentally different physical assumptions. An important distinction between the two approaches is the role of phenomenological parameterizations. The Abrasion model relies on parameterized descriptions of quantities such as the excitation energy and angular momentum of the prefragment, which can be optimized to fit experimental data, whereas INCL++ is designed to minimize the use of free parameters by allowing these quantities to emerge from the microscopic cascade dynamics. Despite these differences, both models ultimately produce an excited projectile-like prefragment that subsequently de-excites through statistical evaporation. Since the present work compares neutron observables predicted by these two approaches while employing the same de-excitation model (ABLA++), it is useful to summarize their principal differences before discussing the de-excitation step. These differences are presented in Table 2.1.

Table 2.1: Comparison of the methods used by the Abrasion and INCL++ reaction models to determine the prefragment mass (A_{PF}), excitation energy (E_{PF}^*), and angular momentum (J_{PF}).

Model	A_{PF}	E_{PF}^*	J_{PF}
Abrasion	geometric overlap	13.3 MeV * N_{abr}	statistical parameterization
INCL++	N-N collisions	energy conservation	angular momentum conservation

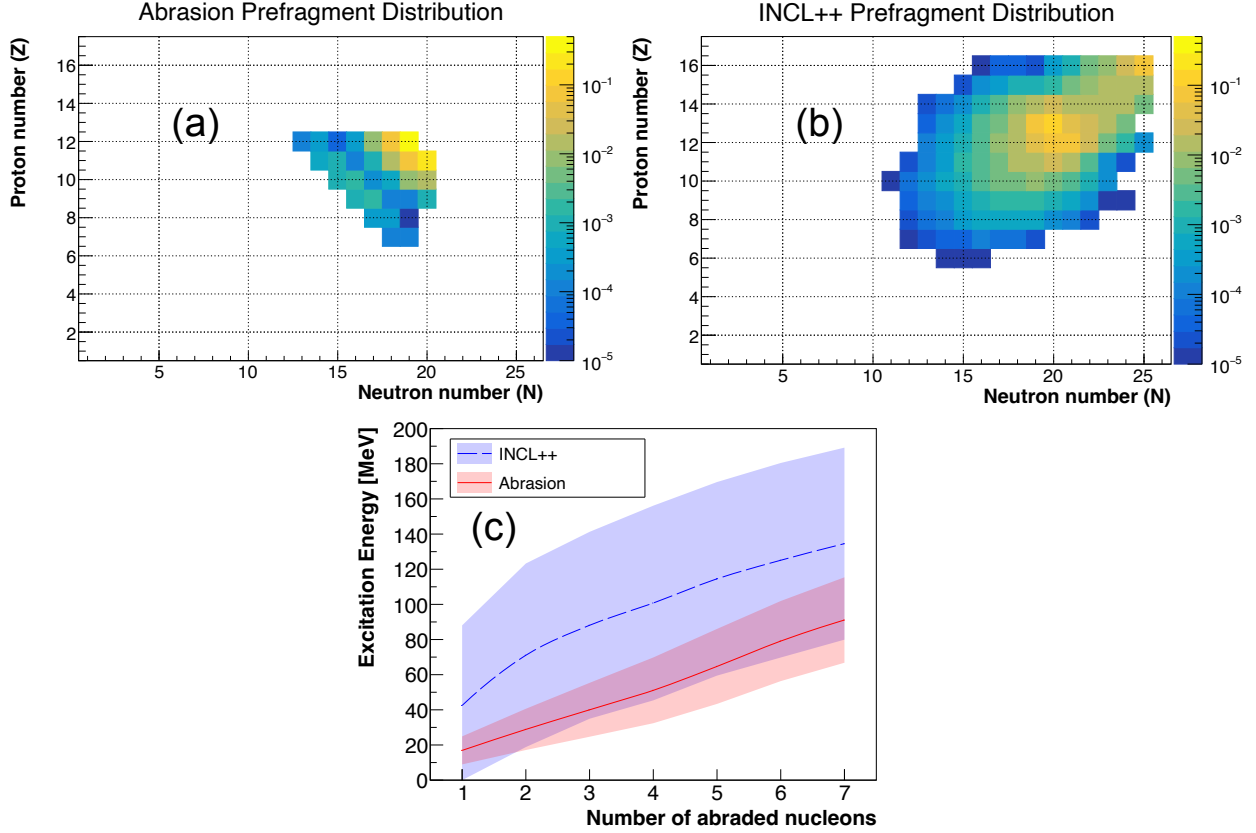


Figure 2.3: Panel (a): Prefragment mass distribution predicted by INCL++ for the fragmentation of a ^{32}Mg projectile on a ^9Be target. Panel (b): Corresponding prefragment mass distribution predicted by the Abrasion model. Panel (c): Excitation energy as a function of number of abraded nucleons. The red solid line with a red band represents the Abrasion model prediction and the blue dashed line with a blue band represents the INCL++ prediction. The width of each band corresponds to the standard deviation of the corresponding excitation energy distribution.

A comparison of the prefragment mass distributions predicted by INCL++ and Abrasion for the fragmentation of an 83 MeV/u ^{32}Mg projectile on a ^9Be target is shown in panels (a) and (b) of Figure 2.3. Panel (c) compares the mean prefragment excitation energy predicted by each model as a function of the number of abraded nucleons. These distributions illustrate the distinct descriptions of the fast step used by the two reaction models. The Abrasion model predicts relatively narrow prefragment mass distributions determined by the geometric overlap between the projectile and target, whereas INCL++ predicts substantially broader distributions that arise from the cascade of nucleon-nucleon collisions. Note that the INCL++ prefragment distribution shows a substantial number of prefragments with more protons and/or neutrons than the projectile, meaning that the

projectile can pick up nucleons from the target. The Abrasion model, by definition, only allows nucleons to be removed from the projectile, resulting in prefragments that are always lighter than the incoming projectile. Both models predict an increase in the mean prefragment excitation energy with increasing mass loss, but INCL++ generally predicts a broader range of overall larger excitation energies than the parameterized excitation-energy prescription used in the Abrasion model.

2.4 ABLA++ De-Excitation Model

Following the fast step of the reaction, the excited projectile-like prefragment undergoes statistical de-excitation through the emission of light particles and γ rays. In the present work, the ABLA++ de-excitation model [35] was chosen to be coupled to both the Abrasion and INCL++ models. Coupling both fast-step models to the same de-excitation model has the advantage that differences in the predicted neutron observables should arise primarily from differences in the fast-step reaction dynamics rather than from the statistical de-excitation treatment.

ABLA++ is a code that describes the de-excitation of an excited nucleus via emission of light particles, simultaneous break-up, and in some cases fission. In the present work, only the most peripheral reactions of a relatively light system are studied, meaning that the emission of light particles is the de-excitation process that will contribute most. At each step of the evaporation cascade, the competition between neutron, charged-particle, and γ emission is determined from their respective decay widths until the residual nucleus no longer possesses sufficient excitation energy for further particle emission.

The probability of emitting a particle, P_ν , is determined using the Weisskopf-Ewing formalism [52]. At a given excitation energy, for each possible decay channel, ABLA++ calculates a decay width Γ_ν which depends on the level densities of the mother and daughter nuclei, the Coulomb barrier, and the cross section for the inverse process. The probability for a particular decay channel P_ν is then obtained by normalizing each decay width to the sum over all possible channels,

$$P_\nu = \frac{\Gamma_\nu}{\sum \Gamma_i}. \quad (2.19)$$

Within ABLA++, the total level density of a given nucleus, which depends on the excitation

energy, is calculated from a Fermi-gas description of the intrinsic nuclear states together with collective enhancements arising from rotational and vibrational excitations. The calculated level density enters directly into the statistical decay widths. One particular notable and important aspect of the ABLA++ model is the treatment of angular momentum. In the standard Weisskopf-Ewing approach, the change of angular momentum in the evaporation process is not considered. Kelcic et al. have developed a modified version of the Weisskopf-Ewing formalism for ABLA++ [35], which calculates the angular momentum taken away from the mother nucleus by the emitted particles. From this follows a modified expression for the level density, which now accounts for rotational energy and reduces the available excitation energy. This model has been known to reproduce experimental data very well when coupled to fast-step models like INCL++ and Abrasion [53, 54].

2.5 Use of Fragmentation Models in GEANT4

Simulations of the $^{32}\text{Mg} + ^9\text{Be}$ fragmentation reaction at 83 MeV/u were performed using the Geant4 simulation toolkit (version 10.7) [33, 34, 55]. Both the nuclear reaction and the detector response were modeled within the same simulation framework, allowing the reaction products to be transported through a realistic representation of the experimental apparatus before reconstructing the same observables measured experimentally. The benchmarked GEANT4 implementations of INCL++ and ABLA++ [16] were used to model the fast-step reaction and statistical de-excitation, respectively. For comparison, the Abrasion model was implemented using the `G4WilsonAbrasion` class [34, 56], which is based on the NUCFRG2 Abrasion model developed by Wilson et al. [57]. In the present work, the `G4WilsonAbrasion` code was modified to incorporate the excitation-energy formalism of Gaimard and Schmidt [14] together with the prefragment angular momentum prescription of de Jong et al. [45]. The excited prefragments generated by both reaction models were subsequently passed to ABLA++ for statistical de-excitation. In addition, the 2020 Atomic Mass Evaluation (AME2020) [58] was adopted in place of the default AME2003 mass tables distributed with the GEANT4 implementation of ABLA++.

CHAPTER 3

EXPERIMENTAL TECHNIQUE

The experiment analyzed in the present work was performed at the National Superconducting Cyclotron Laboratory (NSCL) on the campus of Michigan State University. This facility utilizes in-flight projectile fragmentation to produce radioactive secondary beams at the Coupled Cyclotron Facility (CCF) [59]. In the present experiment, a secondary beam of ^{32}Mg was produced at an energy of 86 MeV/u to undergo a secondary fragmentation reaction on a ^9Be target. The reaction products (charged fragments and neutrons) of the $^{32}\text{Mg} + ^9\text{Be}$ fragmentation reaction were measured using the MoNA-Sweeper experimental setup in the N2 vault. In this chapter, details of the beam production, the experimental setup, and the detector operation are presented.

3.1 Beam Production

A primary beam of $^{48}\text{Ca}^{8+}$ was injected from the ion source to the K500 cyclotron, where it was accelerated to an energy of 12.32 MeV/u and then sent through a foil to strip the ion of any remaining electrons (where the final charge state then is 20+). Subsequently, this beam entered the K1200 cyclotron, where it was accelerated to 140 MeV/u. The fully-ionized beam was then transported and focused onto a 1316 mg/cm² beryllium production target to produce the desired nucleus for this study, ^{32}Mg .

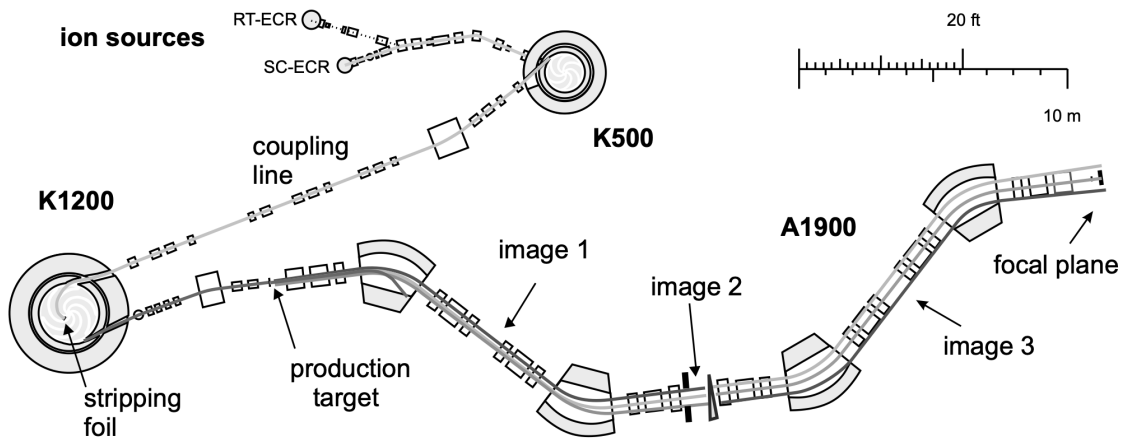


Figure 3.1: Schematic of the K500 and K1200 coupled cyclotrons and the NSCL A1900 beamline. Figure from [60].

The collision between the ^{48}Ca beam and beryllium target produced a myriad of nuclei aside from the desired ^{32}Mg . All products of this reaction were transported through the A1900 fragment separator [60], shown in Figure 3.1, where the final secondary beam of ^{32}Mg was isolated and delivered to the N2 vault. The A1900 consists of four bending dipole magnets with focusing elements in between, filtering the unreacted primary beam and reaction products by selecting the expected magnetic rigidity, $B\rho = mv/q$, of the ^{32}Mg fragments. At the intermediate focal plane between the second and third dipole was a 600 mg/cm^2 aluminum achromatic wedge degrader that was used to improve the separation of the reaction products. Since energy loss is proportional to Z^2 , a unique energy loss was imparted to fragments with the same $B\rho$ but different atomic numbers. These fragments exited the wedge with different velocities (and therefore different $B\rho$), allowing the ^{32}Mg fragments to be selected in the final two dipoles. In addition, slits were placed at the intermediate image (image 2) to limit the momentum acceptance to 0.5%. The final dipole magnet was set to a magnetic rigidity of 3.6416 Tm, corresponding to a ^{32}Mg beam energy of 86 MeV/u. The beam was transported from the A1900 focal plane to the entrance of the N2 vault with a purity of 95% and at a rate of 46 pps/pnA.

3.2 Experimental Configuration

Within the N2 vault, there were a variety of detectors used to identify the incoming ^{32}Mg beam, measure and identify the various charged reaction products, and measure neutrons produced from the reactions. A schematic of the full experimental setup within the N2 vault is shown in Figure 3.2. The ^{32}Mg beam was focused onto a beryllium reaction target at a rate of 3×10^3 pps to undergo projectile fragmentation reactions. Fragments produced during the reaction between the ^{32}Mg beam and the target entered the Sweeper magnet, where they were bent off the beam axis into a suite of charged fragment detectors: two cathode-readout drift chambers, an ionization chamber, a thin timing scintillator, and a thick scintillator. The Sweeper magnet was operated at three different settings during the course of the experiment to maximize the number of measured fragments.

Neutrons produced during the reactions continued along the beam axis, unaffected by the magnetic field of the Sweeper magnet. The neutrons exited the Sweeper vacuum chamber through

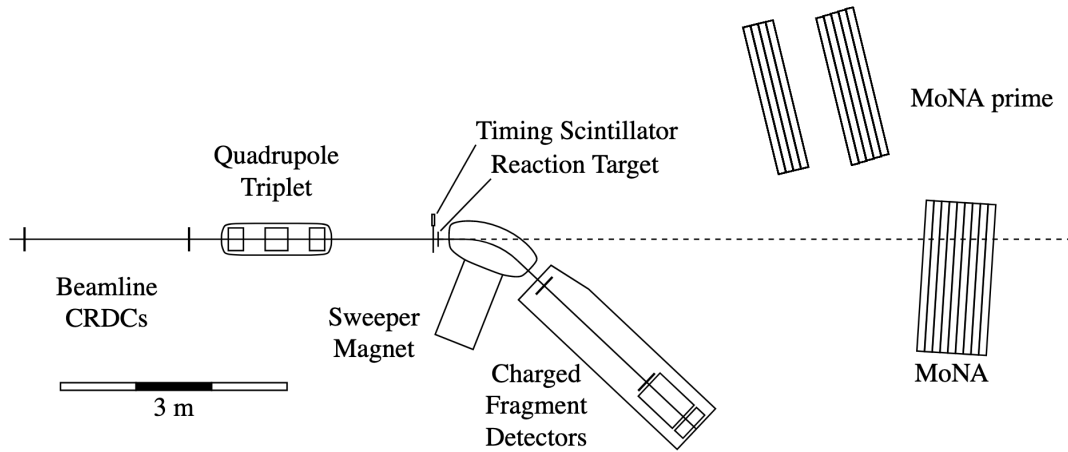


Figure 3.2: Schematic of the experimental vault layout. Figure from [27].

a thin window and then traveled through air until they interacted with the plastic scintillators in the Modular Neutron Array (MoNA). MoNA was configured in a wide-angle, two-stack configuration each consisting of 9 layers stacked 8 bars high.

This experimental configuration allowed for the coincident measurement of neutrons and charged reaction products to provide new insights into the projectile fragmentation reaction mechanism.

3.2.1 Beamline Detectors

3.2.1.1 A1900 Focal Plane Scintillator

A 127 μm thick plastic scintillator made of Bicron BC-408 material sat at the focal plane of the A1900 to provide a timing reference signal used to identify the ^{32}Mg beam entering the experimental vault. As a charged particle passes through and deposits energy into the scintillating material, some of the organic molecules are excited. In particular, the electrons are excited to the singlet π -electronic states, and then de-excite mainly through prompt (on the order of a few nanoseconds) fluorescence [61]. In order to collect and measure the scintillation light, the scintillator was optically coupled to a single photomultiplier tube (PMT). The incident light was converted to electrons in the photocathode via the photoelectric effect and then amplified and processed into a signal.

3.2.1.2 Tracking Cathode Readout Drift Chambers

The trajectory of the beam incident on the target was reconstructed using position measurements from two cathode readout drift chambers (CRDCs) [62]. A schematic of the detector is shown in Figure 3.3. Each detector was filled with a mixture of 80% CF_4 and 20% isobutane gases held at a pressure of 50 Torr. Incident charged particles ionized the gas. The freed electrons were then drifted under a -250 V drift field toward an anode wire held at +1100 V. The electrons passed through a Frisch grid to reduce position-dependent response effects before they were collected onto the anode. The drift time determined the position in the vertical (y) plane. The electrons collected on the anode induced a charge on 64 aluminum pads with a 2.54 mm pitch placed perpendicular to the wire. The distribution of charge on the pads was fit with a gaussian to determine the position in the horizontal (x) plane. The centers of the CRDCs were positioned 1.723 m and 3.546 m upstream of the target along the beam axis. Downstream of the tracking CRDCs was a focusing triplet quadrupole magnet, which was used to focus the ^{32}Mg beam onto the reaction target.

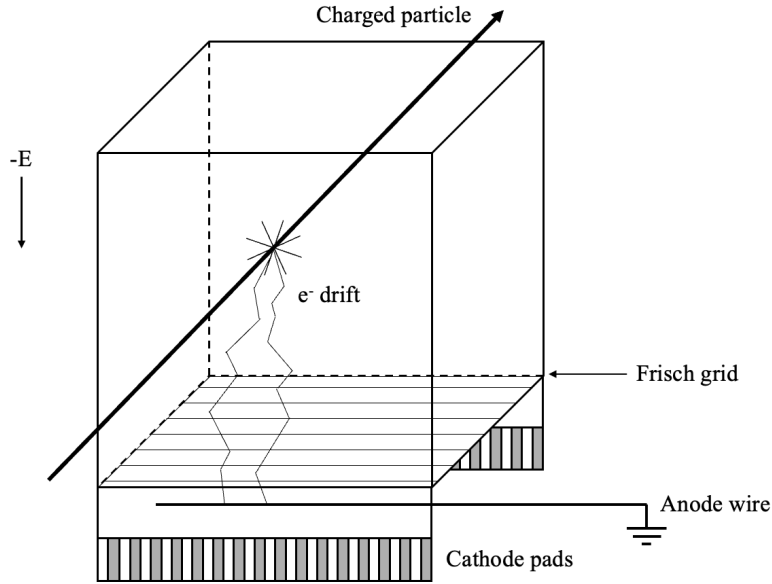


Figure 3.3: Schematic of a cathode readout drift chamber. Figure reproduced from [62].

3.2.1.3 Target Chamber

A 453 μm thick BC-404 plastic timing scintillator, which will be referred to as the target scintillator throughout this work, was placed just upstream of the reaction target. This detector was operated in the same fashion as described in Section 3.2.1.1, and was also coupled to a single PMT. The target scintillator acted as both the stop timing signal for the incoming beam (where the A1900 scintillator was the start reference signal), and the start timing signal for the charged reaction products and neutrons. This detector was operated in the fringe field of the Sweeper magnet, which at high currents can degrade the performance of the detector. Timing resolution degradation was experienced in this experiment and will be discussed in more detail in Chapter 3. A 235 mg/cm^2 beryllium target was located 6.5 cm downstream of the target scintillator. The beam energy incident on the target was approximately 83 MeV/u.

3.2.2 Sweeper Detectors

A schematic of the Sweeper magnet and charged fragment detectors is shown in Figure 3.4. This portion of the experimental setup deflected the charged reaction products away from the beam axis, measured their position and angle, energy loss, and time-of-flight. This information was used to identify each charged fragment on an event-by-event basis.

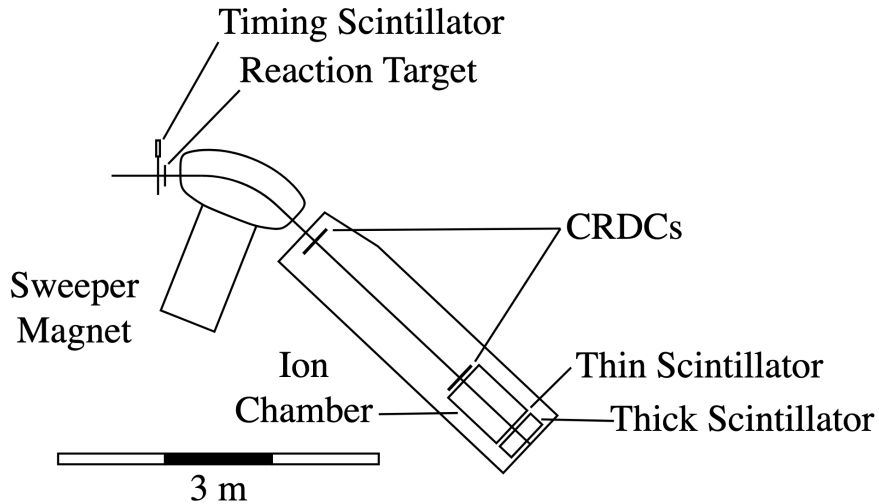


Figure 3.4: Schematic of the Sweeper detectors. The target timing scintillator and the reaction target are also shown. Figure from [27].

3.2.2.1 Sweeper Magnet

After the ^{32}Mg beam reacted with ^9Be in the target chamber, the unreacted beam and reaction products continued into the Florida State University-Michigan State University Sweeper magnet [30], where they were deflected off the beam axis into a suite of charged fragment detectors. This superconducting dipole magnet has a bending radius of 1 m, a maximum field of approximately 4 T, and in this configuration a bending angle of 43° . The Sweeper magnet also has a large 14 cm vertical gap which allowed neutrons to exit the Sweeper vacuum chamber and reach the array of neutron detectors, MoNA. This gap creates nonuniformities in the magnetic field, which were characterized by a Hall-probe mapping of the magnetic field. The neutrons passed through a 6.4 mm thick steel plate along the beam axis to exit the Sweeper magnet.

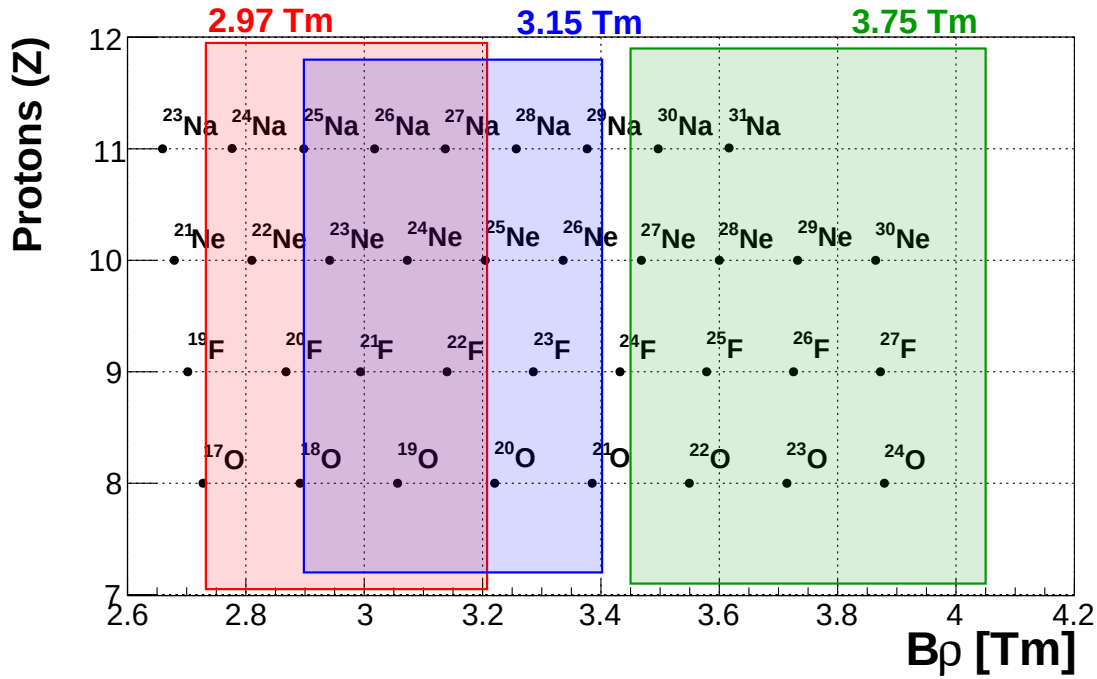


Figure 3.5: Calculated magnetic rigidities of each fragmentation reaction product. The acceptance of each magnet setting, which are labeled according to the central magnetic rigidity, are highlighted in different colors. Figure inspired by Figure 3.4 in Ref. [27].

The Sweeper magnet was operated at three different magnetic field settings in order to maximize the number of nuclides measured in the present study: 3.75 Tm, 3.15 Tm, and 2.97 Tm. The nuclides that were predicted to fall within the acceptance of each of these magnet settings are shown

in Figure 3.5. At the exit of the Sweeper magnet, a tungsten beam blocker was used in the 3.75 Tm magnet setting to stop the unreacted ^{32}Mg beam (which entered the Sweeper magnet at a rigidity of approximately 3.41 Tm) from reaching the charged fragment detectors.

3.2.2.2 Cathode Readout Drift Chambers

Two cathode readout drift chambers (CRDCs) were used to measure the dispersive (x) and non-dispersive (y) positions and angles of the charged reaction products at the exit of the Sweeper magnet. The CRDCs function in the same way as described in Section 3.2.1.2, but the specifications are somewhat different. They each have an active area of $30 \times 30 \text{ cm}^2$ and 128 aluminum pads with a pitch of 2.54 mm used for measuring position in the dispersive plane. Both of these detectors contained the same mixture of 80% CF_4 and 20% isobutane gases as the tracking CRDCs and were held at a pressure of 50 Torr. The anode voltage was set to +950 V and the drift voltage was -800 V. The two CRDCs were placed 1.82 m apart.

3.2.2.3 Ionization Chamber

An ionization chamber sat directly downstream of the second CRDC. This detector measured the energy lost by the fragments that passed through it, which was used to identify the element (atomic number Z) of the charged reaction products. The ionization chamber was filled with P-10 gas (90% argon and 10% methane) at a pressure of 300 Torr. Similarly to the CRDCs, the charged particles that entered the ionization chamber ionized the gas, releasing electron-ion pairs. A drift voltage of -800 V drifted the freed electrons through a Frisch grid and onto 16 charge collection pads which were held at +1100 V. The charge on each pad was integrated to provide a signal that is proportional to the energy deposited in the gas.

3.2.2.4 Thin Timing Scintillator

After passing through the ionization chamber, the charged reaction products went through a 500 μm thick BC-404 plastic timing scintillator, referred to throughout this work as the thin scintillator. This scintillator operates in the same manner as the timing scintillators described in Sections 3.2.1.1 and 3.2.1.3, but due to its large 40 cm $\times$ 40 cm active area, is coupled to 4 PMTs to ensure efficient light collection. Each of the PMTs is coupled to the scintillator with light guides—

two on the top edge and two on the bottom edge of the detector.

3.2.2.5 Thick Scintillator

The charged fragment detector furthest downstream of the reaction target was a 15 cm thick BC-404 plastic scintillator. This scintillator is thick enough to stop the charged fragments, and similarly to the thin scintillator, has an active area of 40 cm $\times$ 40 cm. The total light collected by the 4 PMTs coupled to this scintillator provided a signal that was related to the total residual energy and atomic number (Z) of the fragment.

3.2.3 MoNA

The position and time-of-flight of the neutrons were measured using the Modular Neutron Array (MoNA). The total detector array consists of 144 individual 2 m $\times$ 10 cm $\times$ 10 cm BC-408 plastic scintillator bars. Each bar is wrapped in a reflective material to reduce light loss and wrapped in an outer layer of black vinyl to prevent ambient light from entering the scintillator volume. A schematic of an individual MoNA bar is shown in Figure 3.6.

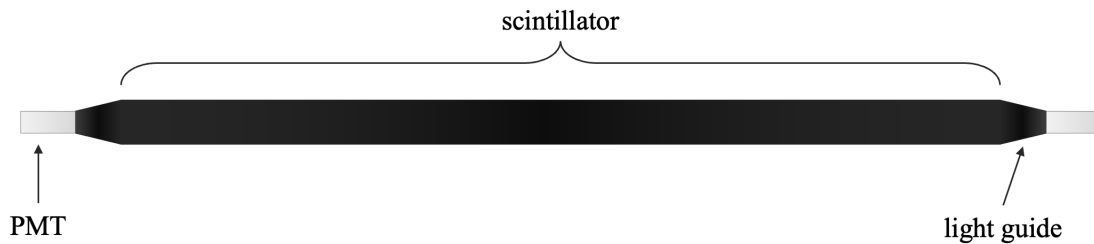


Figure 3.6: Schematic drawing of a single MoNA bar.

MoNA was arranged in an extended two-stack configuration, splitting the array into two walls: one located on the beam axis (MoNA), and the other off to the side of the beam axis (MoNA prime) to allow for the detection of neutrons at wider angles, spanning a total horizontal angular coverage of 52°. Each of these two stacks consisted of 9 vertical layers of bars stacked 8 high. The front face of MoNA was positioned 6.29 m downstream of the target, and the front face of MoNA prime 4.3 m from the target. The support tables were raised such that the bars were centered on the beam axis in the y -direction. A schematic of this configuration is shown in Figure 3.7, and a diagram

denoting the arrangement and labeling of the bars is shown in Figure 3.8.

When a neutron enters the plastic scintillator material, it can scatter on hydrogen or carbon nuclei. When a neutron elastically scatters on a hydrogen nucleus, the proton recoil deposits energy into the scintillator and fluoresces via the same process as described in Section 3.2.1.1. The same process can happen between the neutron and a carbon nucleus, but very little scintillation light is produced because the mass ratio between carbon and a neutron is much larger than the mass ratio between a proton and a neutron (by roughly an order of magnitude). As a result, most of the measured light originates from neutrons scattering on protons. The resulting scintillation light propagates to both ends of the bar and are collected and measured with photomultiplier tubes (PMTs). MoNA was constructed with two Photonis XP2262/B PMTs on each end of the bar. Each PMT has two signal outputs: an anode signal and a dynode signal. The signal from the anode was sent into a constant fraction discriminator (CFD) to generate a logic pulse which was then sent to a time to digital converter (TDC). These TDC modules operated in a common stop mode, where the logic pulse from the MoNA CFD acted as the start signal, and a signal from the target scintillator CFD acted as the common stop, providing a neutron time-of-flight measurement.

3.3 Electronics and DAQ

The Sweeper-MoNA data acquisition (DAQ) system has been described in detail in previous works [63, 64] and for the present work in Ref. [27], so only a brief outline with essential details will be included in this section. The MoNA and Sweeper DAQ subsystems are independent, and while in principle they can be operated separately, they are coupled together to record neutron-charged fragment coincidences.

The trigger logic is handled by programmable Xilinx Logic Modules (XLMs) that are separated into two levels. Level 1 determines whether a valid event was recorded in at least one MoNA bar. A valid event in MoNA constitutes a valid timing signal (above the CFD threshold of 10 mV) on both PMTs of a single MoNA bar. This information is passed to Level 2, which is the module that determines whether the entire event should be processed. The system trigger for the experiment comes from the CFD output of the left-upper (LU) PMT on the thin timing scintillator. Once Level

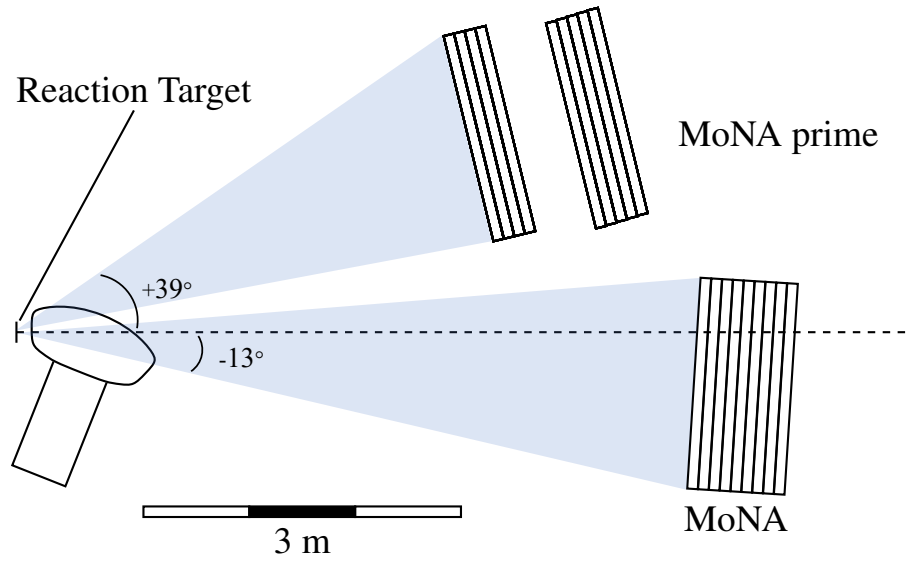


Figure 3.7: Schematic showing the configuration of MoNA and MoNA Prime in the experimental vault. The neutron horizontal angular acceptance with respect to the target is highlighted and labeled in blue and the beam axis is shown as the dotted line.

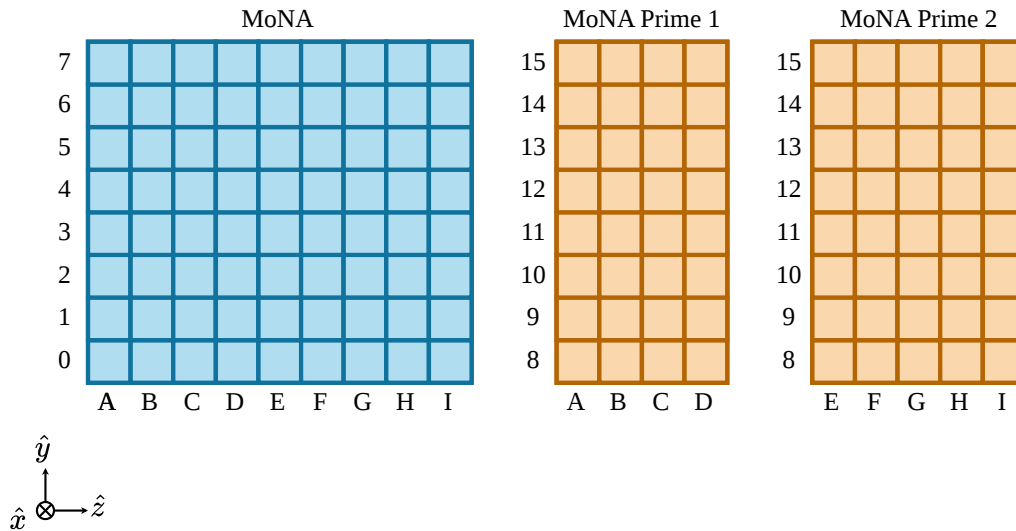


Figure 3.8: Diagram denoting labels for each bar in MoNA as seen from a side view. This diagram does not represent the positions of the stacks relative to one another.

2 receives a trigger, it opens a 250 ns coincidence window for neutron events in MoNA. If the Level 1 module received a valid event during this coincidence window, data from both MoNA and the Sweeper systems were read out. If the Level 1 module did not receive a valid event from MoNA during the coincidence window, then only data from the Sweeper detectors were read out. In other words, all charged fragment events were recorded regardless of the presence of a neutron signal.

CHAPTER 4

DATA ANALYSIS

4.1 Calibrations and Corrections

Calibrations and corrections of the detector data were performed and applied during the prior analysis of this data set and are documented in detail in Ref. [27]. These procedures converted raw detector values to meaningful quantities that could be used for physical interpretation. A brief overview of the types of calibrations and corrections that were performed in Ref. [27] is shown below.

1. **Target timing scintillator:** The timing signal from the target scintillator was calibrated by converting TDC channels to physical time units using a pulser operating at a known frequency. A linear calibration was used to determine the relationship between TDC channel and time in nanoseconds.
2. **Cathode Readout Drift Chambers (CRDCs):** Pedestal subtraction and gain matching were performed to ensure a consistent charge response across all pads. The dispersive position was determined by performing a gaussian fit of the collected charge as a function of pad number, where the calibration slope (from pad number to physical position) was set by the pad pitch and the offset was determined from mask runs. The non-dispersive position was calibrated from the electron drift time using the known locations of the mask holes in the vertical (non-dispersive) direction.
3. **Ionization Chamber:** The ionization chamber signals were gain matched using unreacted ^{32}Mg beam with a known energy. Corrections were also applied to account for drift that occurred during the experiment.
4. **Thin and Thick Scintillators:** Position-dependent variations in the scintillator response were corrected using runs where the beam was swept across the face of the detectors using

the Sweeper magnet. The scintillators were also aligned relative to one another in time using unreacted ^{32}Mg beam with known energy and path length.

5. **MoNA:** The PMTs were gain-matched using the energy deposited by cosmic-ray muons, corresponding to approximately 20 MeVee. TDC channels were converted to physical time units using pulser calibrations. Additional timing-offset corrections using cosmic ray muons were applied to align individual bars and detector layers in time, and the global timing offset relative to the target was determined using γ -rays originating from the target. Additionally, the horizontal interaction position was determined from the timing difference between the two photomultiplier tubes attached to each detector module

The present work utilized these calibrated and corrected detector quantities as input for the remainder of the analysis procedures discussed in this chapter. Only additional corrections developed specifically for this work are discussed in detail below.

4.1.1 MoNA CFD Timing Walk Correction

In order to place MoNA correctly in time relative to the target, γ -rays produced from reactions in the target are used to align MoNA correctly in time. Several past MoNA experiments have demonstrated a CFD timing walk for low energy deposition events, which needed to be corrected to ensure that the γ -ray timing is accurate. Walk was also observed in the present experiment: the correlation between the time of flight and the energy deposition of γ -ray events is shown in Figure 4.1.

In previous experiments, this walk was characterized and demonstrated to be a consistent property of the MoNA electronics [65, 66]. The form of the walk correction function is given as:

$$t_{\text{corr}} = t - \begin{cases} -2.56625e^{-0.62272/q} & q < 1.8 \\ \frac{2.861}{q} - 1.761 & q \geq 1.8, \end{cases} \quad (4.1)$$

where t_{corr} is the walk-corrected time of flight, t is the uncorrected time of flight, and q is the energy deposited in MoNA. The same functional form was taken from this characterization and

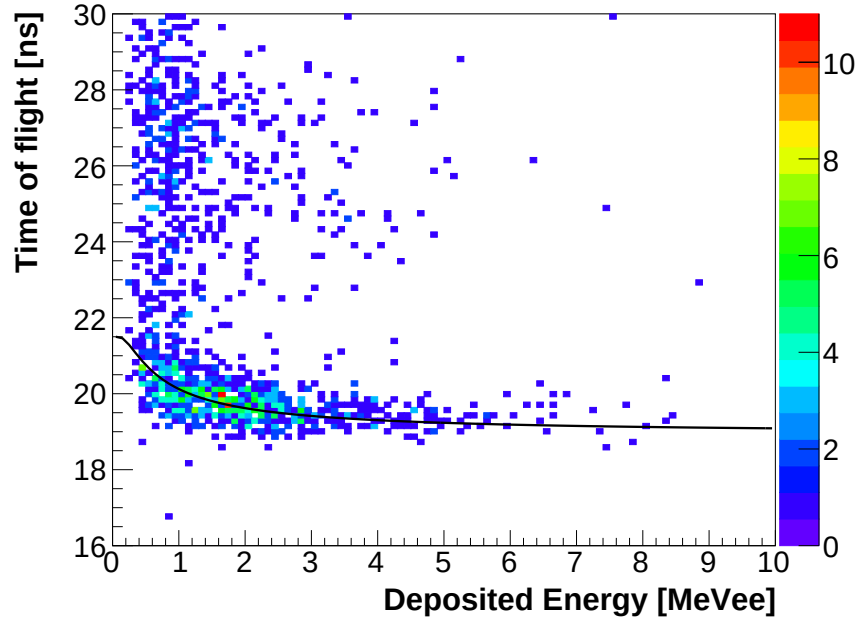


Figure 4.1: Time of flight from the target to the first layer of MoNA versus the energy deposited in MoNA. The plot is zoomed in to focus on the prompt γ -ray peak near 20 ns. The black curve indicates the function used to correct the observed walk at deposited energies below 1.8 MeVee. More details are in the text.

used to correct the CFD walk in the present experiment. The correction function for deposited energies below 1.8 MeVee is overlaid onto the histogram (with the offset adjusted for the location of the γ -ray peak) as the solid black line in Figure 4.1, demonstrating that the walk characterization used in the past was also valid for the present experiment.

4.1.2 Revision of MoNA Timing Offsets

The relative times between the individual bars of MoNA must be known in order to get an accurate neutron time of flight (ToF) measurement. Timing offsets were applied to ensure that the time of an interaction in MoNA was correctly calibrated relative to the target and between each bar.

The timing signals from layers C and D in MoNA were not positioned correctly relative to the other layers in MoNA, also causing these layers to have incorrect timing relative to the target. γ -rays that originated from reactions in the target were detected in MoNA, and could be used to illustrate the timing of layers C and D relative to the other layers, for example, in the top row of Figure 4.2. The known velocity of the γ -rays, $v_\gamma = 29.9792$ cm/ns, and the known distance between the target

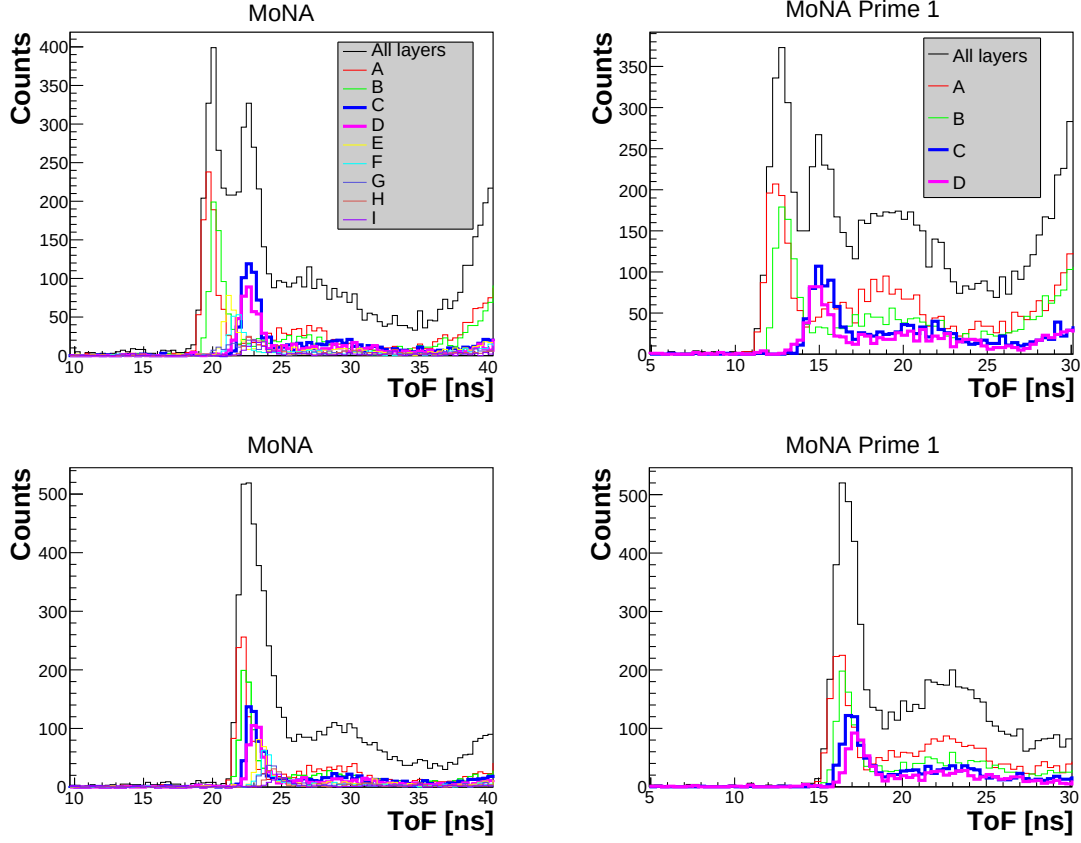


Figure 4.2: MoNA timing spectrum for the 2.97 Tm setting, shown in a narrow timing range to highlight the location of the γ peak. The top row represents the MoNA and MoNA Prime 1 timing spectra before the offset correction, and the bottom row represents after the offset correction.

and MoNA were used to construct an expected time of flight of a γ -ray from the target to each layer of MoNA.

The correction to the timing offsets were determined by taking the difference of the expected γ -ray time of flight and the current γ -ray time of flight. The results with the corrected timing offsets are shown in the bottom row of Figure 4.2 for MoNA and MoNA Prime in the 2.97 Tm setting. These offsets correct the relative timing between the layers of MoNA and MoNA Prime as well as the global time relative to the target. The systematic trend toward higher time of flight in the bottom row of Figure 4.2 confirms the correct relative timing between layers, as each successive layer is located farther from the target. To check the global timing relative to the target, Figure 4.3 shows the velocity spectrum for MoNA and MoNA Prime-1 with v_γ denoted as a vertical line. One can see that the experimental γ -ray peaks are positioned appropriately in the velocity spectra for

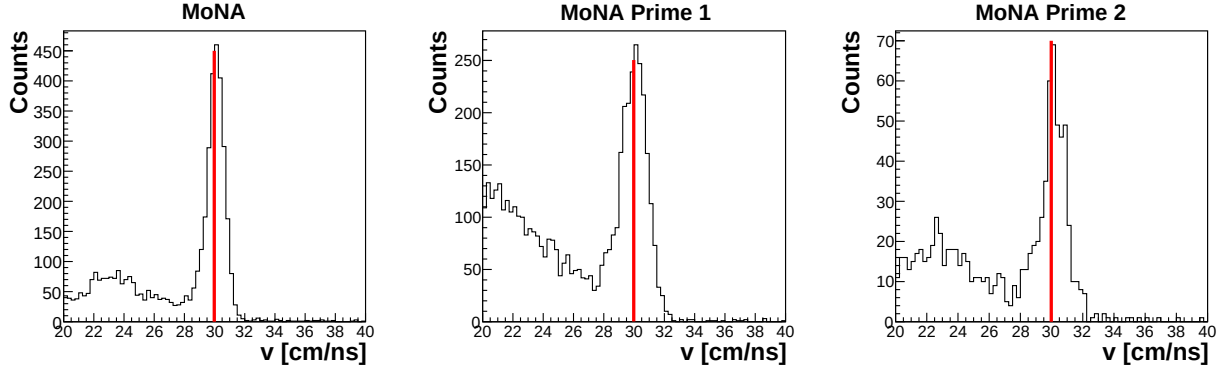


Figure 4.3: Reconstructed velocity spectrum of γ -rays originating from the target and interacting in MoNA. The corrected timing offsets align the centroids of the γ peaks at $v_\gamma = 29.9792$ cm/ns, indicated by the vertical red lines.

each stack of MoNA, centered at a velocity of v_γ .

4.2 Event Selection

A large number of events were recorded during the course of the experiment, with only a subset of the events containing the physics information of interest. Events that either did not originate from the reaction of interest, or contained unreliable detector signals, were filtered out so that only events suitable for analysis remained. This section describes the process of selecting the relevant physics events in the experimental data. The process begins by identifying and selecting the incoming ^{32}Mg beam, followed by determining events in which the detectors have "valid" signals. The charged reaction products were then identified using the Sweeper detector system, followed by the selection of neutron interactions in MoNA.

4.2.1 Beam Identification

The ^{32}Mg beam was selected by the A1900 fragment separator and sent into the experimental vault with 95% purity. The main contaminant was ^{34}Al , which made up 1.5% of the beam. All fragments entering the vault had the same magnetic rigidity, $B\rho$, of the final segment of the A1900, which was 3.6416 Tm. Since the contaminants had different masses, they also had different velocities. With this information, the ^{32}Mg beam could be selected by the time of flight from the A1900 object scintillator to the target timing scintillator, as seen in the left panel of Figure 4.4.

Additionally, reactions in the A1900 wedge produced light charged fragments that made it

Table 4.1: The main components of the beam sent to the N2 vault along with their velocities at the entrance of the vault and their expected time of flight between the A1900 and Target scintillators.

beam component	velocity [cm/ns]	ToF _{A1900-Target} [ns]
^{32}Mg	12.06	95.5
^{34}Al	12.26	93.96
^{29}Ne	11.22	102.67
^{33}Al	12.57	91.65

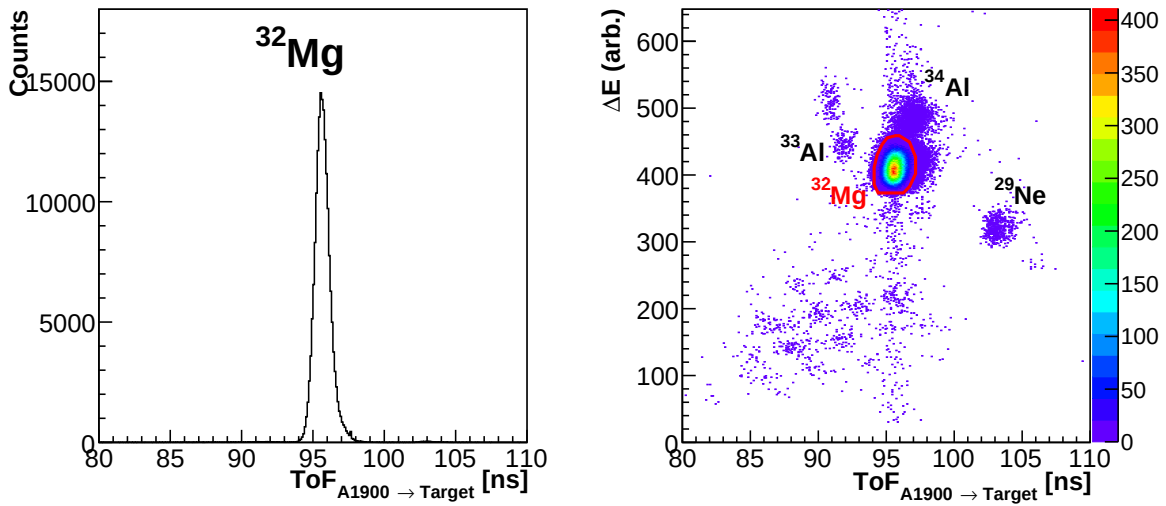


Figure 4.4: Beam component identification: (left) time of flight from the A1900 object scintillator to the scintillator just upstream of the reaction target. The most intense peak is the ^{32}Mg secondary beam. (right) Energy loss in the ionization chamber versus the time of flight from the A1900 object scintillator to the target scintillator. The desired ^{32}Mg beam is circled in red.

through the acceptance, which can be seen as the low ΔE spots in the right panel of Figure 4.4. This figure uses data from a run where the reaction target is removed from the beamline and the ^{32}Mg beam is delivered through the center of the Sweeper magnet. This type of run allows for a clean identification of the desired beam and the contaminants that accompany it using the ΔE measurement from the ionization chamber. During a production run when the target is inserted into the path of the beam, the ionization chamber cannot be used for the ΔE , so the energy loss value from the target scintillator is used for the final ^{32}Mg beam selection. An example of the ΔE versus time of flight plot to select the ^{32}Mg beam for a production run is shown in Figure 4.5.

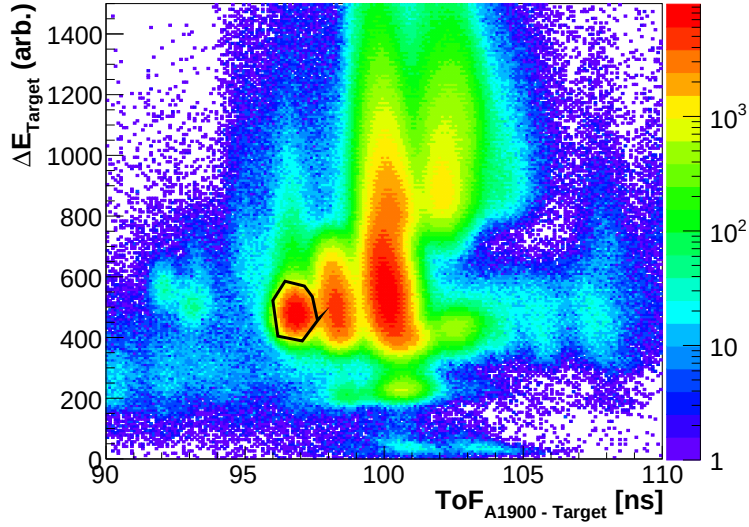


Figure 4.5: Energy loss in the target scintillator versus the time of flight from the A1900 object scintillator to the target scintillator for the 2.97 Tm setting. The final ^{32}Mg beam selection is circled in black.

4.2.2 Event Quality Gates

In order to identify the fragments that make it into the charged fragment detectors, position information was needed from the CRDCs. Sometimes these detectors failed to collect all the charge deposited in an event, resulting in an unreliable position reconstruction. These events were identified by examining the σ of the gaussian fit for the x -position versus the total integrated charge. A graphical cut, shown in Figure 4.6, was drawn to exclude events in which the detector did not provide a reliable signal. Additionally, only events in which both CRDCs collected a similar amount of charge were accepted. Events where one CRDC collected a low charge and the other collected a high charge could also produce unreliable position information, which complicates the fragment identification process. In Figure 4.7, the gate that was drawn around events which exhibited a linear relationship in charge collection between the two detectors is shown.

4.2.3 Element Identification

The $^{32}\text{Mg} + \text{Be}$ fragmentation reaction products must be identified. The first step is to determine the reaction products by their element, or number of protons. The reaction products were swept through the Sweeper superconducting dipole magnet into a suite of charged particle detectors. The

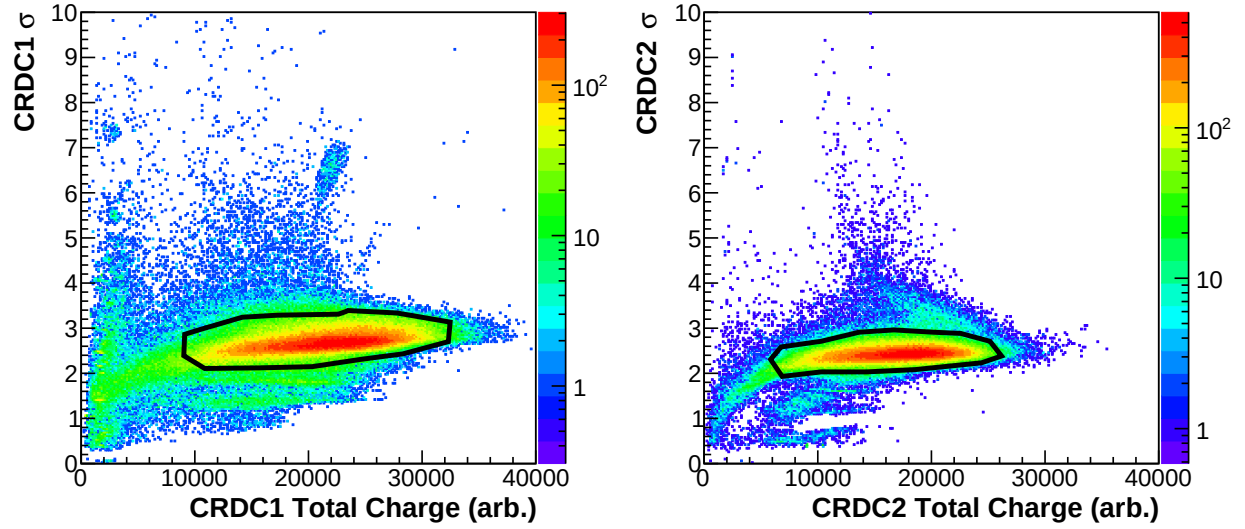


Figure 4.6: CRDC x-position gaussian fit σ versus the total collected charge for the 2.97 Tm setting. The quality gates which exclude events with a bad position reconstruction are drawn in black.

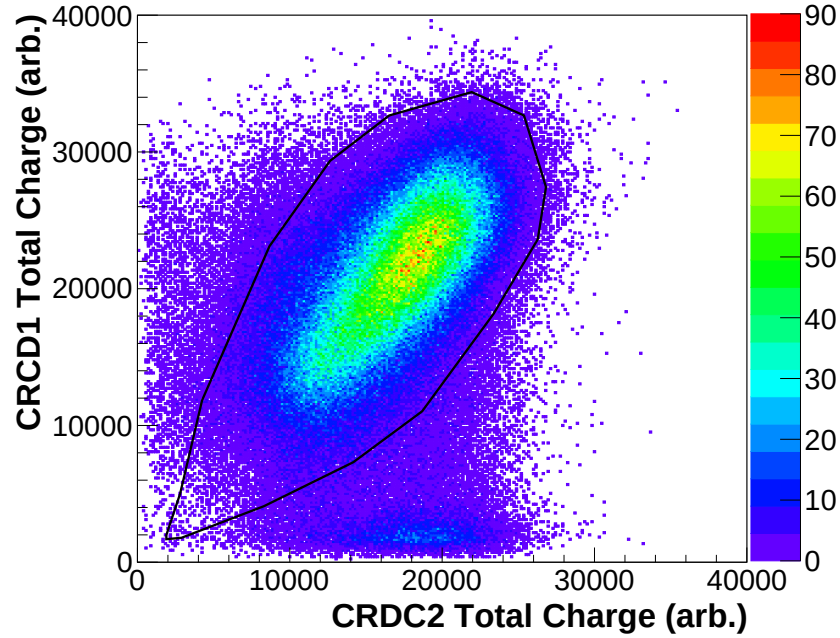


Figure 4.7: CRDC 1 charge plotted against the CRDC 2 charge for the 2.97 Tm setting. The gate which selects events with linear charge collection in both detectors is drawn in black.

charged fragments lost energy in the ionization chamber following the Bethe Bloch formula [61], which relates the energy loss to several parameters– the most significant being the charge, Z , and the velocity, v .

$$-\frac{dE}{dX} \propto \frac{Z^2}{v^2} \quad (4.2)$$

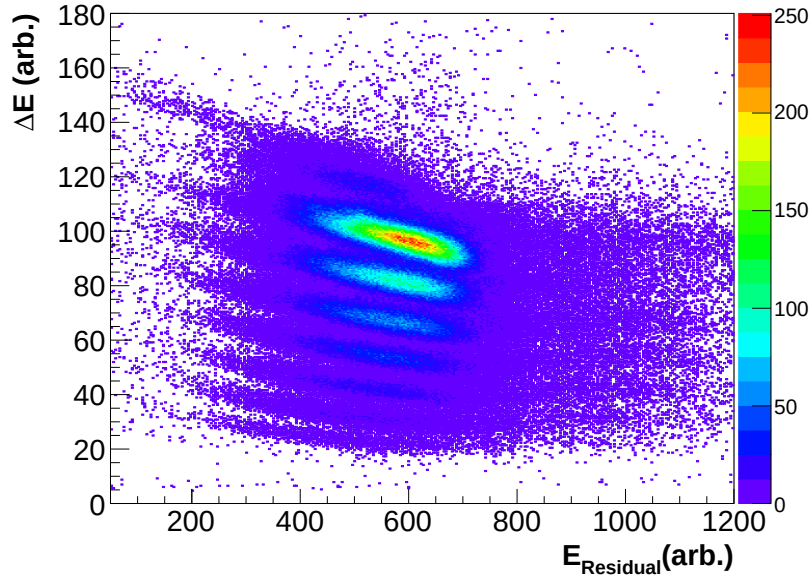


Figure 4.8: Element identification using the energy loss in the ionization chamber versus the total kinetic energy in the thick scintillator. The most intense band shows $Z = 12$ fragments. Each band beneath $Z = 12$ denotes a lighter element, ranging from $Z = 11 - 6$.

Fragments could be identified by their charge number by looking at the relationship between energy loss and velocity. There were two independent measured quantities that depend on velocity in this experimental setup: time of flight and total residual energy. Elemental bands can be seen most clearly by looking at energy loss versus total residual energy in Figure 4.8.

4.2.4 Isotope Identification

Once fragments have been identified by their element, it is necessary to separate them by mass, A . The magnetic rigidity of a non-relativistic particle is defined as the momentum to charge ratio:

$$B\rho = \frac{p}{q} = \frac{mv}{q}. \quad (4.3)$$

If the mass, m , is rewritten as $m = Am_u$ and velocity, v , is rewritten as $v = \frac{\Delta L}{t}$, where A is the atomic mass number, m_u is the atomic mass unit, ΔL is the path length through the magnet, and t is time of flight, then the final fragment's mass number can be related to the time of flight as follows:

$$t = \frac{Am_u \Delta L}{qB\rho}. \quad (4.4)$$

Isotopes of a given element have differing $B\rho$, meaning that each isotope takes a slightly different path through the Sweeper magnet, with more rigid fragments being bent less and taking a longer flight path and less rigid fragments being bent more for an overall shorter flight path. In principle, then, the fragments can be separated from one another after they exit the Sweeper magnet. However, realistically, each isotope experienced variations in ΔL and $B\rho$. These variations occurred due to factors including reaction dynamics, energy and angular straggling in the target, and nonuniformities in the Sweeper magnetic field, resulting in broad, overlapping time of flight distributions. Nonetheless, there are correlations between the emittance (dispersive angle and position) and the time of flight at the exit of the Sweeper magnet. These correlations were accounted for by creating a "corrected" time of flight parameter that separated the different isotopes of an element in such a way that they could be properly identified.

The first step of this process is to examine the three-dimensional relationship between dispersive position, angle, and time of flight. Figure 4.9 shows an example of clear correlations for neon isotopes in this three-dimensional plot. The time of flight was then projected down onto the (x, θ_x) plane as seen in Figure 4.10. Changes in color represent contours of iso-time of flight and were fit with a second order polynomial,

$$f(x) = p_0 + p_1x + p_2x^2. \quad (4.5)$$

The function $f(x)$ was used to construct a parameter describing the emittance (x, θ_x) for a constant time of flight:

$$e(x, \theta_x) = \theta_x - f(x). \quad (4.6)$$

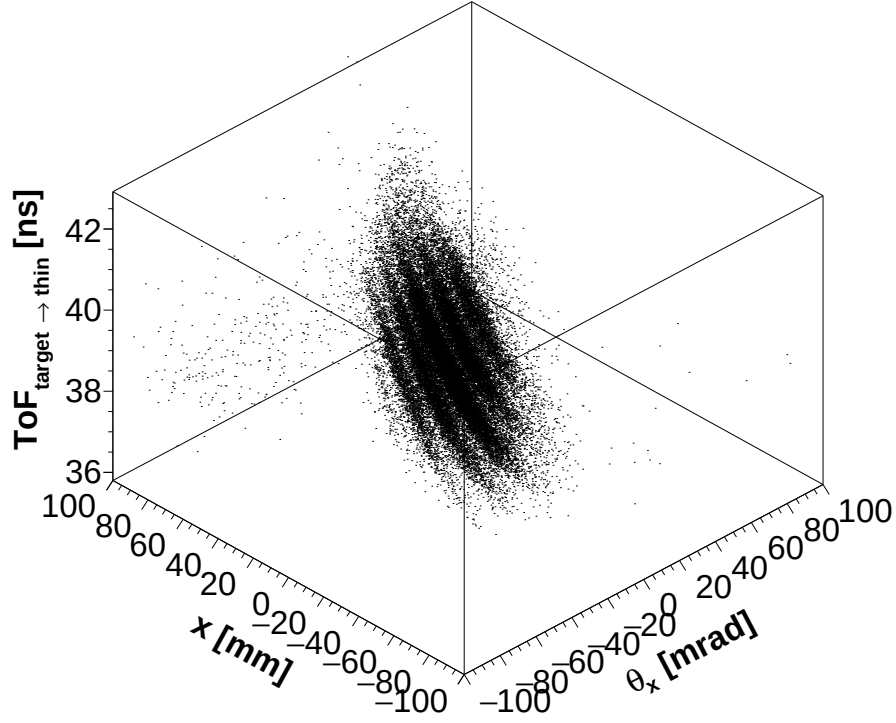


Figure 4.9: Three-dimensional correlations between the dispersive position (x), angle (θ_x), and time of flight (ToF) for Ne isotopes in the 3.15 Tm setting. Isotopic separation in the Ne isotopes is visible.

The parameter $e(x, \theta_x)$ can be plotted as a function of the time of flight to demonstrate the onset of isotopic separation, which is seen for Neon isotopes from the 3.15 Tm Sweeper magnet setting in Figure 4.11. A "corrected" time of flight parameter, t_{corr} was created by projecting onto the axis perpendicular to the black line in Figure 4.11, which is defined as

$$e(x, \theta_x) = c_0 t_{\text{target} \rightarrow \text{thin}} + b_0, \quad (4.7)$$

where c_0 is the slope of the line, and b_0 is an arbitrary offset. The new parameter, t_{corr} , is then defined by

$$t_{\text{corr}} = t_{\text{target} \rightarrow \text{thin}} - c_0 e(x, \theta_x). \quad (4.8)$$

From this point, a linear combination of other smaller corrections were added to this "corrected"

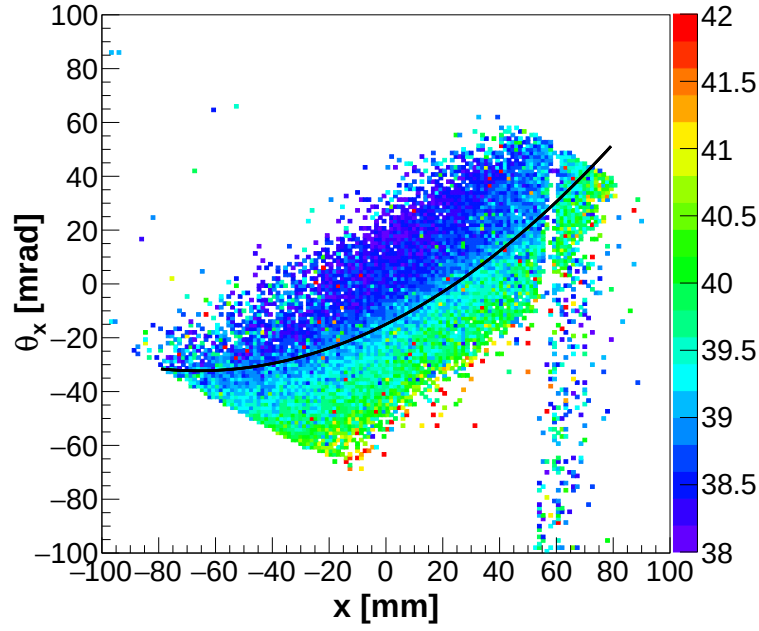


Figure 4.10: Projection of Figure 4.9 onto the emittance plane. The color axis represents the projection of the time of flight onto the emittance plane. The black line demonstrates the second order polynomial iso-time of flight fit used in the analysis.

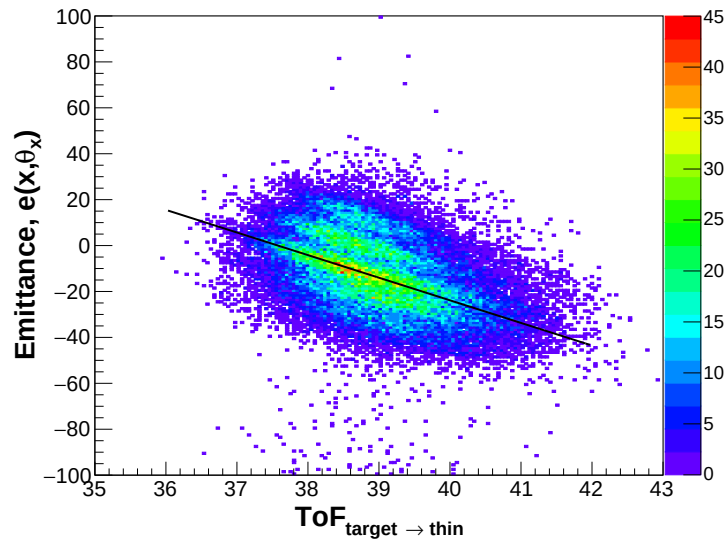


Figure 4.11: Emittance, $e(x, \theta_x)$, as a function of the time of flight from the target to thin scintillator for neon isotopes in the 3.15 Tm Sweeper magnet setting. A black line is drawn to present the linear fit used to create the corrected time of flight parameter.

time of flight parameter to further improve the isotopic separation. These additional corrections are sometimes taken to higher orders, so t_{corr} can be expressed in a more general format

$$t_{\text{corr}} = t_{\text{target} \rightarrow \text{thin}} - \sum_{i=0}^n (c_i p_i), \quad (4.9)$$

where c_i is the correction coefficient and p_i is the respective parameter. A table of the final correction parameters and coefficients are given in Table 4.2. Because the experiment was run at three separate magnet settings, this procedure was repeated for each magnet setting.

To confirm that the corrected time of flight parameter placed isotopes in the right order, we can use neon isotopes produced in the reaction as an example. Several neon isotopes were produced in the reaction and fell within the Sweeper magnet acceptance. These reaction products all exited the

Table 4.2: The correction coefficients (c_i) used for isotopic separation in the three Sweeper magnet settings, 2.97 Tm, 3.15 Tm, and 3.75 Tm.

parameter	2.97 Tm	3.15 Tm	3.75 Tm (Ne)*	3.75 Tm (Na)
$t_{\text{target} \rightarrow \text{thin}}$	0.1033489	0.1016	0.1005	0.1601
y	-0.001234	-0.008731	-	-0.003795
y^2	-0.0002914	-0.0004237		-0.0005743
θ_y	-0.005111	-	-	-
θ_y^2	-0.0006988	-	-	-
x	0.005743	-0.0007939	-	-
x^2	0.0001524	-0.0003087	-	-
θ_x	-0.005489	-0.0074066	-	-
θ_x^2	-0.0001018	-	-	-
E_{residual}	-0.008542	0.001233	-0.0002387	-
E_{residual}^2	6.672×10^{-6}	-	-	-
y_{CRDC2}	-	0.004866	-	-
y_{CRDC2}^2	-	-5.981×10^{-5}	-	-

* $t_{\text{A1900} \rightarrow \text{thin scint.}}$ is used for Ne isotopes in the 3.75 Tm setting.

target with approximately the same velocity, therefore, the heavier fragments had larger momenta than the lighter fragments. Following this logic, the heaviest neon isotopes were more rigid (higher $B\rho$) than the lighter neon isotopes, so their trajectories were bent less by the magnet and took a longer flight path through the Sweeper magnet. This, then, should result in the heavier isotopes having a longer time of flight and a more positive CRDC 2 x -position than the lighter isotopes. This behavior is seen in Figure 4.12 for neon isotopes in the 3.15 Tm setting. The isotopes arriving at a later corrected time of flight have a more positive CRDC 2 x -position than the isotopes arriving at a shorter corrected time of flight, which means that the corrected time of flight behaves as expected.

This process separates the isotopes, but does not identify their masses. Equation 4.2 shows that the energy loss is proportional to Z^2 . Next, recall that $B\rho = mv/q$ where $q = Z$ and $m = A$. Assuming non-relativistic kinematics and a constant $B\rho$, it follows that $v \propto Z/A$. Since velocity is inversely proportional to time of flight, then time of flight is proportional to A/Z .

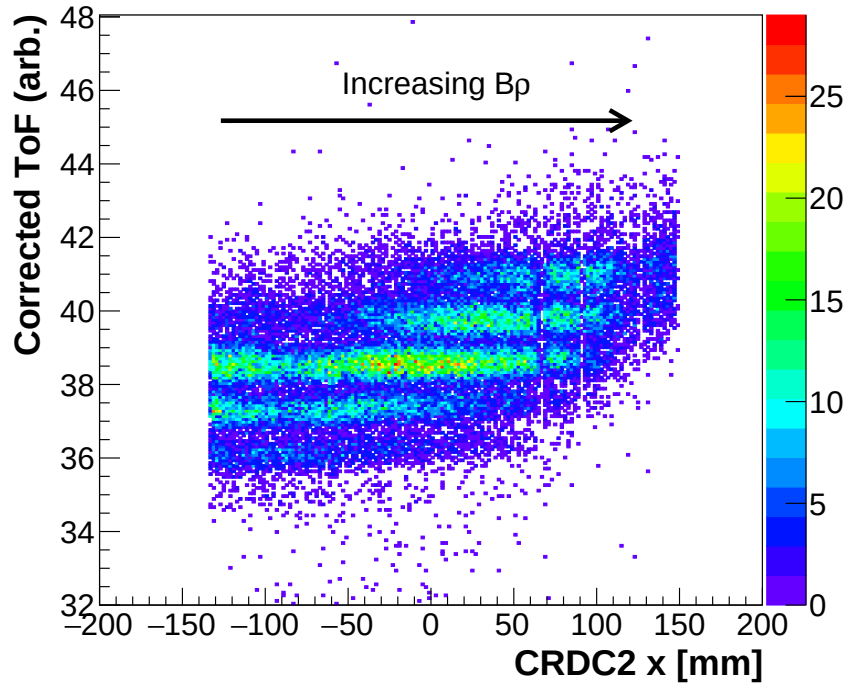


Figure 4.12: Corrected time of flight versus the CRDC 2 dispersive (x) position for neon isotopes in the 3.15 Tm setting. Positive CRDC 2 x -positions correspond to $B\rho$ values greater than the central rigidity of 3.15 Tm, and negative x -positions correspond to lower $B\rho$ values.

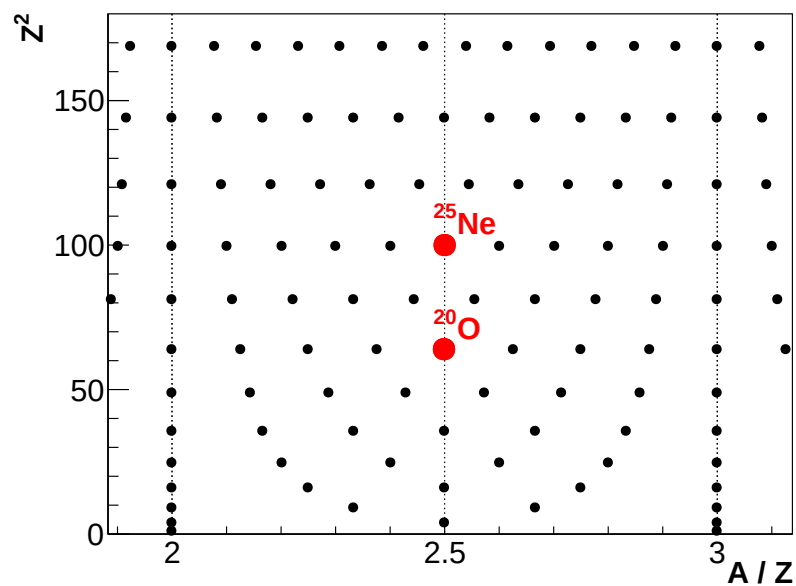


Figure 4.13: Square of the atomic number, Z^2 , as a function of the mass to charge ratio, A/Z .

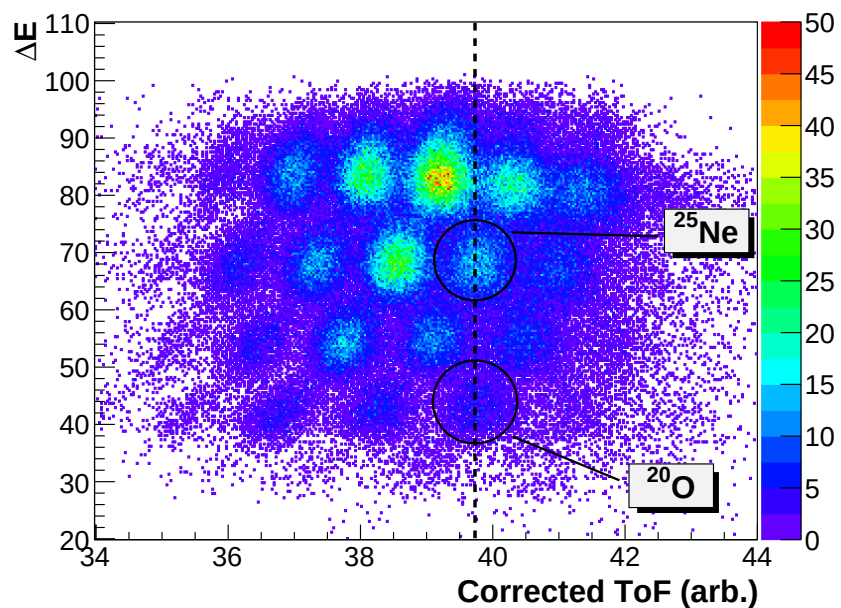


Figure 4.14: Example of particle identification using ΔE vs. corrected time of flight in the 3.15 Tm Sweeper magnet setting. The black dotted line indicates the location of the $A/Z = 2.5$ line, and the (even- Z) ^{25}Ne and ^{20}O isotopes that fall along that line are labeled.

The measured energy loss and the corrected time of flight can therefore be utilized to identify the masses of the nuclides produced in the reaction by Z^2 and A/Z . An example of this pattern is shown in Figure 4.13, where Z^2 is plotted against A/Z for a wide range of nuclides, some being unphysical. A particular pattern that stands out is that nuclides fall in a vertical line at integer values of A/Z . Unfortunately, in this work, no integer A/Z isotopes were measured in any of the Sweeper magnet settings. Another pattern that stands out is that at $A/Z = 2.5 = 5/2$, isotopes of even Z are vertically aligned. For the 2.97 and 3.15 Tm settings, fragments with $A/Z = 2.5$ (^{20}O and ^{25}Ne) fell within the Sweeper acceptance. The mass identification ΔE vs. corrected ToF plot for the 3.15 Tm magnet setting is shown in Figure 4.14. The two nuclides, ^{20}O and ^{25}Ne , that fall along the $A/Z = 2.5$ line were easily identified, and the rest of the nuclides were identified via their relation to the $A/Z = 2.5$ line. For the 3.75 Tm setting, the heaviest Na isotope that could be produced in the reaction was ^{31}Na , and therefore the rest of the fragments in the setting were identified in relation to ^{31}Na .

Between the three Sweeper magnet settings, a total of twenty-nine nuclides were measured with sufficient statistics for data analysis. Isotopes of sodium, neon, fluorine, and oxygen were observed. The final isotope identification plots for the 2.97, 3.15, and 3.75 Tm settings are shown in Figures 4.15, 4.16, and 4.17, respectively. Very good mass separation was achieved in the 2.97 and 3.15 Tm settings. The target scintillator was operated in the fringe field of the Sweeper magnet, therefore, during the 3.75 Tm setting, the fringe field began to quench the PMT attached to the target scintillator, severely degrading its timing resolution. As a result, the mass separation is not to the same standard set by the lower two magnet settings. For instance, mass separation in the Ne isotopes was best achieved by using the time of flight between the A1900 and thin scintillators instead of between the target and thin scintillators.

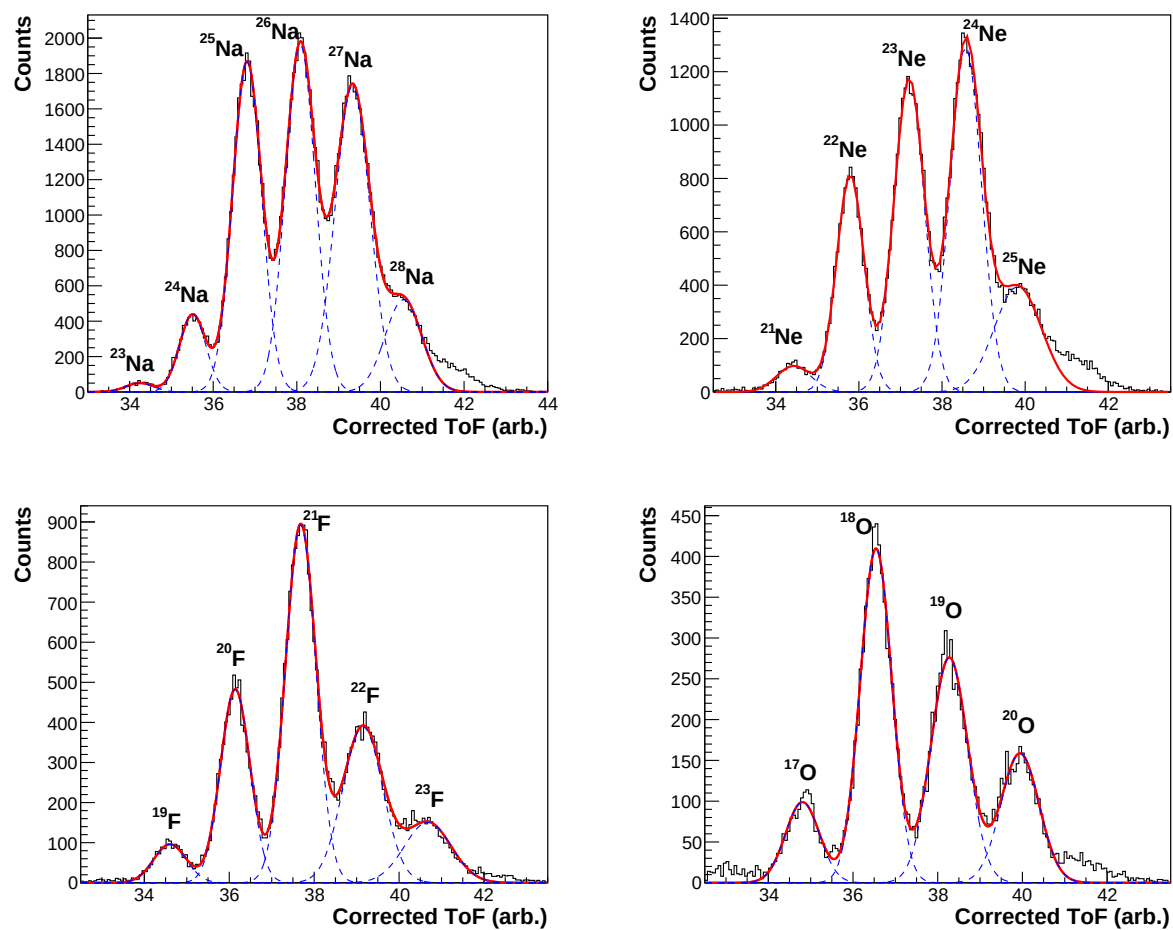


Figure 4.15: Mass identification for the 2.97 Tm magnet setting.

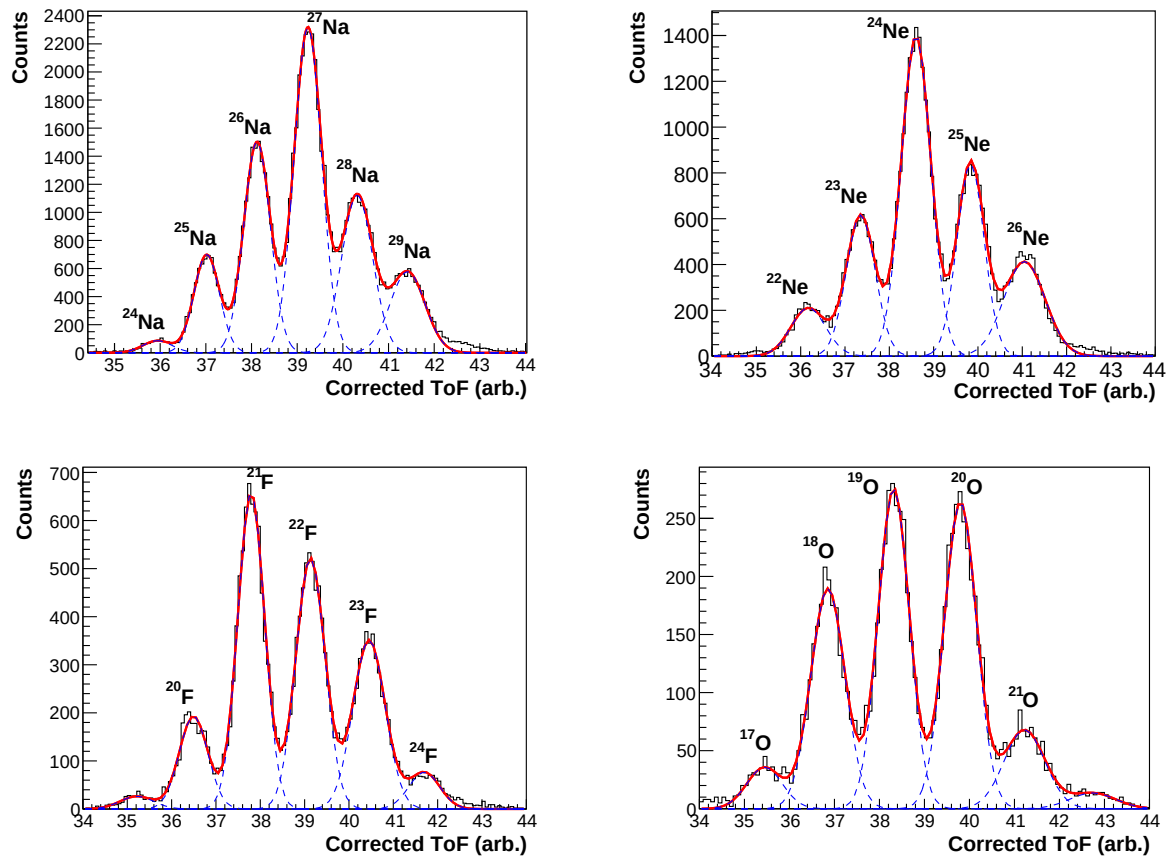


Figure 4.16: Mass identification for the 3.15 Tm magnet setting.

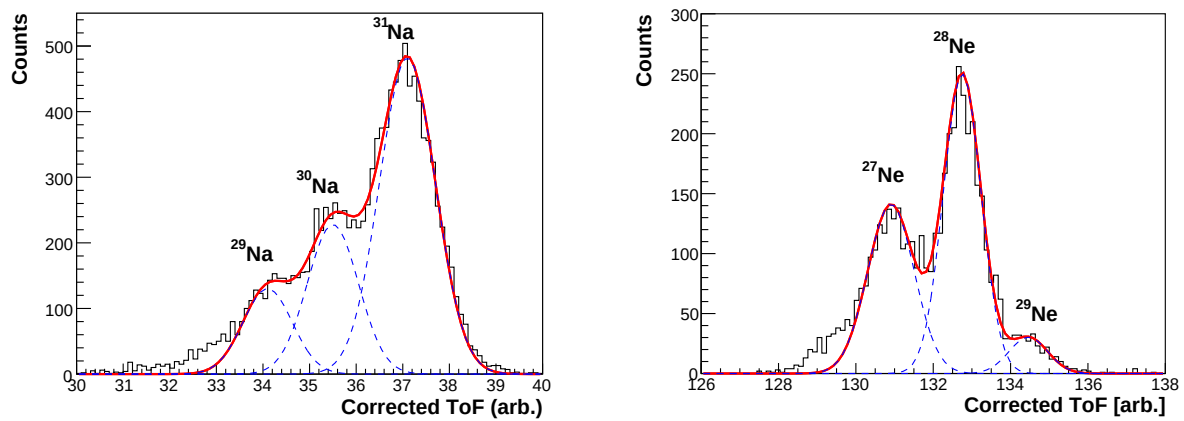


Figure 4.17: Mass identification for the 3.75 Tm magnet setting.

4.2.5 Neutrons in MoNA

Before neutron observables can be reconstructed, neutron interactions must be distinguished from signals originating from sources of background such as γ -rays and cosmic-ray muons. In this analysis, it was important to be able to correctly identify neutron interactions. This section discusses the procedures used to select neutron events in MoNA. In a single event, an array of interactions in MoNA were recorded. This array was time-sorted to make the process of selecting neutron interactions more straightforward. For measured quantities such as time, position, and light yield, only the first time-sorted interaction within the array was analyzed to minimize the contribution from a single neutron scattering multiple times within MoNA. All valid interactions within an event were used to construct the interaction multiplicity.

The neutron time of flight was constructed from the time difference between the target scintillator and the time of an interaction in a MoNA bar. The interaction time in MoNA was taken as the mean of the timing signals from the PMTs on each end of the bar. Examining the time of flight from the target to MoNA as well as the two-dimensional relation between energy deposited versus time of flight allowed most non-neutron coincidences to be eliminated from the analysis procedure. Figure 4.18 shows the time of flight from the target to the first time-sorted interaction in MoNA (blue) and MoNA Prime (red). The small peaks near 20 ns are γ -rays that originated from the target and interacted in MoNA, and the larger peaks near 45 and 60 ns are neutron interactions. The locations of the γ and neutron peaks are different between MoNA and MoNA Prime because the front faces of the stacks were located at different distances from the target. When looking at the two-dimensional histogram in Figure 4.19, one can see that the gammas deposited very little charge into MoNA, whereas neutrons deposited a wide range of energies, ranging from a few MeV up to approximately the beam energy.

The γ -rays that originated from the target were excluded from the analysis by placing a time gate which only accepted events with a time of flight greater than 30 ns, which is the earliest that neutrons could have arrived to MoNA from the target. Uncorrelated sources of background, if present, would have appeared as a horizontal band extending across the full coincidence time

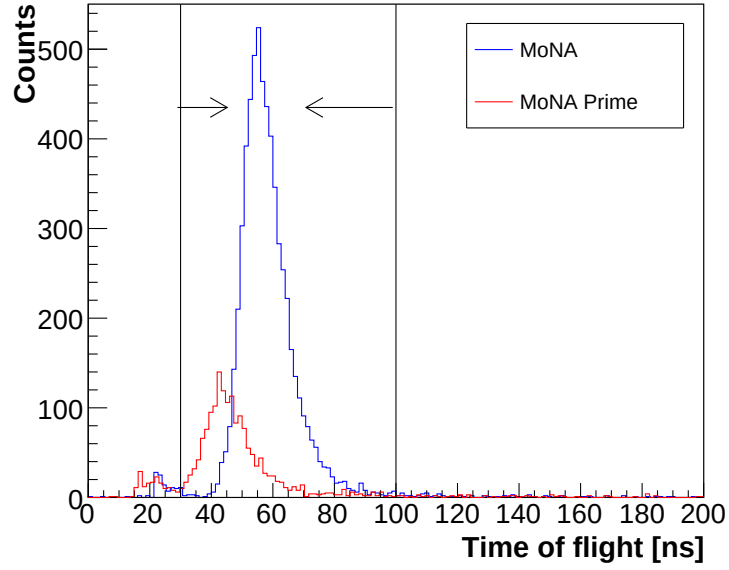


Figure 4.18: MoNA time of flight in coincidence with a ^{23}Ne fragment. The black histogram denotes the neutrons detected in MoNA, while the red histogram denotes neutrons detected in MoNA Prime. The location of the time of flight gates (described in the text) are shown by the black lines, and the arrows point toward events which are considered "valid" neutron events.

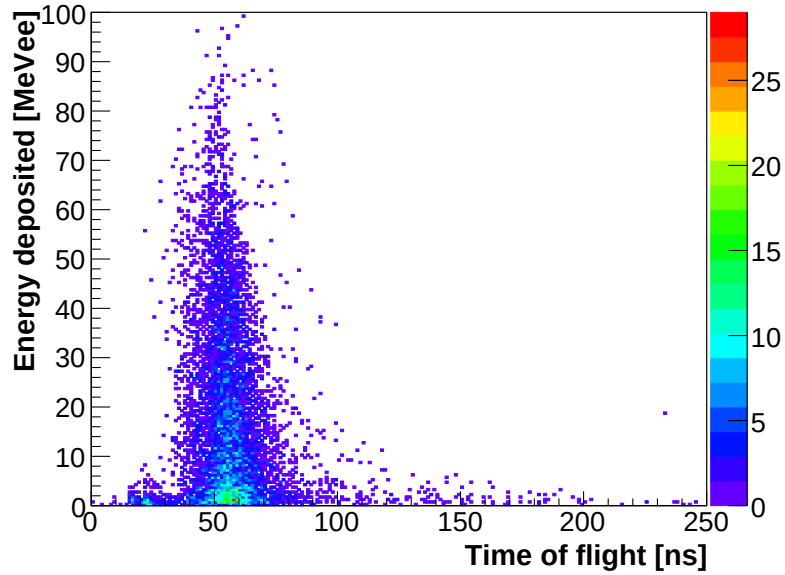


Figure 4.19: Energy deposited in MoNA in MeVee versus the time of flight in nanoseconds in coincidence with a ^{23}Ne final fragment. The bright distribution around 55 ns shows the prompt neutrons arriving to MoNA.

window of 250 ns. A cosmic-ray muon background would be uncorrelated in time and centered at approximately 20 MeVee. This signature was not present in the current data, likely due to the high trigger rate in this experiment. Although there was negligible cosmic-ray muon background in the data, there was a small amount of uncorrelated background at very low deposited energy (below a few MeVee) present in the current data. Most of this background was eliminated by excluding any interactions with a time of flight greater than 100 ns. This gate also eliminated neutrons with a kinetic energy less than 10 MeV. The remaining uncorrelated background that was present within the two timing gates only contributed to 1% of the overall valid first time-sorted interactions. Both time cuts are shown in Figure 4.18 with arrows pointing toward the events which were included in the analysis of quantities that were reconstructed using the neutron time or position information.

The position of the neutron interaction in MoNA was used both to determine the neutron kinetic energy and the angular distribution. The y - (vertical) and z - (along the beam axis) components of the neutron interaction position vector were determined by the physical location of the bar that was struck and the x -component (horizontal) was determined by the time difference between the two PMTs on the bar in which the interaction occurred. The neutron kinetic energy was calculated by first determining the velocity, v_n ,

$$v_n = \frac{d_n}{t_n} \quad (4.10)$$

Where d_n is the length of the neutron position vector and t_n is the time of flight. Then, the rest of the calculation proceeds from relativistic kinematics, as follows:

$$\beta = \frac{v_n}{c} \quad (4.11)$$

$$\gamma = \sqrt{\frac{1}{1 - \beta^2}} \quad (4.12)$$

$$\text{KE} = m_n(\gamma - 1) \quad (4.13)$$

where m_n is the rest mass of the neutron, 939.565 MeV. The angular distribution was reconstructed using the position vector of the interaction in MoNA. For this work, the horizontal angular

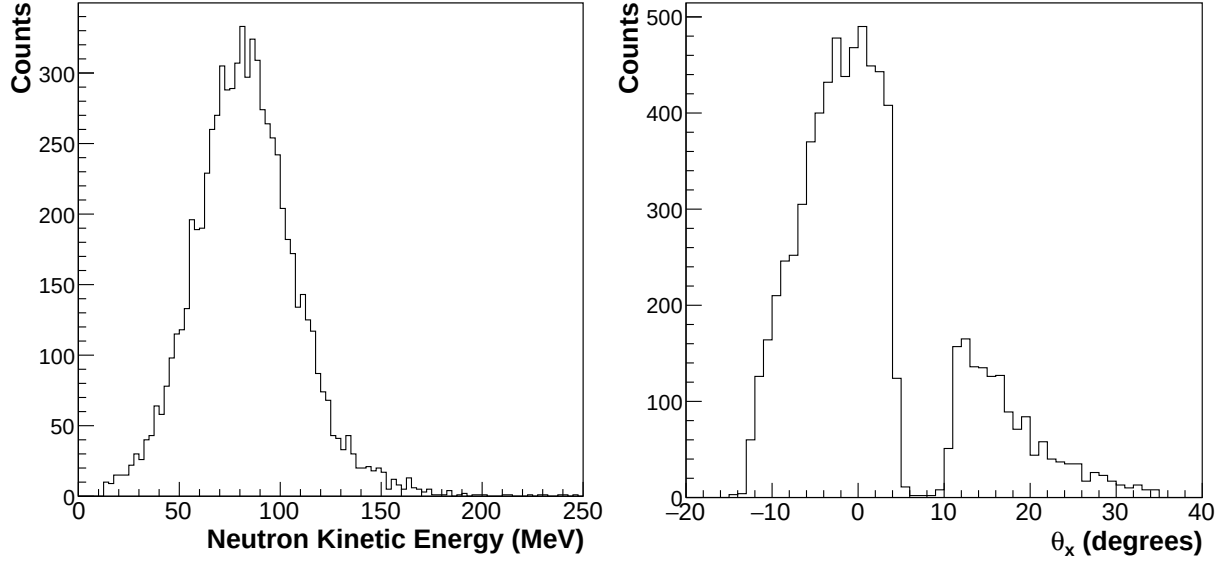


Figure 4.20: (left) Neutron kinetic energy in coincidence with ^{23}Ne in the Sweeper. (right) Neutron angular projection, θ_x , in coincidence with ^{23}Ne in the Sweeper. Both histograms use data from the 2.97 Tm setting.

projection,

$$\theta_x = \tan^{-1} \left(\frac{x}{z} \right), \quad (4.14)$$

was analyzed. The kinetic energy and angular distributions of the neutrons recorded in coincidence with a ^{23}Ne fragment are shown in Figure 4.20. The neutron kinetic energy spectrum peaks at approximately the beam energy per nucleon at the center of the target and the angular distribution is forward-focused, which is consistent with neutrons being emitted in the rest frame of the projectile prefragment and then boosted into the lab frame.

Another quantity measured in MoNA is the number of valid interactions coincidence with a charged fragment event. The number of interactions in a given event is referred to as the interaction multiplicity. An interaction was considered valid and was counted toward the multiplicity if it fell within the time gates discussed above. The interaction multiplicity is not a direct measure of the true neutron multiplicity since a single neutron, if it enters MoNA's acceptance, can either scatter multiple times within the volume of MoNA, enter the active detection volume without interacting, or interact without producing a valid signal. The latter process is referred to as dark scattering.

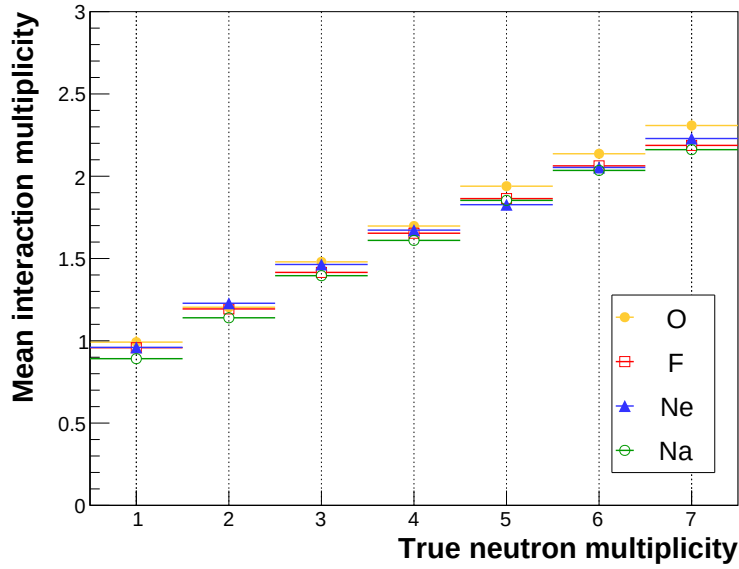


Figure 4.21: The average simulated interaction multiplicity in MoNA as a function of the true neutron multiplicity, or the number of evaporated neutrons. The different markers indicate the element of the final fragment. The interaction multiplicity, on average, increases as a function of the true neutron multiplicity, regardless of the final fragment species.

Neutrons can scatter off of either hydrogen or carbon nuclei in the plastic scintillator material. When a neutron scatters off a carbon nucleus, the carbon recoil is too small to generate enough scintillation light for a valid signal. The effects of the detection efficiency, acceptance, multiple scattering, and dark scattering convoluted the true neutron multiplicity into the measured interaction multiplicity. Rather than attempting to unfold the detector response to extract the true neutron multiplicity, the measured interaction multiplicity was compared directly to GEANT4 simulations that incorporated the detector response.

Although the interaction multiplicity is not a direct measurement of the emitted neutron multiplicity, it remains sensitive to the overall neutron emission and therefore provides a useful observable for interpreting the experimental data. A result from a GEANT4 simulation in Figure 4.21 shows how the neutron interaction multiplicity, on average, increases as a function of the true neutron multiplicity, or the number of emitted neutrons.

Neutron interaction multiplicity spectra were extracted for each final fragment measured in this experiment. An example of an experimental interaction multiplicity spectrum in coincidence with

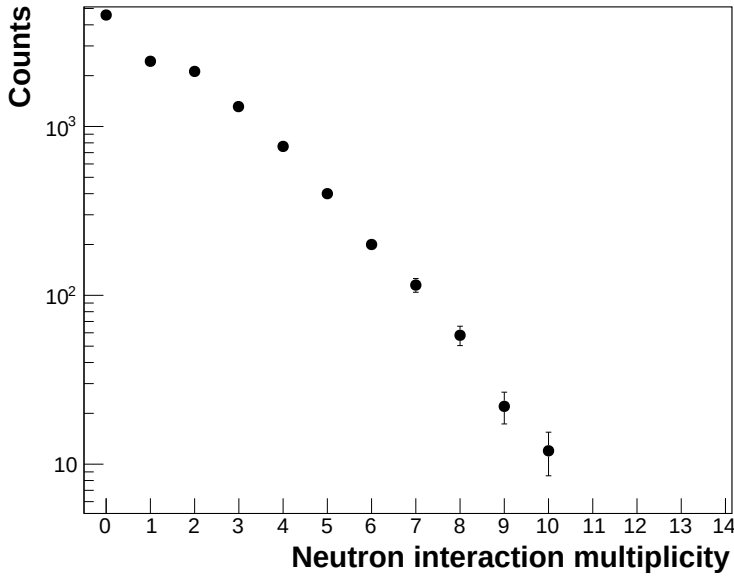


Figure 4.22: Experimental interaction multiplicity spectrum in coincidence with a ^{23}Ne fragment.

a ^{23}Ne fragment is shown in Figure 4.22. Because the data acquisition was operated in singles mode (discussed previously in Section 3.3), events with an interaction multiplicity of zero, where the charged fragment is not detected in coincidence with a neutron interaction, are recorded. The interaction multiplicity spectrum in this case extends to a multiplicity of 10 even though there were only a total of 7 neutrons removed from ^{32}Mg to ^{23}Ne . This demonstrates the impact of neutrons scattering multiple times within the scintillator array.

4.2.6 Neutron Coincidences-to-Total Ratio

A complementary observable to the interaction multiplicity is the coincidences-to-total (C/T) ratio, which was defined as the number of events where at least one neutron interaction was measured in MoNA ($N_{\text{coincidences}}$) divided by the total number of fragment events (N_{total}).

$$C/T = \frac{N_{\text{coincidences}}}{N_{\text{total}}}, \quad (4.15)$$

The coincidences-to-total ratio can be interpreted as the probability that a charged fragment is detected in coincidence with at least one neutron interaction. By reducing the interaction multiplicity information to a single value for each fragment species, the coincidences-to-total ratio

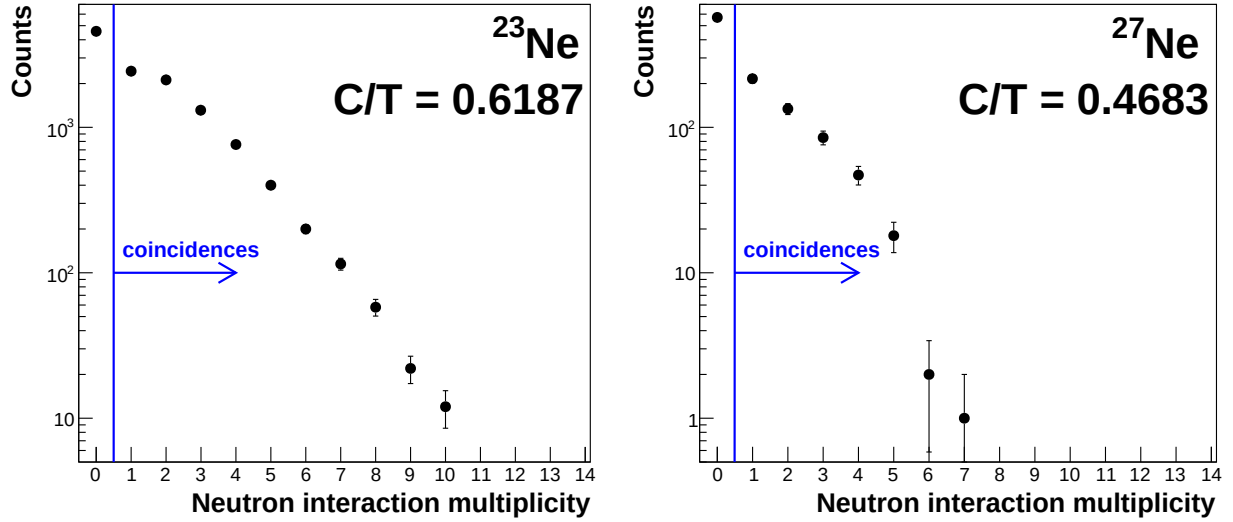


Figure 4.23: Experimental interaction multiplicity spectrum in coincidence with a ^{23}Ne fragment (left) and a ^{27}Ne fragment (right). The vertical blue line highlights which events are counted as coincidences, and the calculated coincidences-to-total ratio for each fragment is shown.

provides a convenient observable for investigating systematic trends across isotopic chains and for comparing experimental data with reaction-model predictions.

The uncertainty on the coincidences-to-total ratio was calculated assuming binomial counting statistics, where each fragment event either contains or does not contain a valid neutron coincidence. For a coincidences-to-total ratio ($C/T = p$) determined from N_{total} fragment events, the statistical uncertainty is given by

$$\sigma_p = \sqrt{\frac{p(1-p)}{N_{\text{total}}}}. \quad (4.16)$$

An example of how the coincidences-to-total parameter was constructed is shown in Figure 4.23. The events that were counted toward the "coincidences" part of the ratio are shown to the right of the vertical blue line. ^{23}Ne and ^{27}Ne fragments have coincidences-to-total ratios of 0.6187 and 0.4683, respectively. These respective ratios seem reasonable, as the difference in neutron number between ^{32}Mg and ^{23}Ne ($\Delta N = 7$) is greater than the difference between ^{32}Mg and ^{27}Ne ($\Delta N = 3$), which is consistent with the expectation that reactions involving larger overall neutron removal generally have a higher probability of being detected in coincidence with at least one

neutron interaction.

4.3 Simulation and Event Selection

As previously described in Chapter 2, the fragmentation reaction was modeled by two fast-step models: the Liège Intranuclear Cascade Model (INCL++) and the Abrasion Model. Both of these fast step models were coupled to the de-excitation model ABLA++. Each of these models exists as selectable physics packages within the GEANT4 simulation toolkit. This means that every step of the reaction, in addition to the experimental configuration and neutron detector response, was fully contained within the GEANT4 simulation. This section covers how the simulated data were filtered such that they could be reliably compared to the experimental data.

4.3.1 Charged Fragment selection

In lieu of simulating the charged final fragments traveling through the Sweeper magnetic field, software gates were applied to the final fragments based on whether they fell within the magnetic rigidity and angular acceptances of the Sweeper setup. During the course of the experiment, unreacted beam was sent through the Sweeper magnet in a series of different magnetic rigidity steps. This moved the position of the unreacted beam across the face of the position-sensitive charged fragment detectors in the dispersive (horizontal) direction. The sweeper magnetic rigidity acceptance was then determined by the settings at which the unreacted beam reached the edges of the charged particle detectors. Using this method, the Sweeper rigidity acceptance was found to be approximately $\pm 8\%$ for this experiment. This acceptance provided the lower and upper rigidity limits for a given magnet setting. The cut was applied to the simulated charged fragments for each of the three magnet settings used throughout the course of the experiment. Ultimately, three different sets of analyzable events were generated for comparison with the three Sweeper settings, with central $B\rho$ values of 2.97, 3.15, and 3.75 Tm.

4.3.2 Neutron Selection

Neutrons that were produced during the fragmentation reaction were propagated forward from the target through the remainder of the experimental setup. Since MoNA was operated in a wide-angle configuration ($-10^\circ < \theta_x < +35^\circ$), neutrons at broad angles could pass through the Sweeper

magnet steel. These interactions in the Sweeper steel could impact the trajectory and energy of the neutrons, so they were simulated accordingly in GEANT4. The steel material of the Sweeper was approximated using the neutron scattering cross sections on iron [67].

The neutrons continued forward until they reached MoNA. The exact experimental configuration of the MoNA bars relative to the beryllium reaction target was replicated in the GEANT4 simulation. All the critical aspects of the detector were modeled, including the plastic scintillator material, light guides, vinyl wrapping, and aluminum PMT shielding covers. The simulated neutrons interacted with the plastic scintillator material through elastic and inelastic scattering on hydrogen and carbon nuclei. These scattering cross sections were taken from the MENATE_R package [68], which is a library of experimental cross sections of elastic and inelastic scattering of neutrons on carbon and hydrogen. The MENATE_R library has been shown to agree more closely with experimental data than the default GEANT4 package [69]. The experimental timing and position resolutions of MoNA [63] were also accounted for in the simulation so that the simulated data could be directly compared to experiment.

Each neutron produced during the reaction and de-excitation steps was tracked independently within the GEANT4 simulation. Information associated with each neutron, such as its four-momentum and production mechanism, was retained throughout the simulation and recorded. The simulated detector signals were subjected to the same selection criteria applied to the experimental data. In particular, a threshold was implemented to mimic the QDC hardware threshold, accepting only interactions that produced signals above 350 keVee in both PMTs of the struck detector module. The accepted interactions were then sorted in time using the same procedure applied to the experimental data.

The neutron kinetic energy and angular distributions were reconstructed using the first time-sorted interaction, while the interaction multiplicity was defined as the total number of valid interactions within an event. The neutron coincidences-to-total ratio was calculated using the same definition applied to the experimental data. By reconstructing the simulated detector signals in the same manner as the experimental data, the resulting observables could be compared on an equivalent

basis. This approach allowed differences between the measured and simulated observables to be more directly attributed to the underlying reaction models, which will be discussed in Chapter 5.

CHAPTER 5

RESULTS AND DISCUSSION

This chapter presents the measured neutron observables in coincidence with charged fragments produced following the fragmentation of ^{32}Mg and compares these measurements with the predictions of the Abrasion and INCL++ reaction models. First, the experimental results are described and compared to the results of the simulations. The following section interprets these comparisons by examining the relationship between the measured neutron observables, detector response, and the prefragment properties predicted by the two reaction models.

5.1 Results

5.1.1 Neutron Kinetic Energy and Angular Distributions

The neutron kinetic energy and angular distributions provided probes of the underlying dynamics of the projectile fragmentation reaction. To investigate how such observables evolve with the mass of the final fragment, light and heavy isotopes of each element measured in the experiment were selected for comparison. The neutron kinetic energy and angular distributions associated with all measured isotopes across the three Sweeper magnet settings are given in Appendix A. These plots are generated by applying the element and isotopic gates, valid neutron timing gates, and event quality gates as described in Section 4.2.4. Additionally, only the first time-sorted interaction was used to construct the neutron kinetic energy and angular distributions in both the experimental and simulated data sets. In this section, the simulated data were normalized to the experimental data, in particular, to the measured number of first time-sorted interactions in coincidence with a given fragment.

The two left panels of Figure 5.1 show the neutron kinetic energy in coincidence with a ^{24}Na fragment (top) and a ^{29}Na fragment (bottom). The experimental neutron kinetic energy spectrum in coincidence with ^{24}Na peaks at approximately 81 MeV, which is nearly equal to the beam energy per nucleon at the center of the reaction target (approximately 80 MeV/u). The results from the Abrasion model show the neutron kinetic energy in coincidence with ^{24}Na to peak at approximately 88 MeV, whereas the results from INCL++ predict the neutron kinetic energy to peak at approximately 74

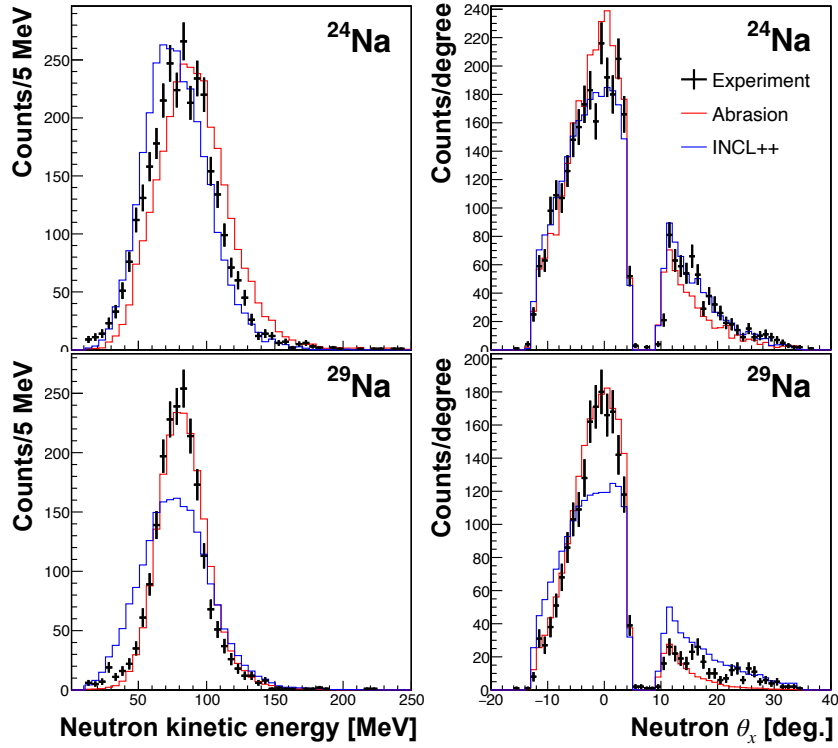


Figure 5.1: Neutron kinetic energy (left) and neutron angular projection θ_x (right) in coincidence with ^{24}Na (top row) and ^{29}Na (bottom row). Experimental data are shown as black data points, results of the Abrasion simulation are shown as the red histograms, and results of the INCL++ simulation are shown as the blue histograms.

MeV. The neutron kinetic energy spectrum in coincidence with ^{29}Na also peaks near 80 MeV but is substantially narrower than that of ^{24}Na . The results from the Abrasion model agree very closely with the experimental data, while the results from INCL++ are both broader and lower in energy than the experimental data.

The two panels on the right side of Figure 5.1 show the neutron angular distributions (θ_x , projected onto the x-axis) in coincidence with ^{24}Na (top) and ^{29}Na (bottom) fragments. As expected, the angular distributions in coincidence with both sodium fragments are strongly peaked at forward angles due to the peripheral nature of the fragmentation reaction. The predictions from both the INCL++ and Abrasion models were found to peak at zero degrees in the lab frame. However, the prediction from INCL++ agrees more closely with the experimental data than the Abrasion model for the ^{24}Na fragment, which predicts an angular distribution that is too narrow. The predictions from the Abrasion model agree more closely with the experimental ^{29}Na angular

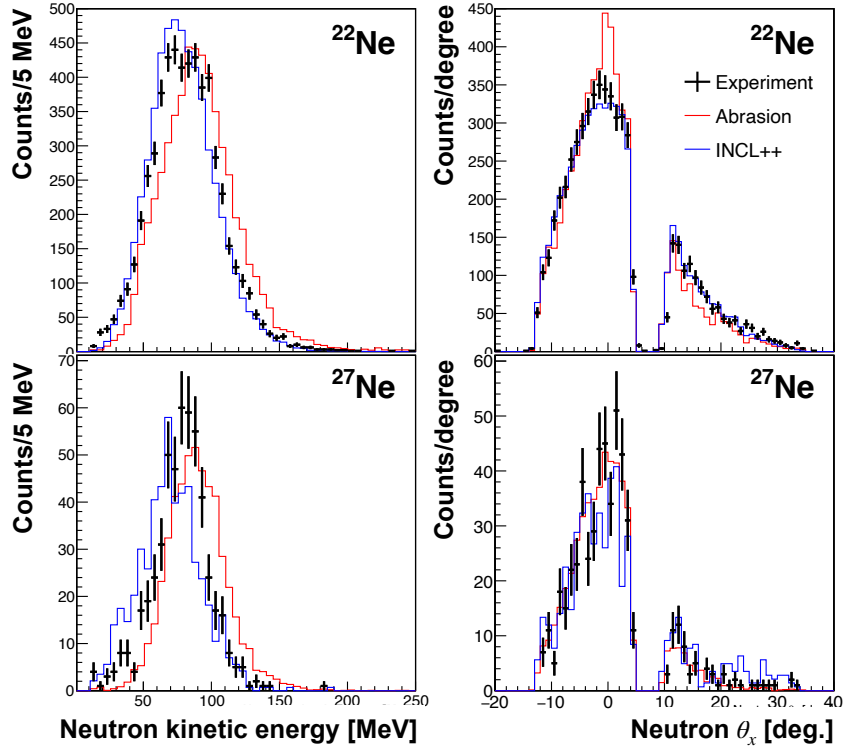


Figure 5.2: Neutron kinetic energy (left) and neutron angular projection θ_x (right) in coincidence with ^{22}Ne (top row) and ^{27}Ne (bottom row). Experimental data are shown as black data points, results of the Abrasion simulation are shown as red histograms, and results of the INCL++ simulation are shown as blue histograms.

distribution than INCL++, which, similarly to the kinetic energy distribution, is broader than the experimental angular distribution.

Figure 5.2 compares the same distributions for ^{22}Ne and ^{27}Ne fragments. The experimental neutron kinetic energy spectra in coincidence with both neon isotopes peak at approximately the beam energy per nucleon at the center of the reaction target. As with the sodium case, the ^{22}Ne kinetic energy distribution is much broader than the ^{27}Ne distribution. The results from the Abrasion model show the neutron kinetic energy in coincidence with ^{22}Ne to peak at approximately 88 MeV, whereas the results from INCL++ are in closer agreement with the data, peaking at approximately 76 MeV. Neither simulation agrees closely with the experimental ^{27}Ne kinetic energy spectrum, with the Abrasion model predicting the kinetic energy to peak at too high of an energy (88 MeV) and INCL++ predicting the kinetic energy to peak at too low of an energy (70 MeV).

Likewise, the angular distribution in coincidence with ^{22}Ne from INCL++ agrees more closely

with the experimental data than the narrower distribution from the Abrasion model. The predictions from the Abrasion model agree more closely with the experimental ^{27}Ne angular distribution than INCL++, which predicts a slightly broader angular distribution than the experimental data.

Similar trends are seen for the fluorine and oxygen isotopes, shown in Figures 5.3 and 5.4, respectively. For the lighter fluorine and oxygen isotopes, ^{19}F and ^{17}O , the measured neutron kinetic energy distributions agree more closely with the results from INCL++, whereas the Abrasion model predicts peaks at higher energy than observed experimentally. For the heavier of the two isotopes, ^{24}F and ^{21}O , the experimental kinetic energy lies between the INCL++ prediction, which is lower than experiment, and the Abrasion results, which are slightly higher than experiment. Unlike the sodium and neon isotopes, the two reaction models predict very similar neutron angular distributions for the selected fluorine and oxygen isotopes. The limited experimental statistics for the fluorine and oxygen isotopes prevent a definitive distinction between the two models. Nevertheless, the measured neutron kinematic observables remain consistent with the behavior established by the sodium and neon isotopic chains

The selected isotopes reveal a systematic evolution of the neutron kinematic observables with final fragment mass. The experimental neutron kinetic energy spectra remain centered near the beam energy but become progressively broader for lighter fragments, and the neutron angular distributions also broaden with decreasing fragment mass. Although both reaction models reproduce these overall trends, neither provides consistently better agreement across all isotopic chains. Instead, the relative agreement depends on the final fragment, with the Abrasion model generally describing fragments nearest the projectile more accurately and INCL++ often providing better agreement for the lighter fragments.

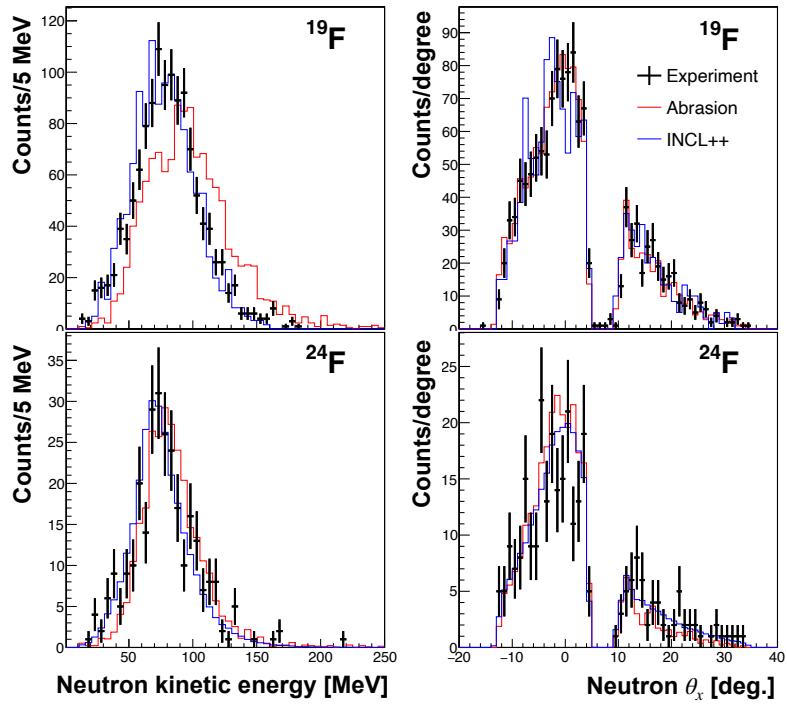


Figure 5.3: Same as Figures 5.1 and 5.2, but for ^{19}F and ^{24}F .

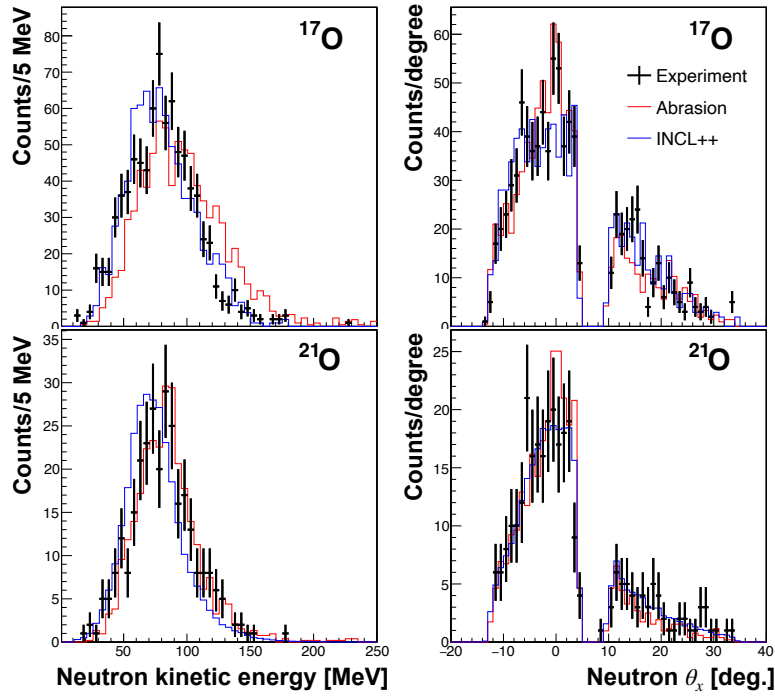


Figure 5.4: Same as Figures 5.1 and 5.2, but for ^{17}O and ^{21}O .

5.1.2 Neutron Interaction Multiplicity

The neutron interaction multiplicity, which is the number of valid interactions in MoNA within a single event, was recorded in coincidence with each measured fragment. The neutron interaction multiplicity spectrum associated with each final fragment is generated using the same gates that were used to create the neutron kinetic energy and angular distributions. The difference in this case is that these spectra also include events that do not come in coincidence with a valid interaction in MoNA and events with one or more valid interactions, rather than just the first time-sorted interaction. For each measured isotope, the simulated interaction multiplicity spectra are normalized to the total number of measured events for that isotope.

Figure 5.5 shows the neutron interaction multiplicity distributions for the same light and heavy isotopes that were discussed in Section 5.1.1. Once again, these specific isotopes were chosen to investigate how the neutron interaction multiplicity evolves with the mass of the final fragment. This figure is organized with elements from sodium to oxygen placed from left to right, respectively. The light isotopes lie on the top row and the heavy isotopes are on the bottom row. The black filled circles represent the experimental data and the red open squares and blue open triangles represent the simulated Abrasion and INCL++ data, respectively. The simulated data were normalized to the total number of events of a given fragment in the experimental data. Neutron interaction multiplicity spectra in coincidence with all fragments from each of the Sweeper magnet settings are presented in Appendix B.

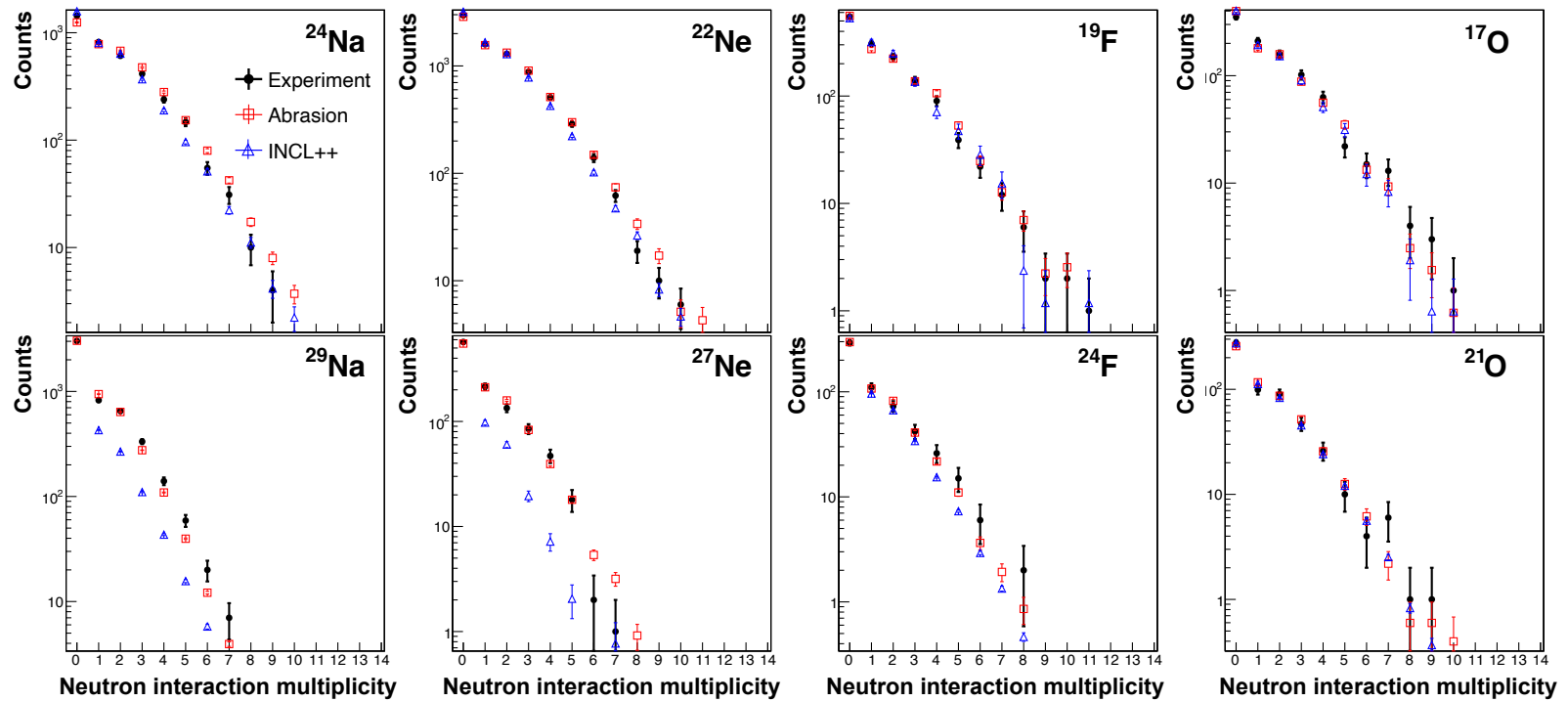


Figure 5.5: Neutron interaction multiplicity spectra in coincidence with "light" (top row) and "heavy" (bottom row) sodium, neon, fluorine, and oxygen isotopes (from left to right, respectively). Experimental data is shown as solid black circles, Abrasion with open red squares, and INCL++ with open blue triangles.

Generally, most charged fragment events are associated with low neutron interaction multiplicities, with the number of events dropping steeply as the interaction multiplicity increases. Because this drop-off is so steep, these plots are shown on a semi-log scale to better highlight the differences between the measured and simulated data. When comparing the neutron interaction multiplicity spectra for the light isotopes to those of the heavy isotopes, one can observe that the heavier isotopes (which are closer in mass to the ^{32}Mg projectile) come in coincidence with fewer neutron interactions than the lighter isotopes. This is not surprising, as there is less overall mass loss required to produce the heavier fragments compared to the lighter fragments. This behavior is most apparent for the sodium and neon isotopes since the heaviest measured isotopes are only a few nucleons away from the projectile, unlike fluorine and oxygen, whose heaviest measured isotopes are eight and eleven nucleons away from ^{32}Mg , respectively.

Both the Abrasion model and INCL++ models capture this trend, although INCL++ significantly under-predicts the number of neutron interactions in coincidence with the heaviest sodium and neon fragments, whereas the results from the Abrasion model agree much more closely with the experimental data. For the lightest sodium and neon isotopes, and both light and heavy fluorine and oxygen isotopes, Abrasion and INCL++ agree with the experimental data quite well. Note that these results are quite similar to those for the neutron kinetic energy and angular distributions, where the greatest difference between the two model descriptions are for the fragments closest in mass to the projectile, namely the most neutron-rich sodium and neon isotopes.

Overall, the neutron interaction multiplicity spectra reveal a consistent evolution with final fragment mass. Fragments nearest the projectile are associated predominantly with low interaction multiplicities, whereas lighter fragments have interaction multiplicity distributions that extend to higher multiplicities. Both reaction models reproduce this qualitative behavior, although the Abrasion model provides a more accurate description for the neutron-rich sodium and neon isotopes where the differences between the models are most pronounced.

5.1.3 Neutron Coincidences-to-Total Ratio

The neutron coincidences-to-total ratio provides a concise summary of the neutron interaction multiplicity distributions presented in the previous section. This ratio is calculated as the number of charged fragment events that are measured in coincidence with at least one valid interaction in MoNA over the total number of measured charged fragment events. Further details on how this parameter was calculated were given in Section 4.2.6. The results are shown in Figures 5.6, 5.7, and 5.8 as a function of final fragment mass for each isotopic chain measured in each of the three Sweeper magnet settings, respectively. The coincidences-to-total ratios for both the measured and simulated data are available in a tabulated format in Appendix C.

The experimental data (shown as solid black circles connected with solid lines), show a consistent trend: a decreasing ratio with increasing final fragment mass in each isotopic chain and each Sweeper magnet setting. In other words, the most neutron-rich final fragments are less likely to be measured in coincidence with at least one valid neutron interaction than fragments with greater total mass loss. This observation is reflected in the neutron interaction multiplicity spectra presented in the previous section, where fragments closer to the projectile have substantially fewer high-multiplicity events than the lighter fragments. Moreover, the rate at which the coincidences-to-total ratio changes also varies across the measured fragment masses. For fragments nearest the projectile, particularly the sodium and neon isotopes in Figure 5.8, the coincidences-to-total ratio decreases rapidly toward zero as the final fragment mass approaches the projectile mass of $A = 32$, that is to say, approaches the neutron number of the projectile, $N = 20$. The variation becomes much more gradual for the lighter fragments, where the coincidences-to-total ratio plateaus near a value of approximately 0.6. This behavior is most clearly observed for the fluorine and oxygen isotopic chains in the 2.97 and 3.15 Tm Sweeper magnet settings, shown in Figures 5.6 and 5.7.

Both the Abrasion and INCL++ calculations reproduce the decrease in the coincidences-to-total ratio with increasing final fragment mass, demonstrating that both models capture the qualitative evolution observed experimentally. The largest differences between the model predictions occur for the neutron-rich sodium and neon isotopes.

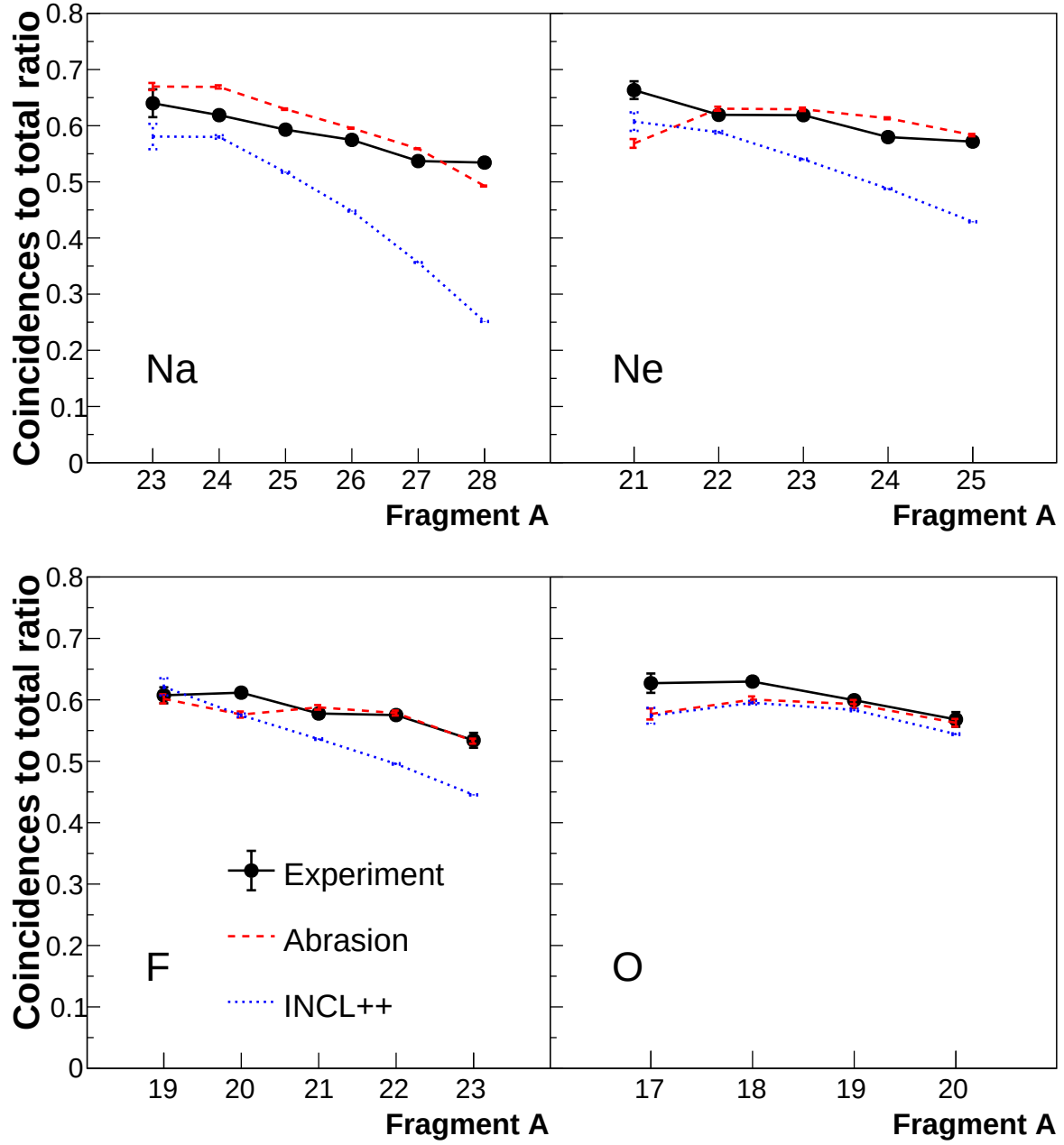


Figure 5.6: Coincidences-to-total ratio as a function of final fragment mass and charge for the 2.97 Tm setting. The four panels show the individual isotopic chains, comparing the experimental data (solid black circles with solid lines) to the results of the Abrasion and INCL++ simulations (red dashed and blue dotted lines, respectively). Error bars are statistical and smaller than the marker size if not visible.

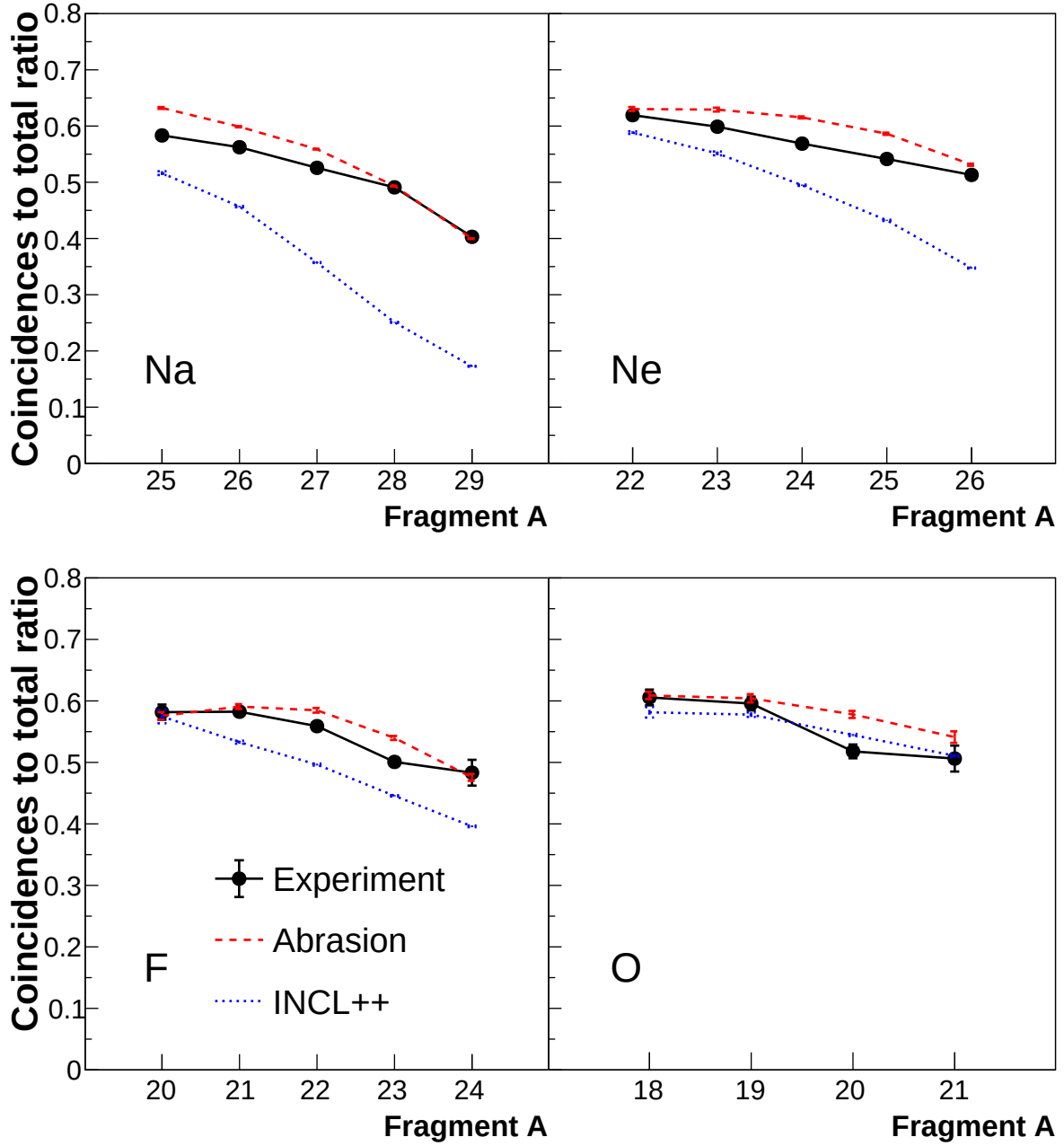


Figure 5.7: Same as Figure 5.6, but for the 3.15 Tm data.

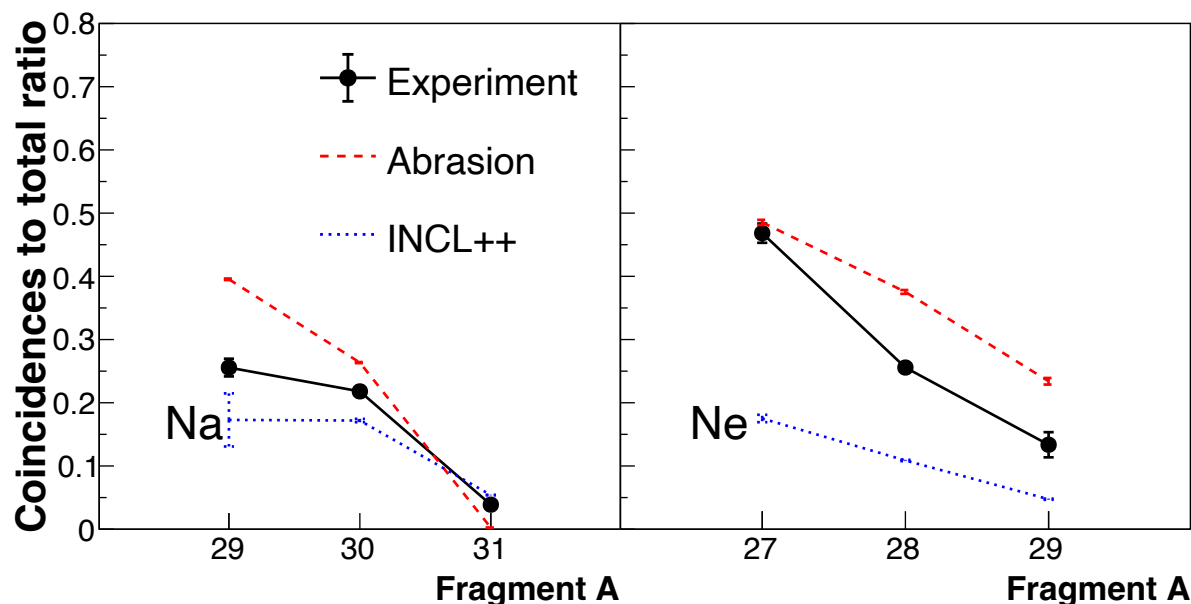


Figure 5.8: Same as Figure 5.6, but for the 3.75 Tm data.

The Abrasion model agrees remarkably well with the measured coincidences-to-total ratios throughout the measured isotopic chains. For the neutron-rich sodium and neon isotopes, the predicted ratios closely reproduce the experimental trend, although the calculations generally overpredict the measured coincidences-to-total ratios by a small amount. Agreement remains good for the fluorine and oxygen isotopes, where the predicted and measured ratios differ only slightly. A notable exception is observed for the lightest measured neon and oxygen isotopes, where the Abrasion coincidences-to-total ratio slightly decreases rather than continuing to level off with decreasing fragment mass.

INCL++ systematically underpredicts the coincidences-to-total ratio for the neutron-rich sodium and neon isotopes. This discrepancy is evident in all three Sweeper magnet settings, although the agreement improves as the final fragment mass decreases. For the lightest measured fragments, the INCL++ predictions are generally comparable to those of the Abrasion model and agree reasonably well with the experimental data.

The coincidences-to-total ratio decreases with increasing fragment mass for every isotopic chain and magnet setting investigated. Both reaction models reproduce this qualitative behavior, although Abrasion generally provides closer agreement for the neutron-rich sodium and neon isotopes while

INCL++ severely underpredicts the measured ratios in this region. The differences between the models—particularly for the neutron-rich sodium and neon isotopes—suggest that this observable is especially sensitive to the differing descriptions of the reaction.

5.2 Discussion and Interpretation of Results

The results presented in the previous sections demonstrate that the measured neutron observables exhibit systematic trends with final fragment mass and that these observables distinguish between the Abrasion and INCL++ descriptions of the reaction. To understand the origin of these differences, the measured observables should be interpreted in terms of the underlying reaction mechanism. The following sections explore how differences in the predicted prefragment properties may account for the observed differences between the two reaction models.

5.2.1 Neutron Acceptance

As demonstrated in the previous section, the coincidences-to-total ratio decreases with increasing final fragment mass. Because the individual evaporated neutrons are not counted directly, the measured interaction multiplicity and coincidences-to-total ratio reflect both the underlying neutron emission and the response of the MoNA detector. Before these observables can be interpreted in terms of the reaction mechanism, it is therefore useful to examine how the detector efficiency and geometric acceptance relate the number of emitted neutrons to the measured observables.

Suppose a prefragment emits N neutrons to de-excite into a given final fragment. Each neutron has a specific probability to be detected in MoNA. This probability, otherwise referred to as the total detection efficiency ϵ , is related to the intrinsic detection efficiency $\epsilon_{\text{det}}(E)$ and the geometric acceptance $\epsilon_{\text{geom}}(E)$ of the detector.

$$\epsilon = \epsilon_{\text{det}}(E)\epsilon_{\text{geom}}(E) \quad (5.1)$$

If the detection of each evaporated neutron is treated as an independent process, the probability of detecting at least one neutron is simply the complement of detecting zero neutrons when N total neutrons are emitted:

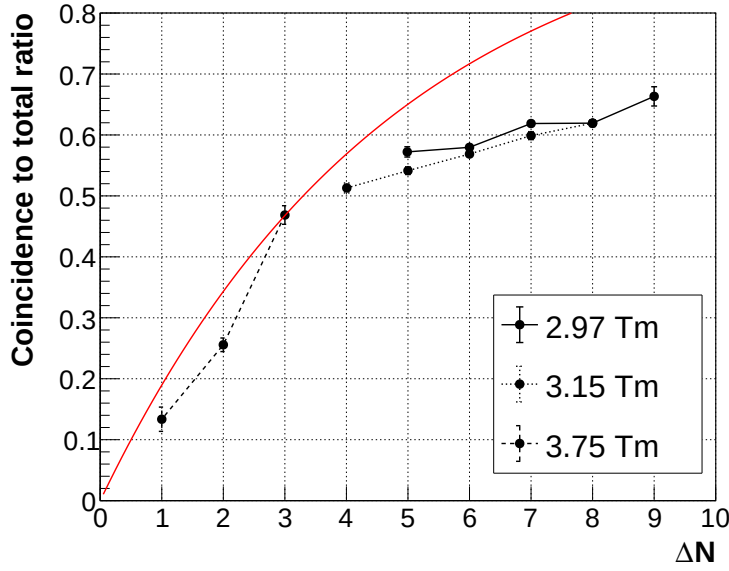


Figure 5.9: Measured coincidences-to-total ratios for the neon isotopes as a function of the number of neutrons removed from the projectile, ΔN (solid black circles). The calculated probability of detecting at least one neutron is shown for 80 MeV neutrons (solid red curve). Although the probability curve is calculated as a function of the number of emitted neutrons, it is overlaid onto the measured coincidences-to-total ratios to illustrate the expected qualitative behavior.

$$P(\text{detect at least one neutron}) = 1 - (1 - \epsilon)^N. \quad (5.2)$$

The intrinsic detection efficiency for 80 MeV neutrons is 0.79 [63], and based on GEANT4 simulations of the present detector configuration, the geometric acceptance for isotropically emitted neutrons moving at a velocity of 80 MeV is 0.24. These values yield a total detection efficiency of $\epsilon = 0.1896$. The probability curve was chosen to be calculated at this energy since the measured neutron kinetic energy spectra are all centered at approximately the beam energy at the center of the target (80 MeV or so).

Figure 5.9 compares the measured coincidences-to-total ratios for the neon isotopes with the calculated probability curve. The coincidences-to-total ratios are plotted as a function of the total number of neutrons removed during the reaction, ΔN , for each Sweeper magnet setting. The probability curve for 80 MeV neutrons is overlaid as a red curve. Note that the probability curve is calculated as a function of the number of neutrons emitted in the reaction, which is not necessarily

equivalent to the total ΔN . Nevertheless, larger values of ΔN are generally associated with the emission of more neutrons and therefore provide a useful qualitative comparison.

The measured coincidences-to-total ratios follow the same general behavior as the calculated probability curve: the ratio increases rapidly at small ΔN and then changes more gradually for larger ΔN . The probability curve corresponds to an approximate upper limit on the neutron coincidences-to-total ratio. Many factors may cause the total detection efficiency to be lower than this stated value. For example, evaporated neutrons cause recoil in the prefragment, so the overall neutron angular distribution will become broader as more neutrons are evaporated. This, in turn, will reduce the geometric acceptance at higher true neutron multiplicities. Nonetheless, the similarity between the coincidences-to-total ratios and the probability curve indicates that, even with detector response and acceptance folded into the measurement, the coincidences-to-total ratio remains consistent with an increasing average number of evaporated neutrons as the final fragment moves farther from the projectile.

5.2.2 Prefragment Distributions

The results from the neutron acceptance suggest that the coincidences-to-total ratio is related to the average number of neutrons evaporated during the de-excitation process. This naturally connects the coincidences-to-total ratio to the underlying distribution of prefragments that de-excite into the measured final fragment. The production of the most neutron-rich final fragments requires the prefragment to retain the majority of its neutrons through both steps of the reaction. Therefore, the reaction must proceed primarily through the removal of protons while leaving the neutron content of the projectile largely intact. In addition, these prefragments must have excitation energies near, or only slightly above, the neutron emission threshold so that only a small number of neutrons are evaporated during de-excitation. Although charged-particle emission could also contribute to the de-excitation process, these channels are strongly suppressed in neutron-rich nuclei because of the Coulomb barrier and the generally lower neutron separation energies.

The opposite behavior is expected for the lighter final fragments. Producing these nuclei requires a larger overall mass loss from the projectile and therefore a longer de-excitation path from

the prefragment to the final fragment. Such de-excitation chains are consistent with prefragments possessing substantially higher excitation energies, allowing the emission of multiple neutrons before reaching the observed final fragment. The higher excitation energies also allow the evaporated neutrons to be emitted with a broader range of energies in the prefragment frame. After transformation into the laboratory frame, the kinetic-energy and angular distributions are broader than de-excitations with lower excitation energy, while the increased number of evaporated neutrons produces larger coincidences-to-total ratios. This picture naturally explains the systematic evolution of the neutron kinetic energy spectra, angular distributions, and coincidences-to-total ratios presented in the previous sections.

To investigate this interpretation, the prefragment distributions predicted by the Abrasion and INCL++ reaction models were extracted from the simulations. During each simulated reaction in GEANT4, the properties of the prefragment produced by the fast step of the reaction (either Abrasion or INCL++) were associated with the corresponding final de-excited fragment. This event-by-event information makes it possible to reconstruct the distribution of prefragments leading to any given final fragment. Figures 5.10–5.13 compare the predicted prefragment distributions for the light and heavy sodium, neon, fluorine, and oxygen isotopes previously introduced in this chapter. These examples were selected to determine whether the evolution of the predicted prefragment properties with final fragment mass is consistent across all measured isotopic chains. In these figures, the top two panels show the prefragment distributions predicted by the Abrasion model for the light and heavy isotopes (left and right, respectively). The bottom two panels are laid out the same way, except showing the prefragment distributions predicted by INCL++. The corresponding excitation energy distributions associated with each prefragment distribution are presented in the inset of each panel. The prefragment distributions are plotted as a function of atomic number (Z) and neutron number (N), where the color scale represents the probability that the final fragment originated from a specific prefragment. Each distribution is normalized such that the total probability summed over all contributing prefragments is equal to one. This normalization allows the prefragment distributions associated with different final fragments, as well as those predicted by the two reaction models, to

be compared directly, independent of differences in the fragment production yields.

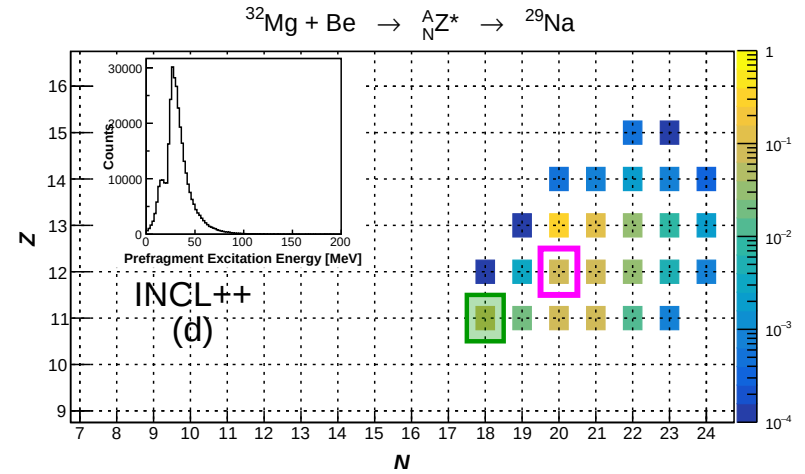
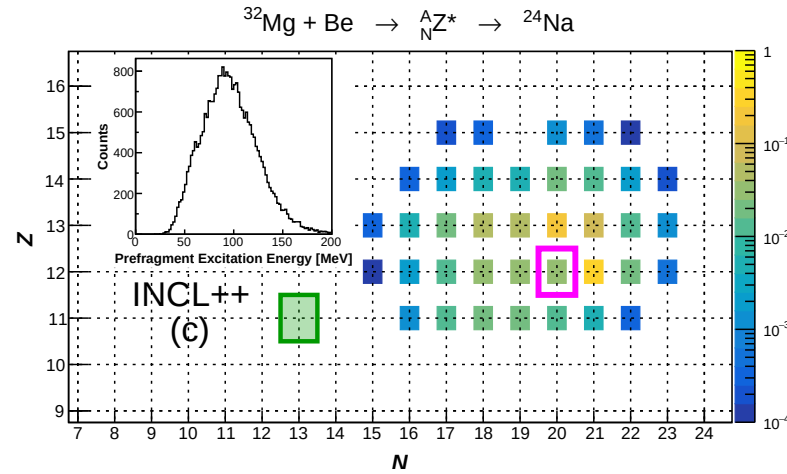
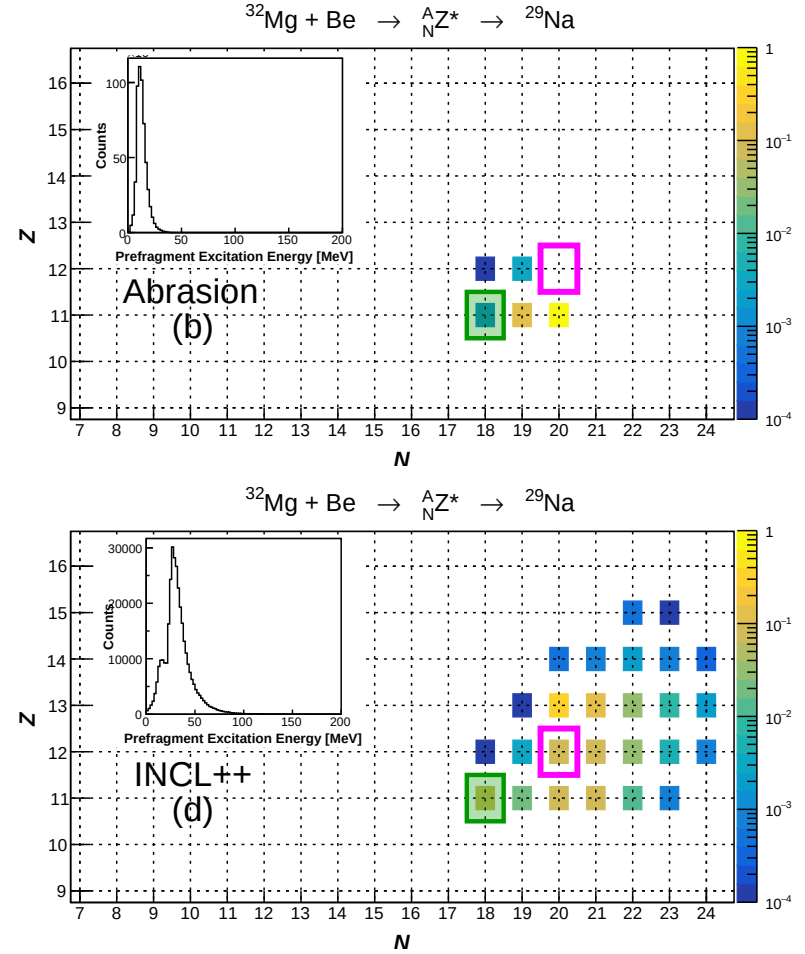
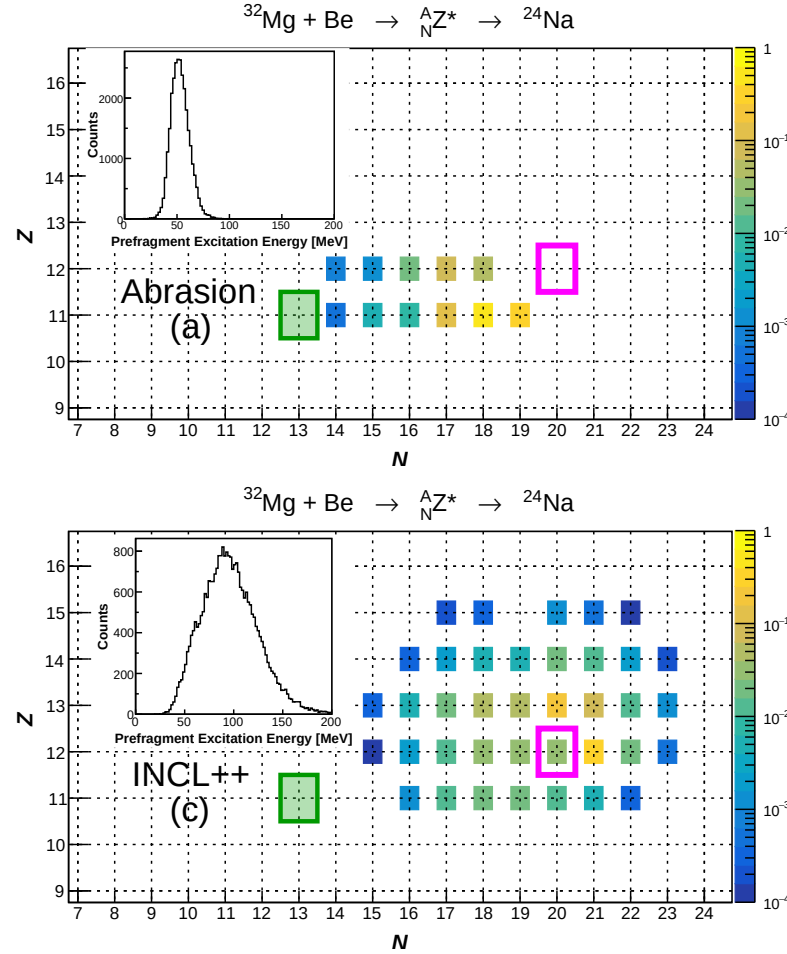


Figure 5.10: Distributions of the prefragments for ^{24}Na and ^{29}Na final fragments shown as a function of Z and N . The ^{24}Na and ^{29}Na prefragment distributions predicted by the Abrasion model are shown in (a) and (b), and the prefragment distributions predicted by the INCL++ model for the same final fragments are shown in (c) and (d). The projectile nucleus is shown by the magenta outlined box and the final nucleus by the green filled box. The inset in each panel shows the excitation energy distribution corresponding to each prefragment distribution.

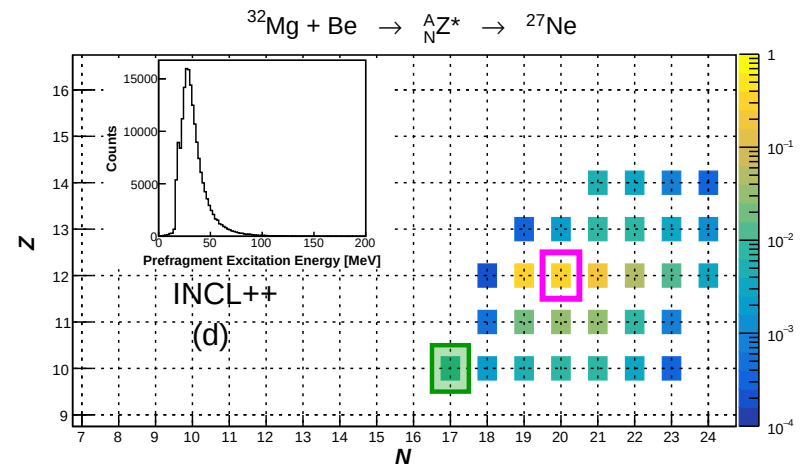
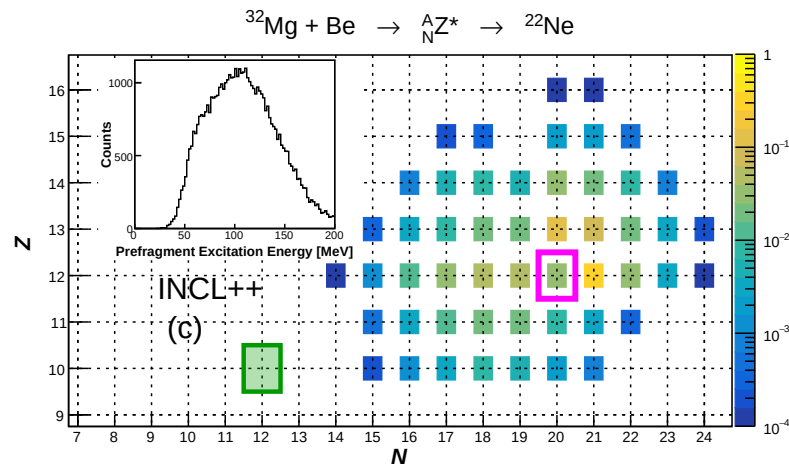
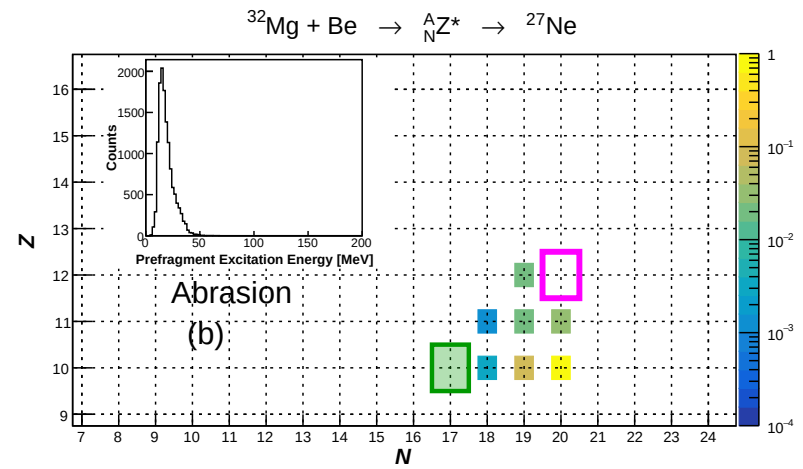
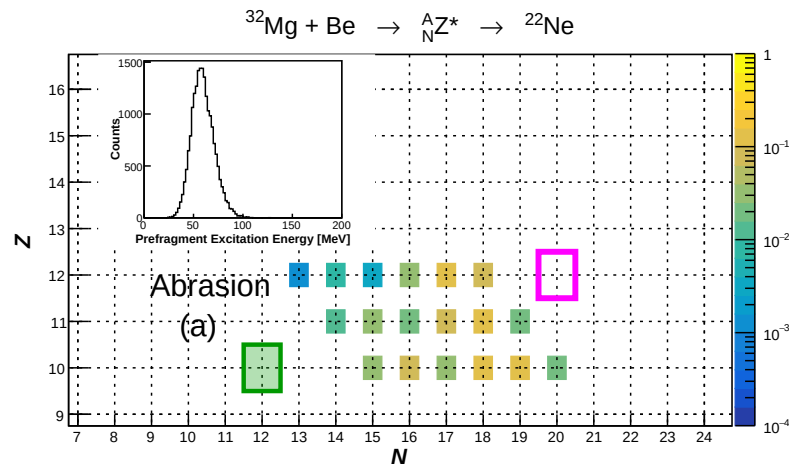


Figure 5.11: Same as Figure 5.10, but for ^{22}Ne and ^{27}Ne .

Figure 5.10 illustrates that the predicted prefragment distributions leading to the production of the heavy ^{29}Na fragment differ substantially between the two reaction models. The INCL++ calculation predicts a relatively broad prefragment distribution that extends to masses greater than the projectile, reflecting a significant contribution from nucleon pickup during the intranuclear cascade step of the reaction. In contrast, the Abrasion model predicts a much narrower distribution dominated by the removal of a single proton from the projectile. These differences are reflected in the corresponding excitation energy distributions shown in the insets of Figure 5.10. The INCL++ distribution is broad and exhibits two distinct components: a smaller peak near 15 MeV and a dominant peak centered around 28 MeV. The higher-energy component is associated primarily with prefragments that have masses greater than the projectile ($A > 32$). In comparison, the Abrasion model predicts a narrow excitation energy distribution centered near 12 MeV with a weak tail extending toward higher excitation energies.

The situation changes considerably for the lighter ^{24}Na fragment. Both reaction models predict broader prefragment distributions together with substantially higher excitation energies, consistent with the longer de-excitation sequences required to reach the lighter ^{24}Na final fragment. The INCL++ model predicts an excitation energy distribution peaking near 100 MeV, whereas the Abrasion model predicts excitation energies centered around 60 MeV. At such high excitation energies, the de-excitation pathways become increasingly complex, and many different sequences of light particle emission can produce the same final fragment. Nevertheless, the longer de-excitation chains produce larger coincidences-to-total ratios, and the increasing number of possible pathways reduces the ratio's sensitivity to the detailed structure of the initial prefragment distributions. As a result, the coincidences-to-total ratios predicted by the Abrasion and INCL++ models become increasingly similar, even though the underlying prefragment distributions remain markedly different.

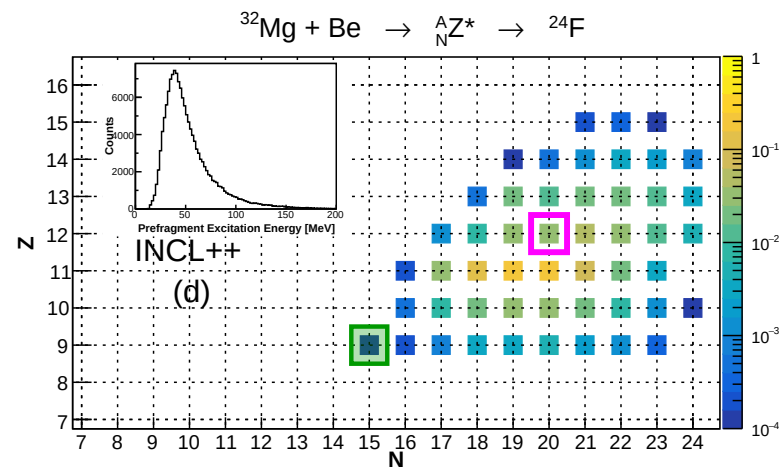
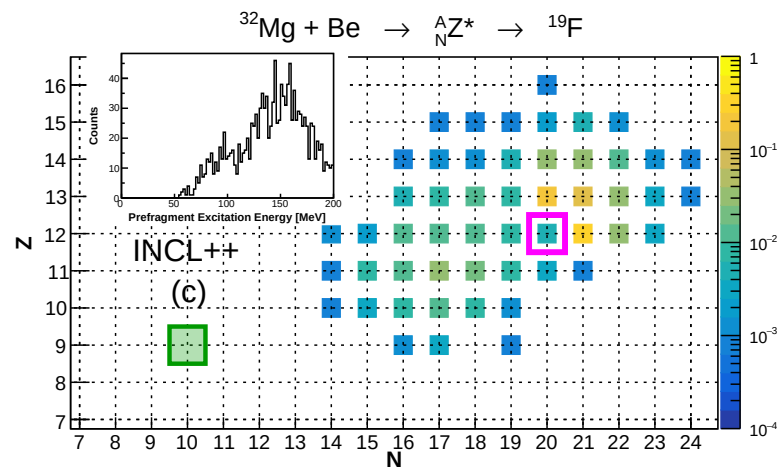
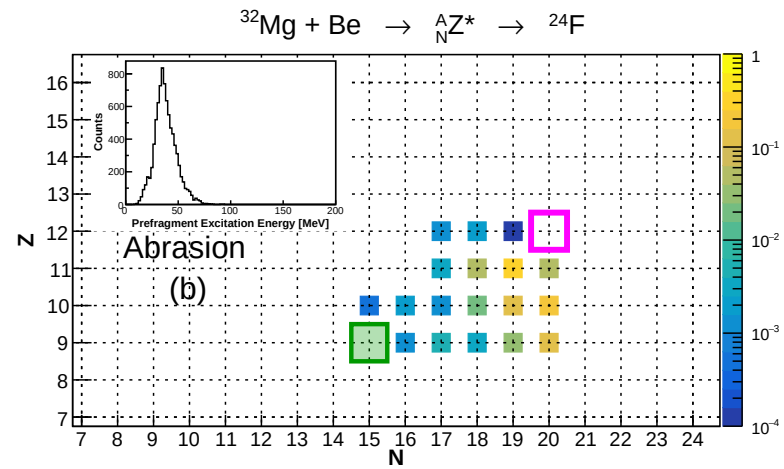
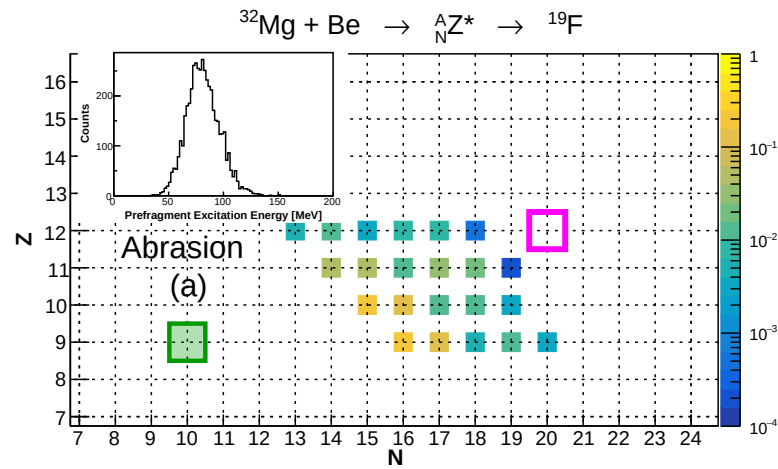


Figure 5.12: Same as Figure 5.10, but for ^{19}F and ^{24}F .

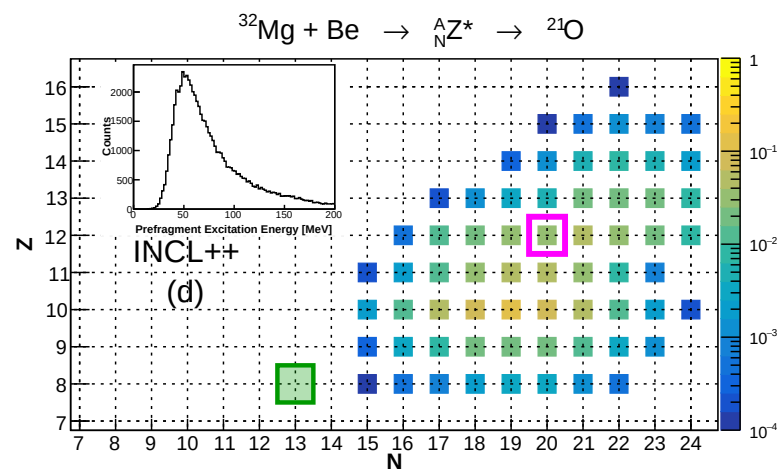
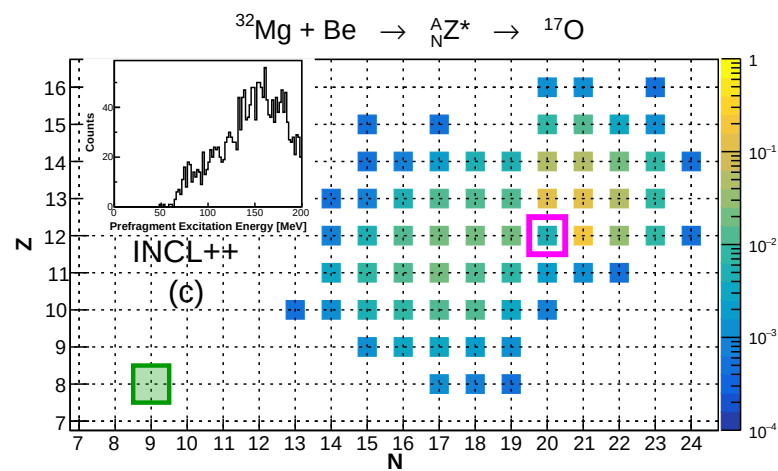
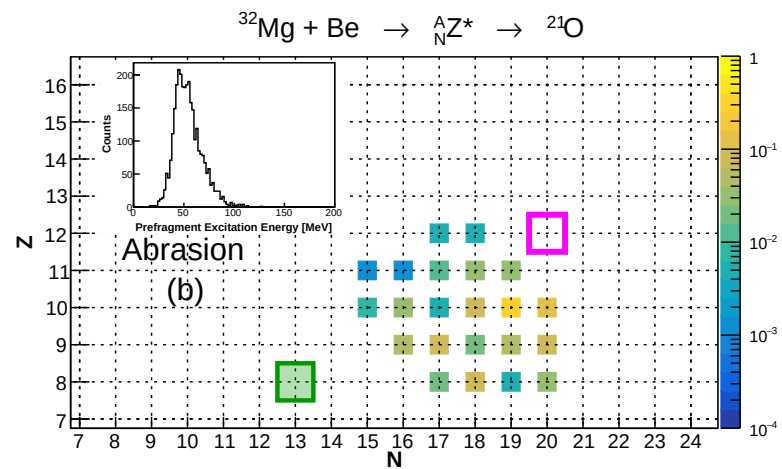
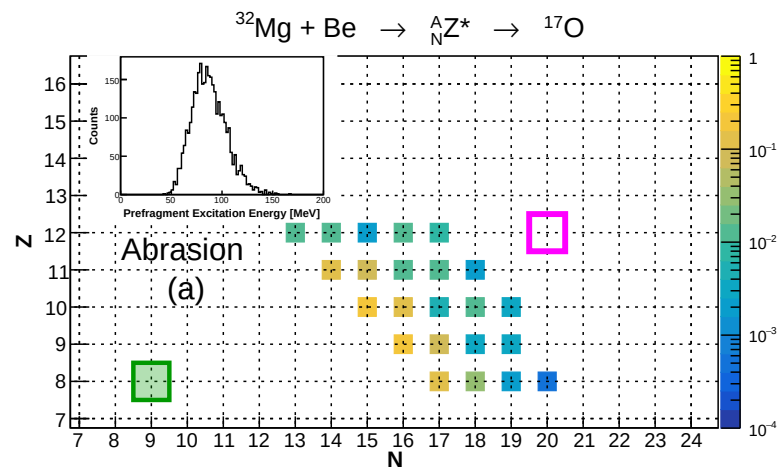


Figure 5.13: Same as Figure 5.10, but for ^{17}O and ^{21}O .

The prefragment distributions for the neon isotopes shown in Figure 5.11 reinforce the trends observed in the sodium isotopes. For the heavier ^{27}Ne fragment, the INCL++ prediction is similarly broad and includes contributions from prefragments with masses greater than the projectile, whereas the Abrasion model predicts a much more localized distribution dominated by the removal of two protons. From this, the Abrasion model reaches the final fragment primarily through the emission of three neutrons, while the broader INCL++ prefragment distribution allows both neutron and charged-particle emission to significantly contribute to the de-excitation process. Likewise, the lighter ^{22}Ne isotope originates from broader prefragment distributions in both models, accompanied by higher and broader excitation energies that are consistent with the longer de-excitation chains required to reach the final fragment.

In the case of fluorine and oxygen, the heaviest measured isotopes are 8 and 11 nucleons away from the projectile, respectively. For both the heavy and light isotopes in these cases, the prefragment distributions predicted by the Abrasion and INCL++ are rather broad and the excitation energies are high, at times with tails exceeding 100 MeV. As described above from the sodium and neon examples, the de-excitation pathways that emerge from these types of prefragment distributions are complex, diminishing the sensitivity of the coincidences-to-total ratio to the differences in the predicted prefragment distributions. Recall that the fluorine and oxygen coincidences-to-total ratios are very similar between the Abrasion and INCL++ predictions.

Overall, the predicted prefragment distributions reveal systematic differences between the Abrasion and INCL++ descriptions of the fast step of the reaction. The Abrasion model consistently predicts relatively narrow distributions of prefragments that are lighter than the projectile, whereas INCL++ predicts substantially larger contributions from prefragments with masses exceeding that of the projectile, indicating a relatively high probability of multiple-nucleon pickup during the intranuclear cascade. The broad prefragment distributions predicted by INCL++ are accompanied by broader excitation energy distributions, leading to de-excitation pathways that differ significantly from those predicted by the Abrasion model, particularly for fragments close in mass to the beam. Because the Abrasion model generally reproduces the measured neutron coincidences-to-total ra-

tios more accurately, the extensive multiple-nucleon pickup predicted by INCL++ may be one contributor to the disagreement with the experimental neutron observables. However, note that the experimental observation of aluminum isotopes following the fragmentation of ^{32}Mg (the band above the most intense band in Figure 4.8) demonstrates that nucleon pickup does occur in these reactions. Since the Abrasion model does not produce fragments heavier than the projectile, this observation indicates that reaction mechanisms beyond the simple abrasion picture contribute to the measured fragment production.

5.2.3 INCL++ Prefragment Angular Momentum

The total angular momentum of the prefragment (J) is taken into account by the ABLA++ de-excitation model through a modified version of the Weisskopf-Ewing formalism, as discussed in Chapter 2. Therefore, it is worthwhile to investigate and compare the prefragment angular momentum predicted by the Abrasion and INCL++ models. Because the properties of the prefragments are tracked in the GEANT4 simulation, the angular momentum distributions predicted by these models can be directly compared to each other. Figure 5.14 shows the total angular momenta of the prefragments that de-excited into the nuclei that were analyzed in this work. The Abrasion model predicts a narrow distribution of total angular momentum, peaking around $3\hbar$, while INCL++ predicts a much broader range of angular momentum, peaking at approximately $20\hbar$ with a tail extending to nearly $40\hbar$.

A recent work by Rodríguez-Sánchez et al. [23] shows that INCL++ predicts a similarly large prefragment total angular momentum for fragmentation of ^{236}U on an Al target at 650 AMeV and, comparably, the total angular momentum predicted by the Abrasion model is smaller and narrower. The observation that INCL++ produces large prefragment angular momentum values for both heavy and light systems at vastly different energies is surprising and warrants additional investigation.

The unusually large prefragment angular momenta predicted by INCL++ motivate an investigation into their influence on the predicted neutron observables. To assess this effect, a study was performed in which the prefragment angular momentum was artificially set to zero prior to de-excitation by ABLA++. All other aspects of the simulation remained unchanged. Comparison of

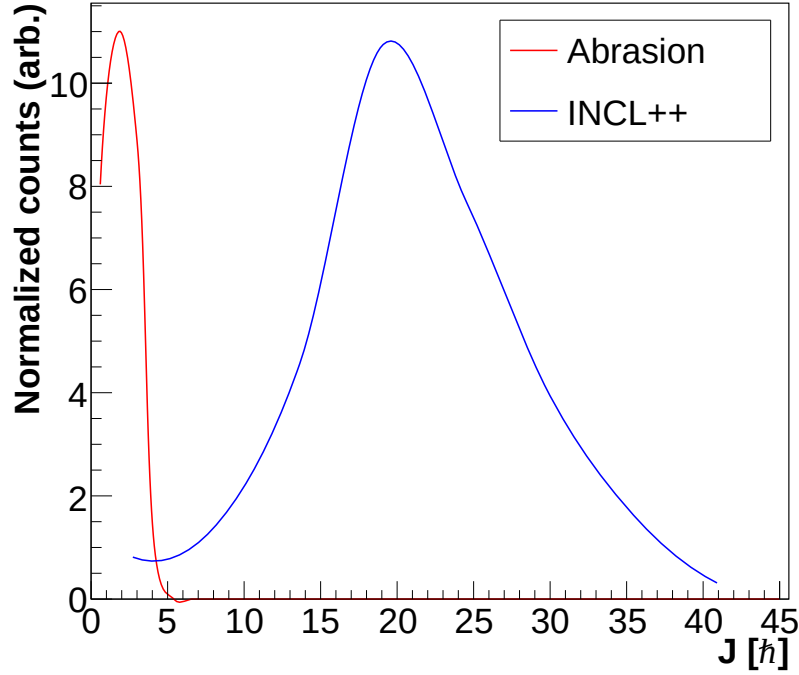


Figure 5.14: Distributions of the prefragment angular momenta from the Abrasion (red) and the INCL++ models (blue).

the two calculations shows that the large angular momenta predicted by INCL++ strongly suppress neutron evaporation, thereby altering the de-excitation paths leading to a given final fragment. This means that for a given final fragment, take for example ^{29}Na , the prefragment distributions that lead to the same final fragment look different between the two sets of simulations (default J and $J = 0$). This effect is shown in Figure 5.15, which shows the distribution of prefragments that lead to a ^{29}Na final fragment in both cases. One can see that the most probable prefragment in the default J case is ^{33}Al , which emits an α particle to reach the final fragment ^{29}Na . On the other hand, when $J = 0$, the prefragment distribution is narrower, with the contribution from nucleon pickup reduced significantly. In this case, the most probable prefragment becomes ^{31}Na , which is also the most probable prefragment predicted by the Abrasion model for this case. Furthermore, the corresponding INCL++ excitation energy distribution becomes more similar to the Abrasion prediction.

Logically following this change in the prefragment distributions, Figure 5.16 shows that the

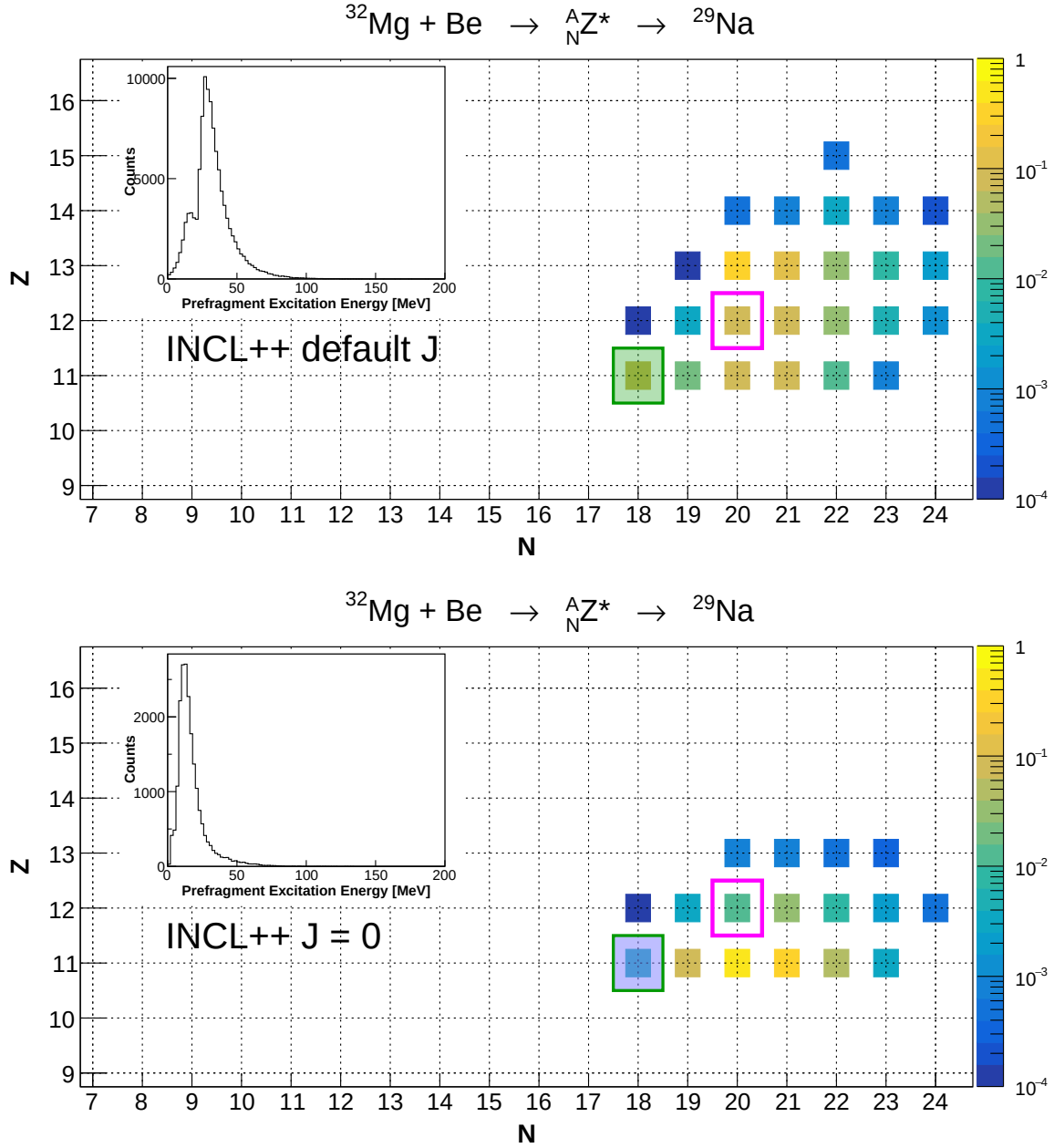


Figure 5.15: Distributions of the prefragments for a ${}^{29}\text{Na}$ final fragment shown as a function of Z and N . The prefragment distribution predicted by the INCL++ model with default prefragment angular momentum J is shown in the top panel and the bottom panel shows the same for $J = 0$. The projectile nucleus is shown by the magenta outlined box and the final nucleus by the green filled box. The inset in each panel shows the excitation energy distribution corresponding to each prefragment distribution.

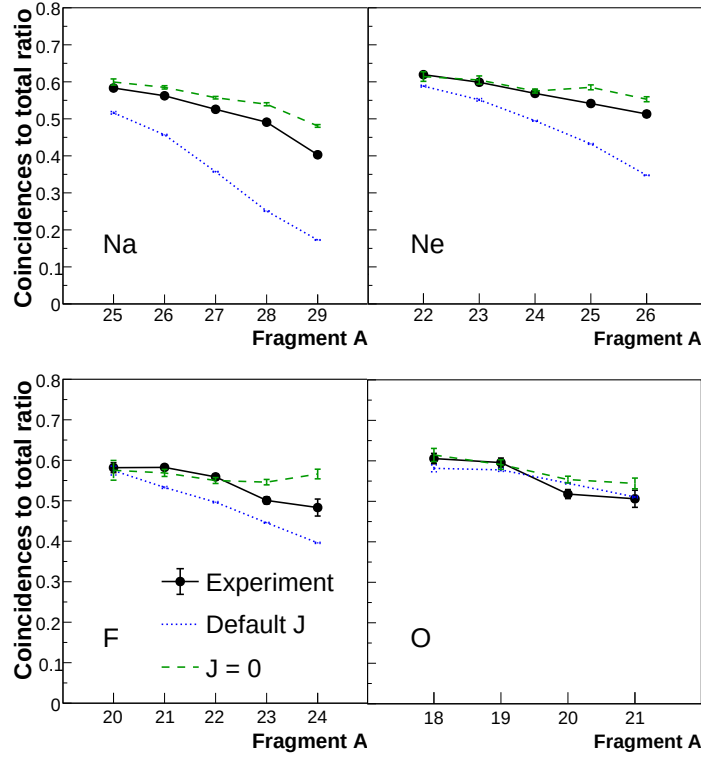


Figure 5.16: Coincidences-to-total ratio as a function of final fragment mass and charge for the 3.15 Tm setting. These plots compare the experimental data (solid black circles with solid lines) to the results of the INCL++ model with the default prefragment angular momentum (J), and $J = 0$ (blue dotted and green dashed lines, respectively). Error bars are statistical and smaller than the marker size if not visible.

neutron coincidences-to-total ratio for ^{29}Na increases and agrees much more closely with the experimental data when the prefragment angular momentum is set to zero. Similar improvement is seen across almost all of the measured fragments, but is most pronounced for the heaviest sodium and neon isotopes where the discrepancy between the default INCL++ calculation and the experimental data is largest. These results suggest that the unusually large prefragment angular momenta predicted by INCL++ are a significant contributor to the discrepancies between the calculated and measured neutron observables. Furthermore, reducing the prefragment angular momentum also leads to prefragment distributions that are more physically reasonable, with substantially reduced contributions from nucleon pickup.

5.2.4 Abrasion Excitation Energy

The prefragment excitation energy is a key input to the de-excitation calculation, as it determines the energy available for neutron and charged-particle emission. Consequently, the excitation energy influences the path from prefragment to final fragment and, thus, the resulting neutron observables. As discussed in Chapter 2, the Gaimard and Schmidt formalism describes the prefragment excitation energy as a fixed amount of energy per abraded nucleon. In its original formulation, this parameter was taken to be 13.3 MeV per abraded nucleon, which is also the value used throughout this work. Numerous studies have attempted to optimize the excitation energy scaling factor by comparing calculated fragmentation cross sections with experimental measurements [70, 21, 19]. These studies have also suggested that the excitation energy may not be described by a universal scaling factor. In particular, the mean excitation energy per abraded nucleon has been found to vary with projectile mass [21], while discrepancies in deeply-bound nucleon removal cross sections have motivated the suggestion that the prefragment excitation energy may also depend on the separation energies of the removed nucleons [71, 72].

To investigate the sensitivity of the neutron observables to the prefragment excitation energy, the excitation energy per abraded nucleon in the Abrasion model was doubled from 13.3 MeV/nucleon to 27 MeV/nucleon with the rest of the simulation remaining unchanged. Although varying the excitation energy scaling factor does not alter the prefragments produced during the fast step of the reaction, it does change which prefragments ultimately populate a given final fragment. Figure 5.17 shows the prefragment distributions that lead to a ^{21}Ne final fragment for both excitation energy scaling cases. With the lower excitation energy scaling factor of 13.3 MeV/nucleon, the contributing prefragments are spread over a broad region but are most probable closer to the final fragment. On the other hand, increasing the scaling factor to 27 MeV/nucleon shifts the distribution toward prefragments closer in mass to the projectile. The higher excitation energy allows these prefragments to undergo longer evaporation chains and still reach the same final fragment.

The change in the prefragment distributions has important consequences for the subsequent de-excitation process. With the lower excitation energy scaling factor, prefragments relatively

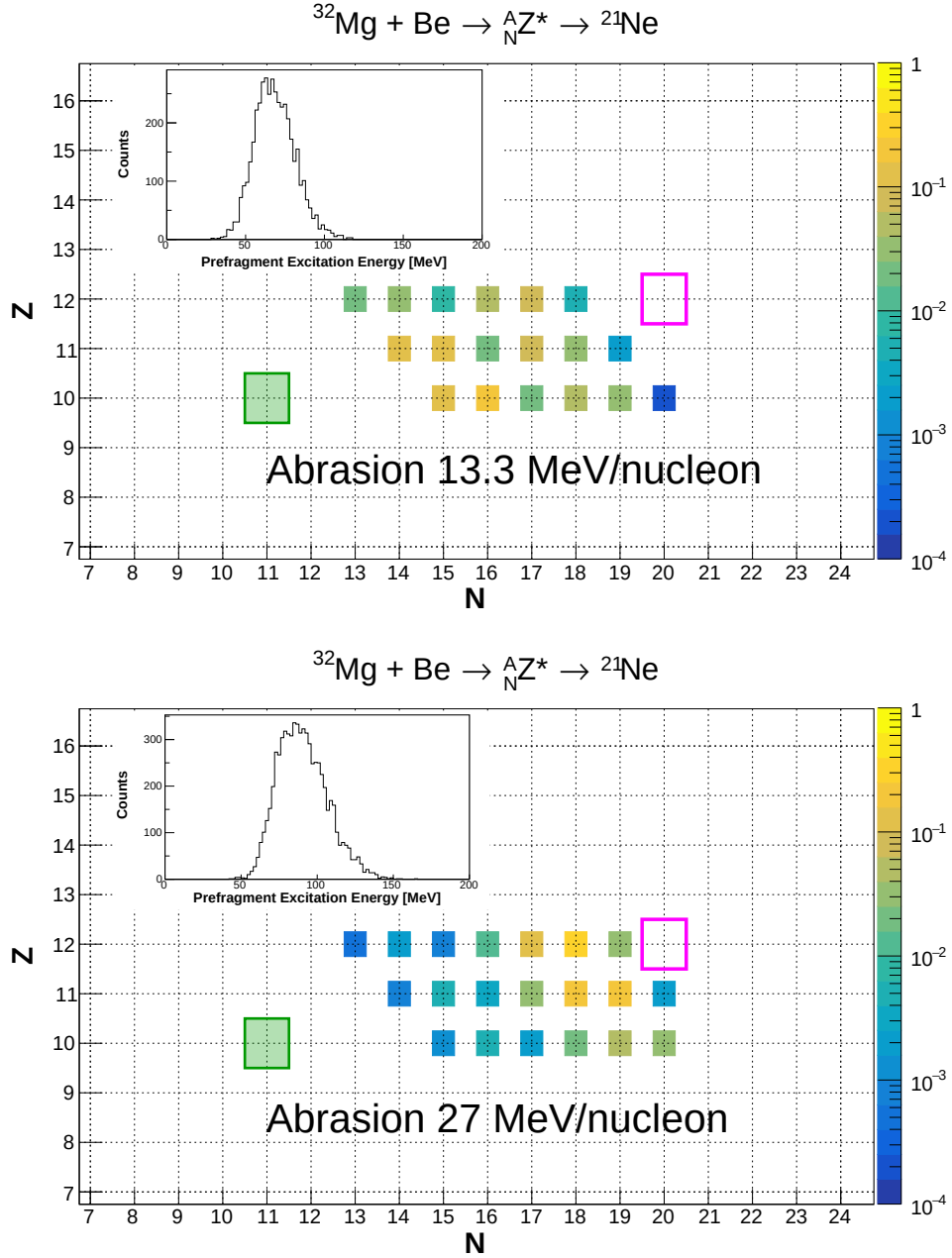


Figure 5.17: Distributions of the prefragments for a ^{21}Ne final fragment shown as a function of Z and N . The prefragment distribution predicted by the Abrasion model with the excitation energy per abraded nucleon of 13.3 MeV/nucleon is shown in the top panel and the bottom panel shows the same for 27 MeV/nucleon. The projectile nucleus is shown by the magenta outlined box and the final nucleus by the green filled box. The inset in each panel shows the excitation energy distribution corresponding to each prefragment distribution.

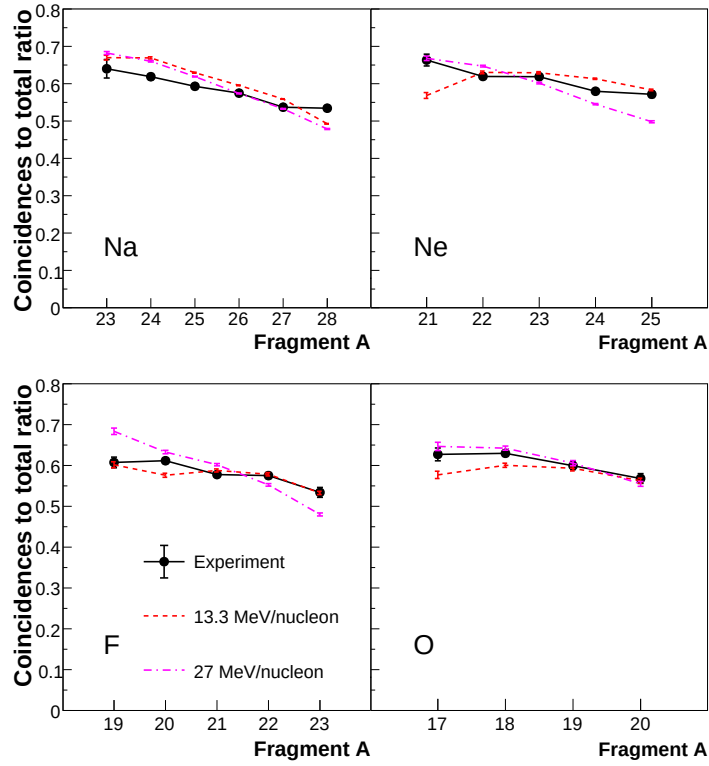


Figure 5.18: Coincidences-to-total ratio as a function of final fragment mass and charge for the 2.97 Tm setting. These plots compare the experimental data (solid black circles with solid lines) to the results of the Abrasion model with an excitation energy per abraded nucleon of 13.3 MeV/nucleon and 27 MeV/nucleon (red dashed and magenta dash-dotted lines, respectively). Error bars are statistical and smaller than the marker size if not visible.

close in mass to the final fragment are more likely to populate the selected nucleus because prefragments closer in mass to the projectile generally do not possess sufficient excitation energy to emit the number of nucleons required to reach the same final fragment. Increasing the excitation energy scaling factor allows prefragments closer in mass to the projectile to populate the same final fragment through longer de-excitation chains. Therefore, a larger fraction of the neutron removal occurs during the evaporation step, increasing the probability of detecting one or more neutrons in coincidence with the final fragment, and therefore should change the corresponding coincidences-to-total ratios.

Figure 5.18 shows that changing the excitation energy scaling factor indeed alters the predicted coincidences-to-total ratios across the measured isotopic chains. One particularly illustrative example occurs for the lightest neon and oxygen isotopes, where the decrease predicted by the

13.3 MeV/nucleon calculation is no longer present when the excitation energy scaling factor is increased to 27 MeV/nucleon. This behavior is a direct consequence of the change in the de-excitation pathways discussed above. At the lower excitation energy scaling factor, the lightest fragments are populated primarily by prefragments closer in mass to the final fragment, resulting in fewer neutrons being emitted during de-excitation. Increasing the excitation energy scaling factor allows prefragments closer in mass to the projectile to contribute through longer de-excitation chains, increasing the number of emitted neutrons and eliminating the decrease in the predicted coincidences-to-total ratios for the lightest neon and oxygen isotopes. While the 27 MeV per abraded nucleon calculations improve the agreement for those isotopes, it does not uniformly improve the agreement across all isotopic chains.

The purpose of the present study was not to optimize the Abrasion excitation energy, but rather to demonstrate the sensitivity of the neutron observables to the excitation energy. The dependence of the coincidences-to-total ratios on the excitation energy scaling factor suggests that measurements of neutrons in coincidence with the final fragments offer complementary constraints on the excitation energy prescription beyond those available from inclusive fragmentation cross sections alone.

5.2.5 Neutron Kinematics

The previous sections focused primarily on the neutron coincidences-to-total ratios and their sensitivity to the predicted prefragment properties. However, the neutron kinetic energy and angular distributions also differ between the Abrasion and INCL++ models. Examining these observables allows for additional comparison of the two models.

As discussed in Section 5.1.1, the neutron kinetic energy and angular distributions show a systematic evolution with the neutron-richness of the final fragment. For fragments closer to the projectile, such as ^{29}Na , the Abrasion model reproduces the measured neutron kinetic energy and angular distributions slightly more closely than INCL++, which predicts lower neutron kinetic energies and broader angular distributions. In contrast, for lighter fragments, such as ^{24}Na , the agreement shifts and the predictions from INCL++ better reproduces the measured neutron kine-

matic observables. This change in the agreement between the two models suggests that they differ in the amount of interaction between the projectile and target nuclei during the fast step of the reaction. The lower neutron kinetic energies and broader angular distributions predicted by INCL++ for the most neutron-rich fragments are consistent with stronger projectile-target interactions and correspondingly slower prefragment velocities. Conversely, the Abrasion model may underestimate the degree of interaction between the projectile and target in reactions that produce fragments further from the projectile. Because the neutron emission is statistical and approximately isotropic in the prefragment reference frame, differences in the predicted prefragment kinematics are reflected in the measured neutron kinetic energy and angular distributions. This interpretation is reinforced by the discussion of the prefragment properties presented in the previous sections. In addition to predicting lower neutron kinetic energies and broader angular distributions for fragments closest to the projectile, INCL++ also predicts remarkably large prefragment angular momenta and substantial nucleon pickup.

Collectively, the neutron coincidences-to-total ratios, interaction multiplicities, kinetic energy spectra, and angular distributions demonstrate that the neutron observables are sensitive to the underlying reaction mechanism. This sensitivity indicates that such measurements provide information beyond inclusive fragment production alone and therefore have the potential to guide future improvements in projectile-fragmentation models like the Abrasion and INCL++ models.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Over the past several decades, projectile fragmentation has become one of the primary methods used to produce exotic nuclei at rare isotope beam facilities around the world. The heavier and more intense beams produced by modern facilities such as the Facility for Rare Isotope Beams (FRIB) allow the frontiers of nuclear physics to be explored further. As we continue to push toward the limits of nuclear existence, accurate models describing projectile fragmentation are essential to the proper planning and execution of such experiments. At present, the vast majority of data used to create and improve these models are the inclusive fragment production cross sections. This dissertation explored whether exclusive measurements of fast neutrons in coincidence with the final reaction products are sensitive to the projectile fragmentation reaction mechanism and therefore provide additional insight into the fast step of the reaction.

This work presented an extended analysis of an experiment that measured fast neutrons in coincidence with charged reaction products [27, 28]. The experiment was performed at the National Superconducting Cyclotron Laboratory (NSCL), where a neutron-rich beam of ^{32}Mg was produced and fragmented on a beryllium target at 83 MeV/u. The heavy, charged reaction products were measured with a suite of detectors at the exit of the Sweeper magnet, while neutrons were detected using the Modular Neutron Array (MoNA) [29]. The Sweeper magnet was operated at three separate magnetic rigidity settings to enable measurements across several isotopic chains ($^{23-31}\text{Na}$, $^{21-29}\text{Ne}$, $^{19-24}\text{F}$ and $^{17-21}\text{O}$) and explore systematic trends as a function of the final fragment mass. A total of twenty-nine different nuclides with overall mass losses ranging from $\Delta A = 1 - 15$ were measured with sufficient statistics for analysis. For each of the measured nuclei, the kinetic energy, angular distribution, and interaction multiplicity of the coincident neutrons were reconstructed and analyzed in this work.

To interpret the experimental results, the projectile fragmentation reactions were simulated in GEANT4 [33, 34, 55] using two fundamentally different descriptions of the fast step of the reaction: the macroscopic Abrasion model [14] and the microscopic Liège Intranuclear Cascade (INCL++)

model [15, 16]. Both models were coupled to the de-excitation code ABLA++ [35] to ensure that any differences in the final observables are due to differences in the fast-step models. The emitted neutrons resulting from the output of these models were then transported through a GEANT4 representation of the experimental setup, where the detector response (e.g. geometry and efficiency) of MoNA was simulated to give an output that was directly comparable to the measured data.

Several systematic trends were observed from the measured neutron observables and their comparison with the Abrasion and INCL++ model predictions. Both the neutron interaction multiplicity and coincidences-to-total ratio increased with decreasing final fragment mass, while the neutron kinetic energy and angular distributions were consistent with the isotropic emission of neutrons in the rest frame of a prefragment moving with approximately the beam velocity. Overall, both models qualitatively reproduced these trends, however, neither model fully reproduced all aspects of the experimental data. The Abrasion model generally provided better agreement with the neutron observables for the heavier final fragments, whereas INCL++ more accurately reproduced the neutron kinematic observables for the lighter fragments while significantly under-predicting the coincidences-to-total ratios for the heaviest neon and sodium isotopes.

The comparison between the experimental data and the reaction model predictions demonstrates that an accurate description of the prefragment properties is essential to reproduce neutron emission following projectile fragmentation. The deviations between the measured data and the INCL++ predictions may be attributed to the remarkably large number of nucleons picked up from the target and high total angular momentum values that suppress the neutron coincidences-to-total ratios. While the Abrasion model provides better overall agreement with the measured neutron coincidences-to-total ratios, it does not completely reproduce the neutron kinematic observables for the lightest fragments. This suggests that there may be some limitations in the reaction kinematics during the fast step of the reaction. Additionally, nucleon pickup (i.e., aluminum fragments) was observed in the present experiment. Because nucleon pickup is not included in the simple abrasion picture by design, this observation indicates that additional mechanisms contribute at these energies. These results clearly demonstrate that such neutron observables are sensitive to

the predicted prefragment properties and therefore provide a valuable probe of the fast step of the projectile fragmentation reaction.

Building upon the work presented in this dissertation, future studies could combine the measurement of fast neutrons with fragment production cross sections to provide complementary information for continued refinement of reaction models. Extending these types of measurements to neutron-rich systems in the medium-mass region (e.g. $Z = 20$ isotopes) where experimental data remain relatively limited [21], would provide further tests of the reaction models. Finally, additional measurements of fragments and neutrons for the few-nucleon removal channels would be valuable, as these reaction channels exhibit the largest differences between the model predictions and have also been the subject of considerable interest [26, 73, 74]. Such measurements could provide additional insight into previously reported discrepancies for strongly bound nucleon-removal reactions, which have been attributed to limitations in the treatment of projectile-target excitation and indirect reaction processes [72].

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APPENDIX A

NEUTRON KINETIC ENERGY AND ANGULAR DISTRIBUTIONS

The measured and simulated neutron kinetic energy and horizontal angular distributions (θ_x) are presented in this appendix for each isotope and Sweeper magnet setting in the figures below. Each simulated distribution is normalized to the integral of the corresponding experimental distribution.

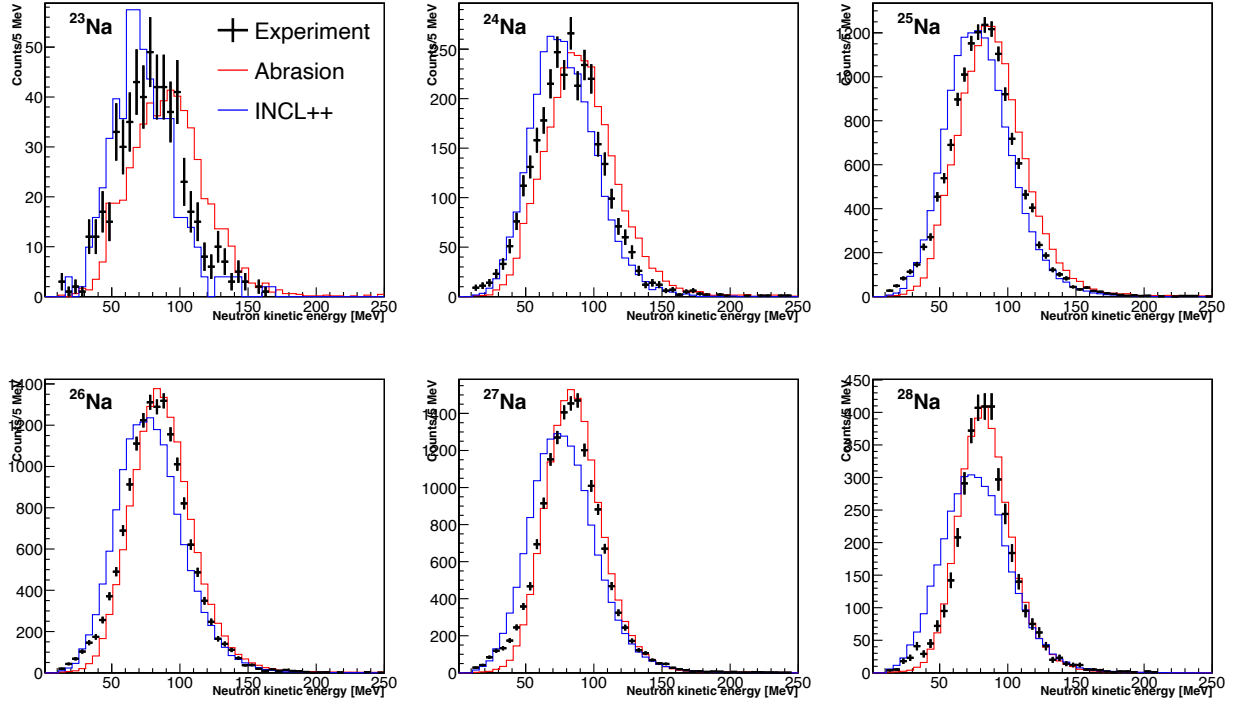


Figure A.1: Neutron kinetic energy distributions for sodium isotopes measured in the 2.97 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

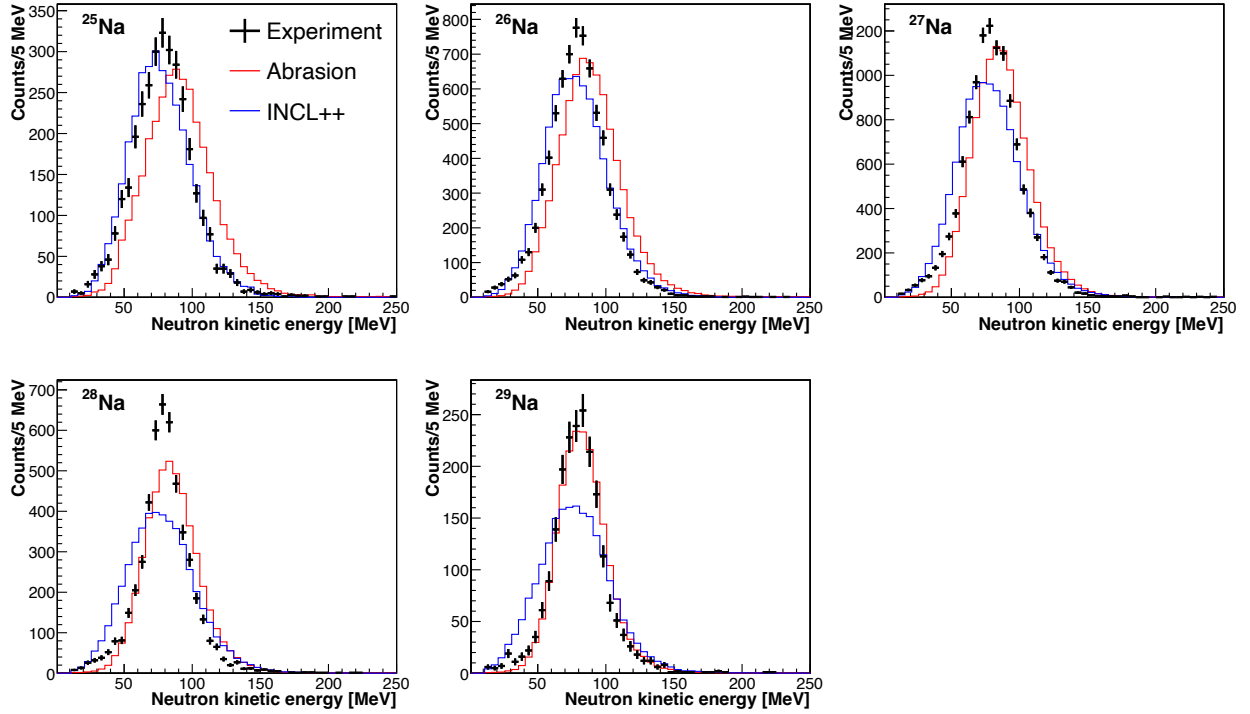


Figure A.2: Neutron kinetic energy distributions for sodium isotopes measured in the 3.15 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

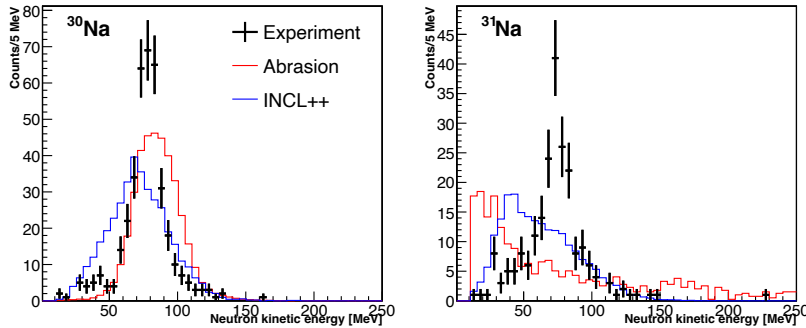


Figure A.3: Neutron kinetic energy distributions for sodium isotopes measured in the 3.75 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

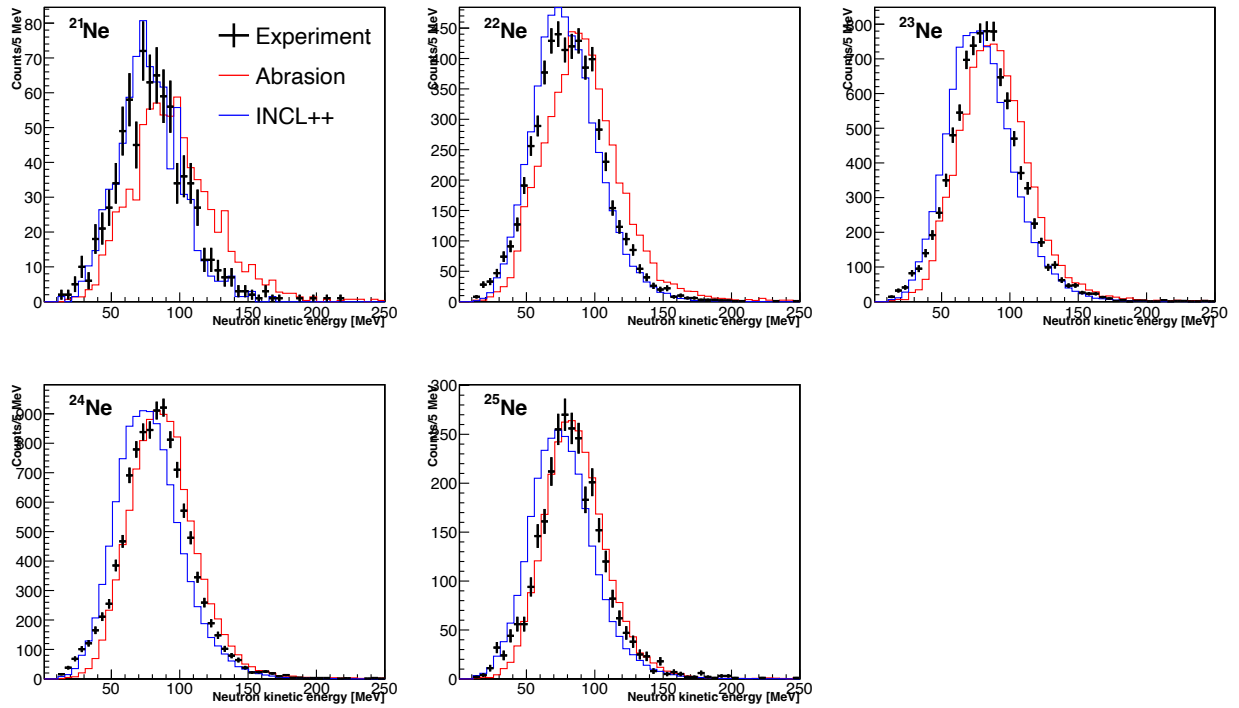


Figure A.4: Neutron kinetic energy distributions for neon isotopes measured in the 2.97 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

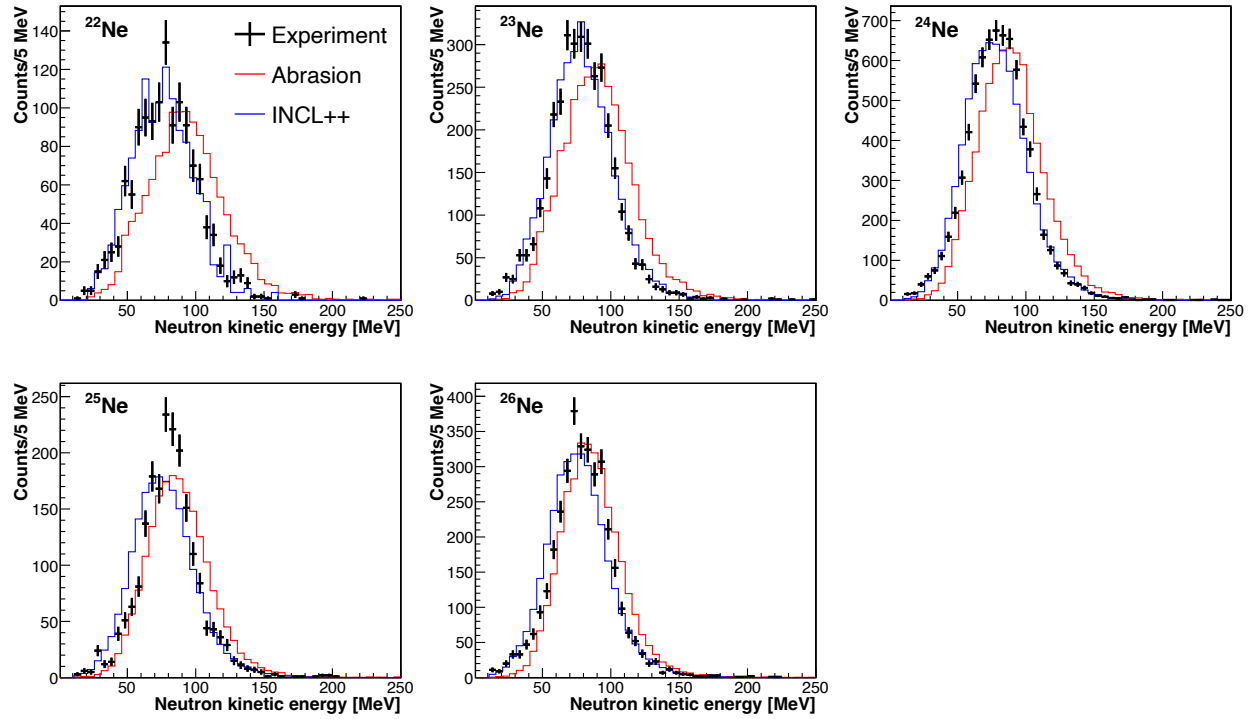


Figure A.5: Neutron kinetic energy distributions for neon isotopes measured in the 3.15 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

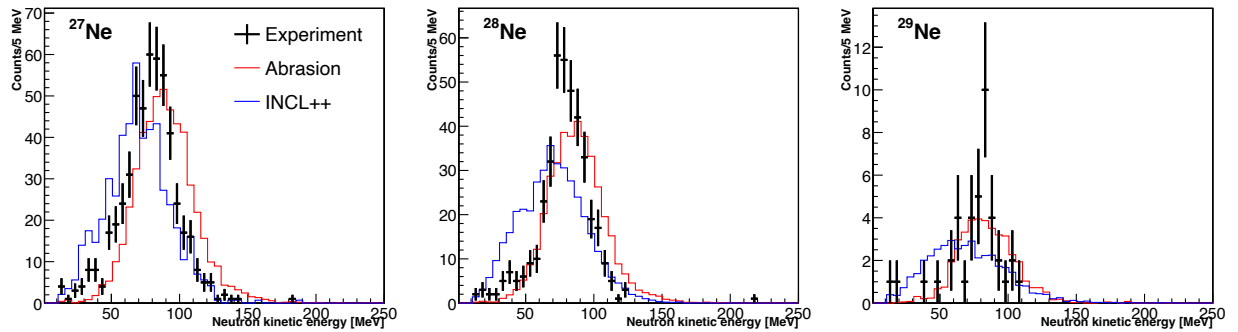


Figure A.6: Neutron kinetic energy distributions for neon isotopes measured in the 3.75 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

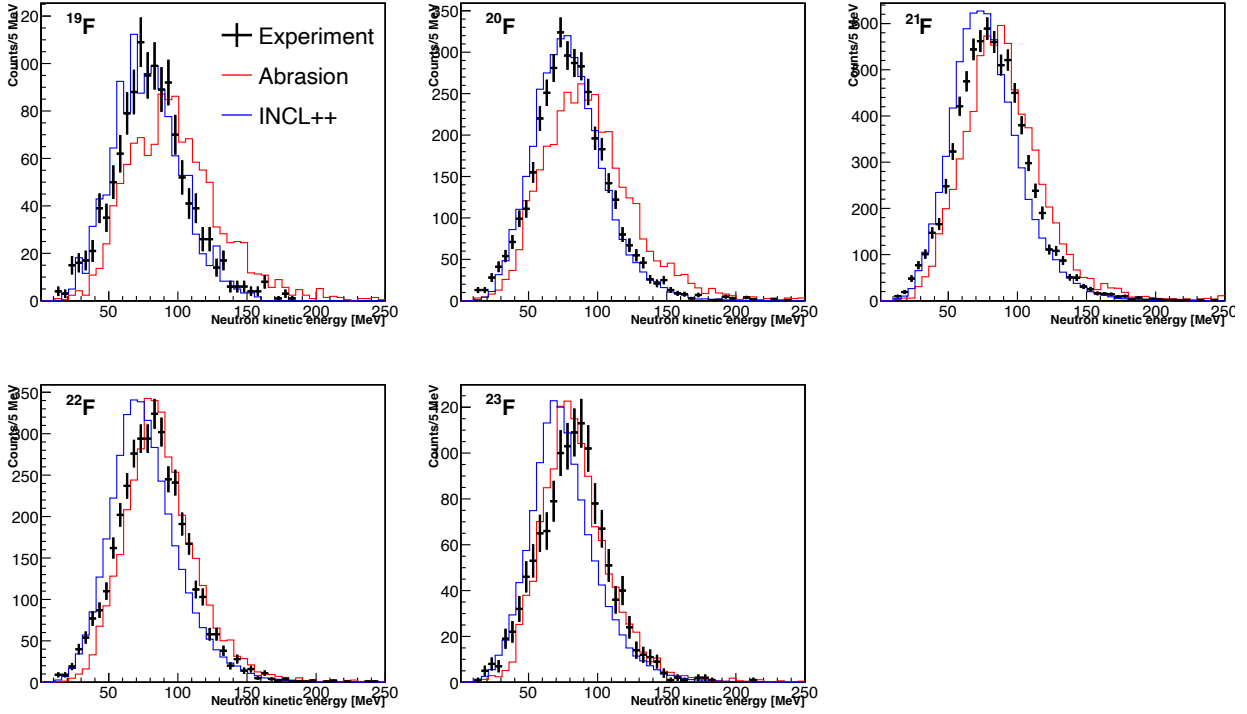


Figure A.7: Neutron kinetic energy distributions for fluorine isotopes measured in the 2.97 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

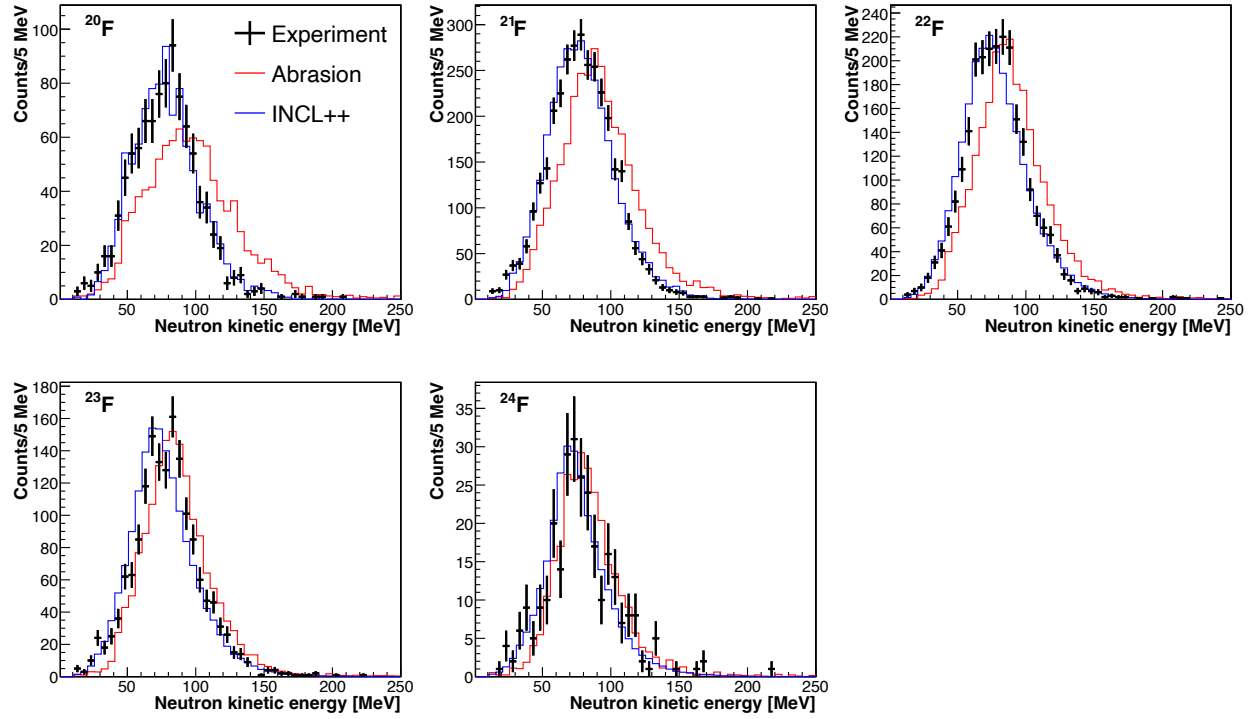


Figure A.8: Neutron kinetic energy distributions for fluorine isotopes measured in the 3.15 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

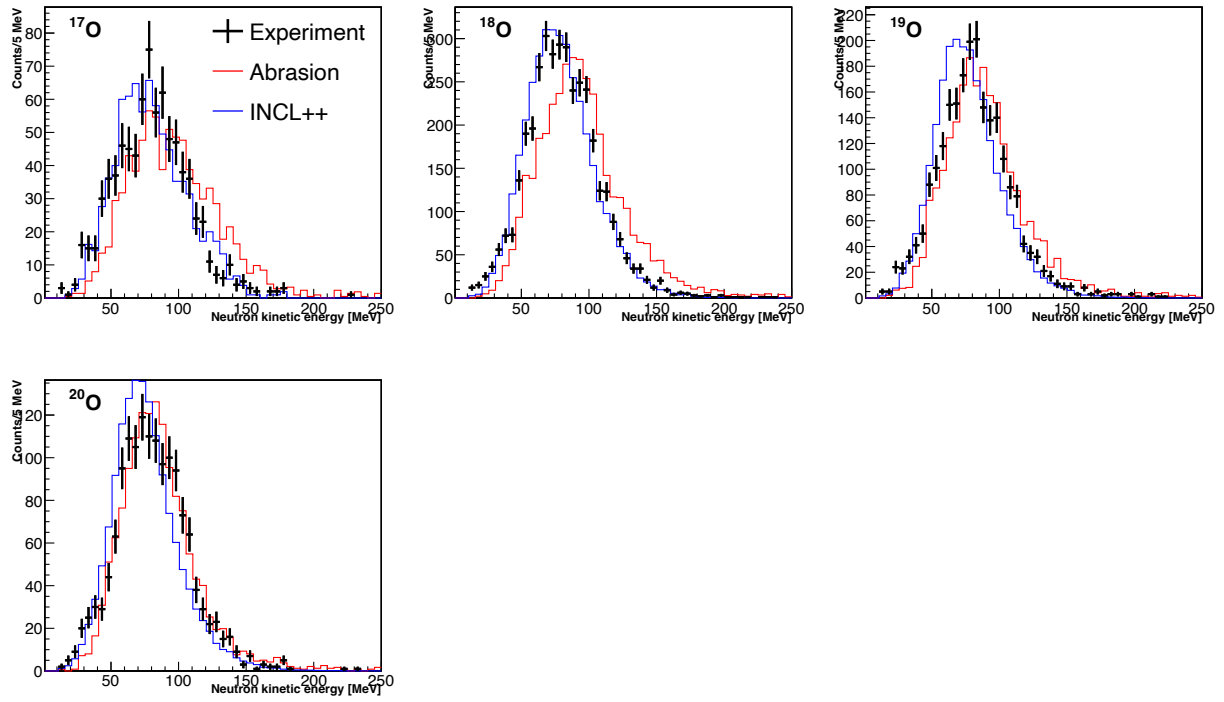


Figure A.9: Neutron kinetic energy distributions for oxygen isotopes measured in the 2.97 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

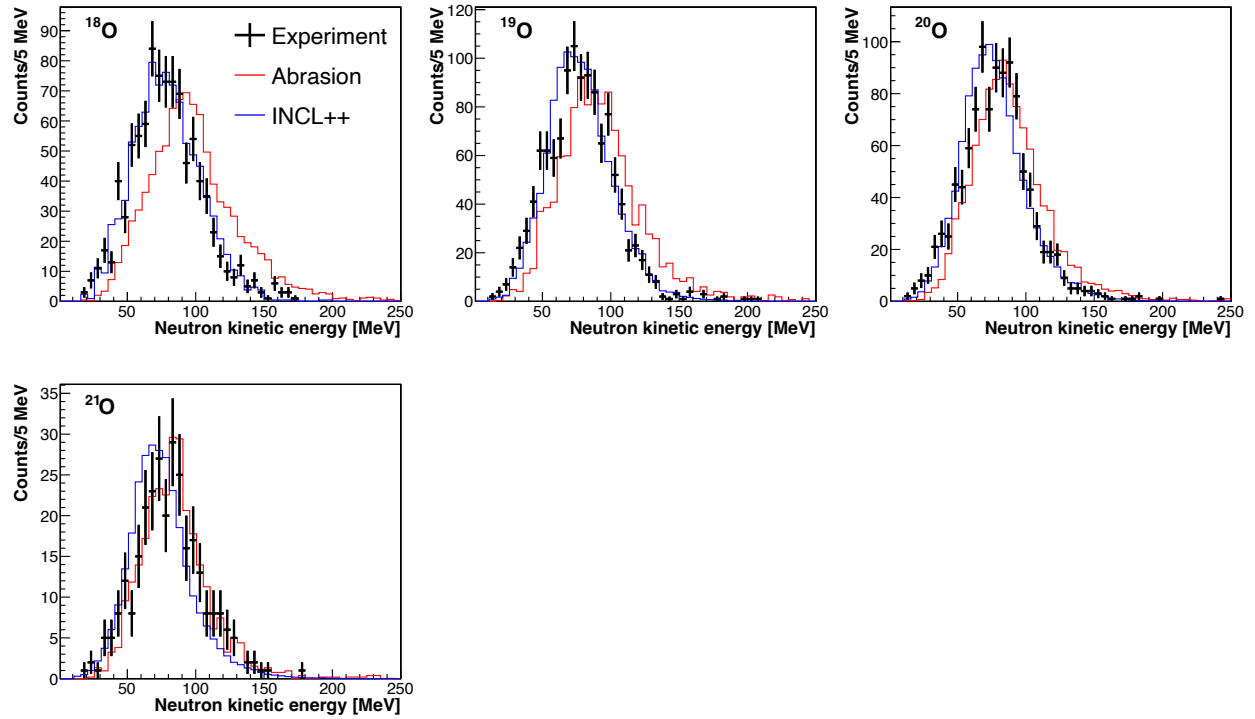


Figure A.10: Neutron kinetic energy distributions for oxygen isotopes measured in the 3.15 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

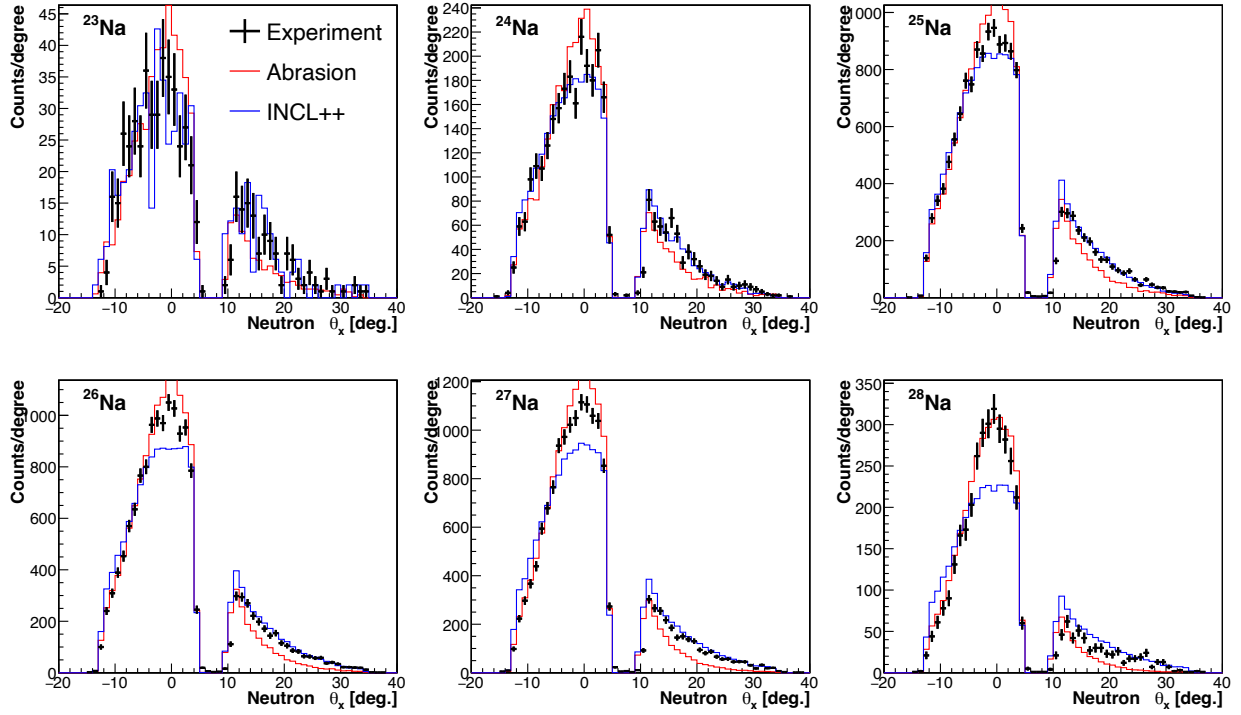


Figure A.11: Horizontal angular distributions (θ_x) for sodium isotopes measured in the 2.97 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

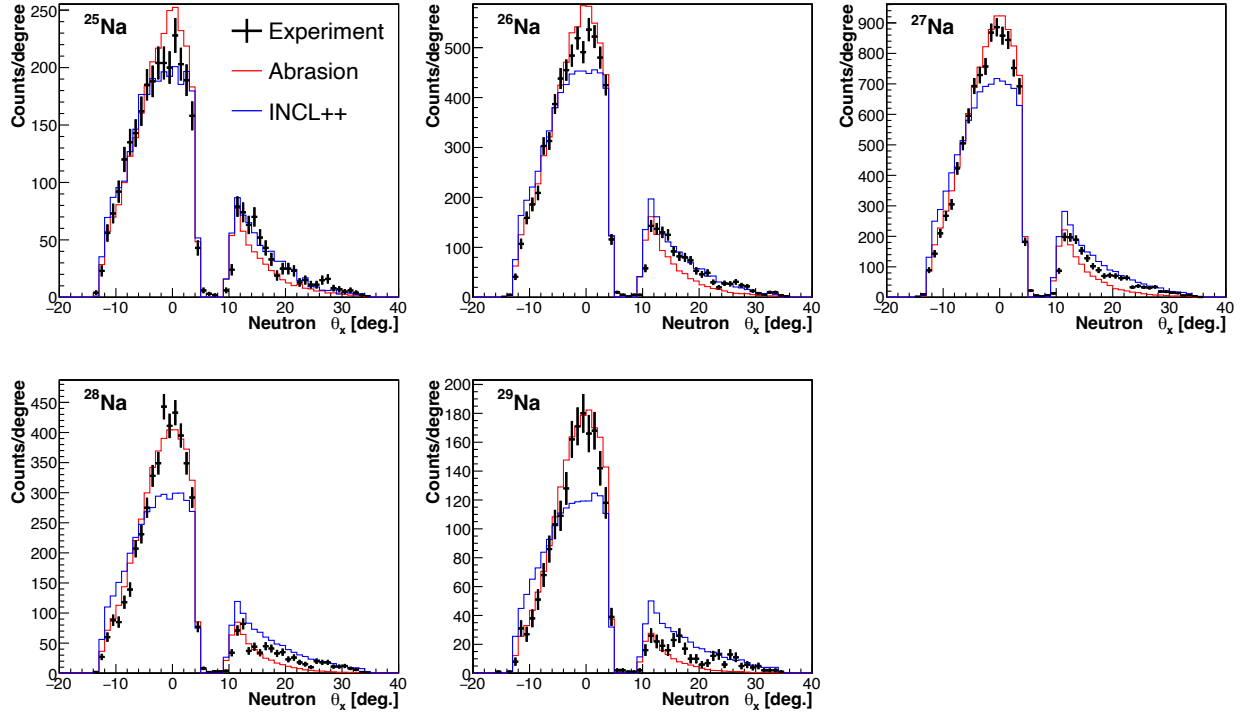


Figure A.12: Horizontal angular distributions (θ_x) for sodium isotopes measured in the 3.15 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

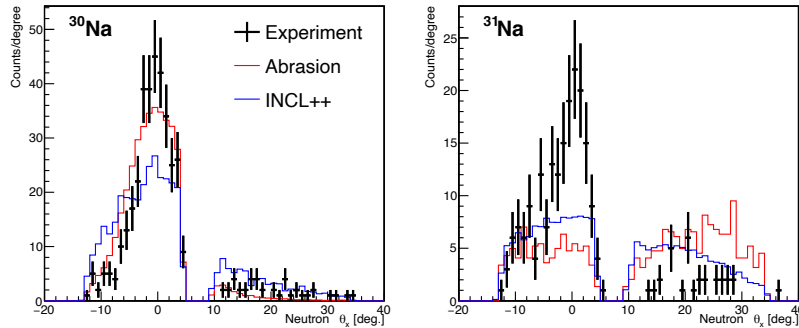


Figure A.13: Horizontal angular distributions (θ_x) for sodium isotopes measured in the 3.75 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

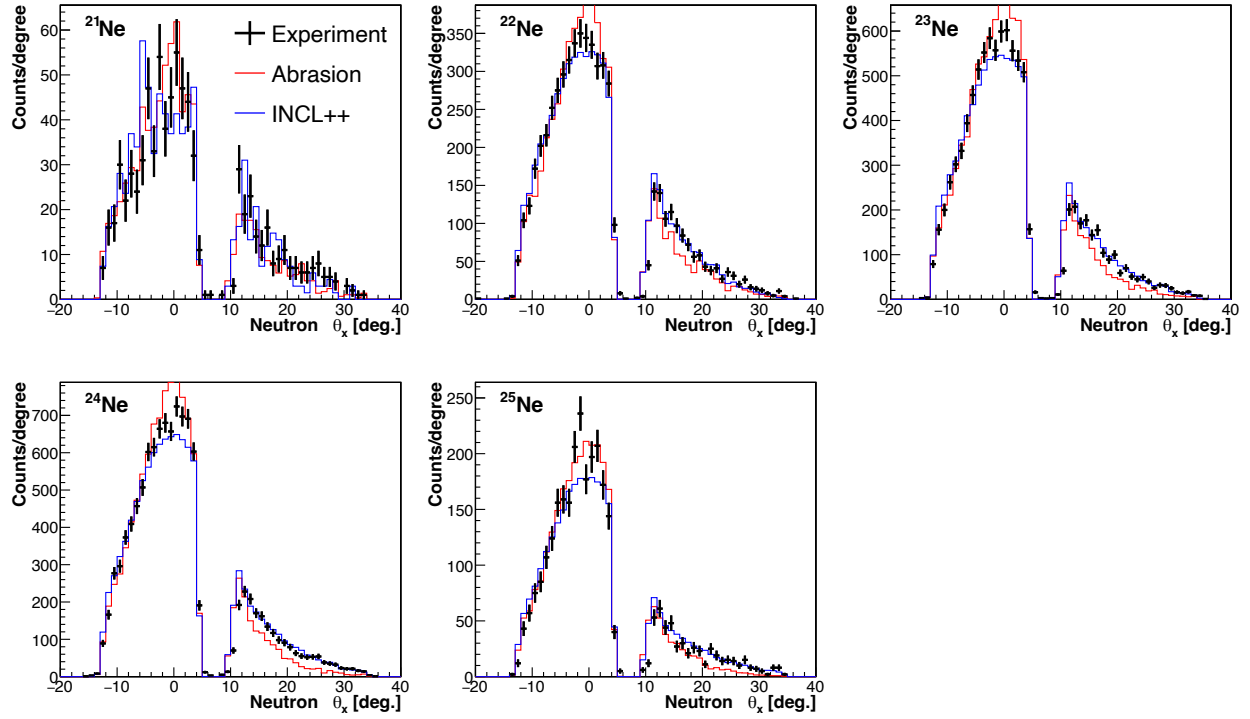


Figure A.14: Horizontal angular distributions (θ_x) for neon isotopes measured in the 2.97 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

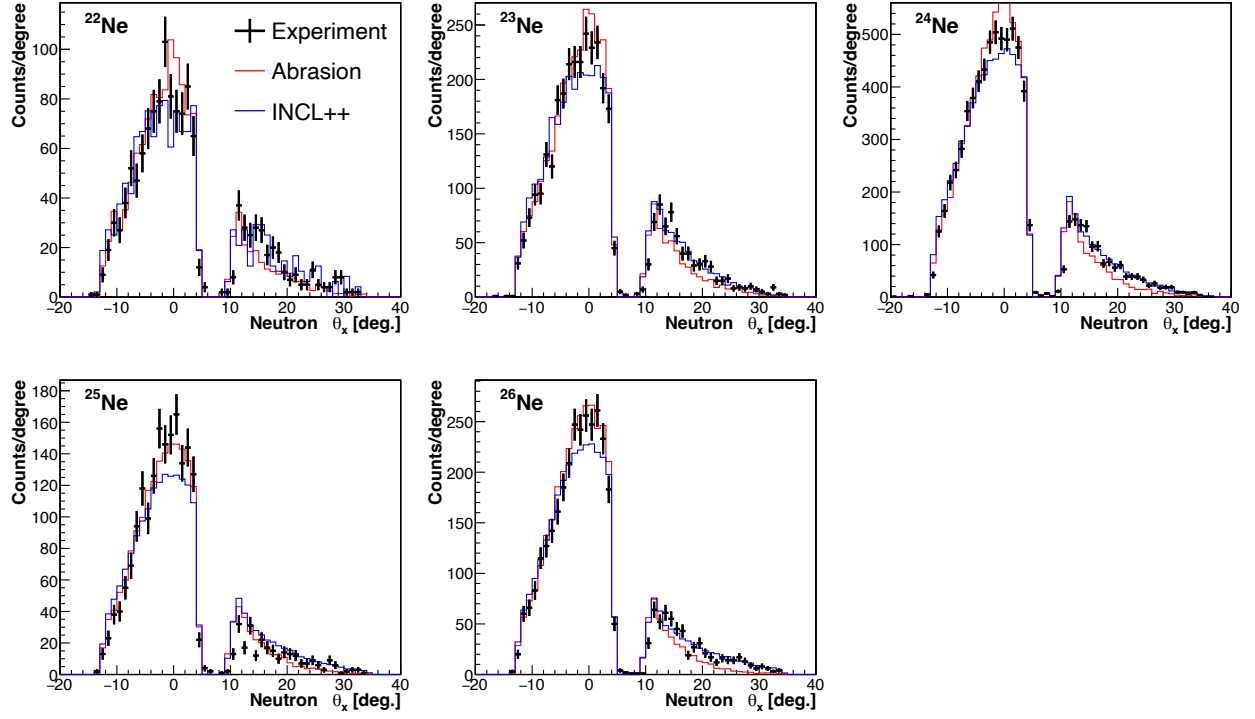


Figure A.15: Horizontal angular distributions (θ_x) for neon isotopes measured in the 3.15 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

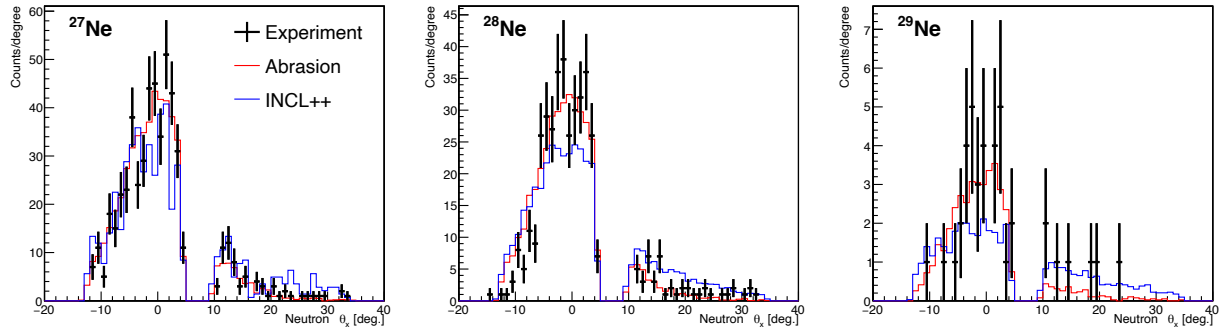


Figure A.16: Horizontal angular distributions (θ_x) for neon isotopes measured in the 3.75 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

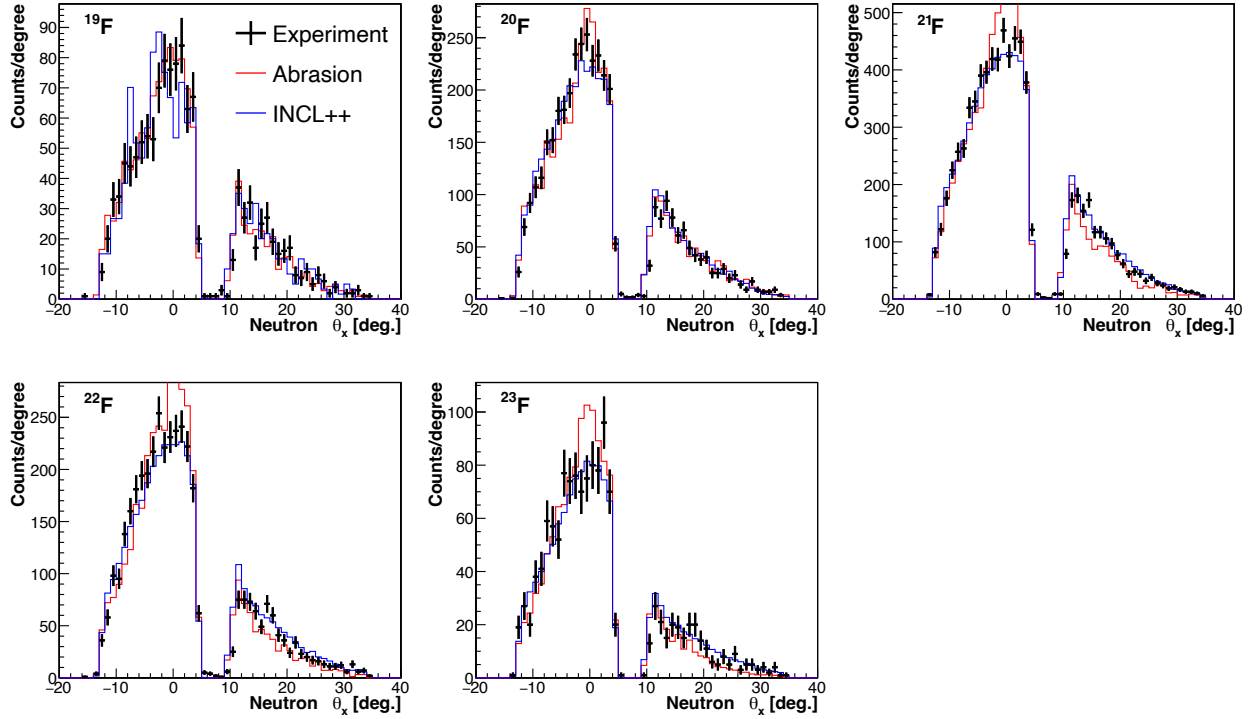


Figure A.17: Horizontal angular distributions (θ_x) for fluorine isotopes measured in the 2.97 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

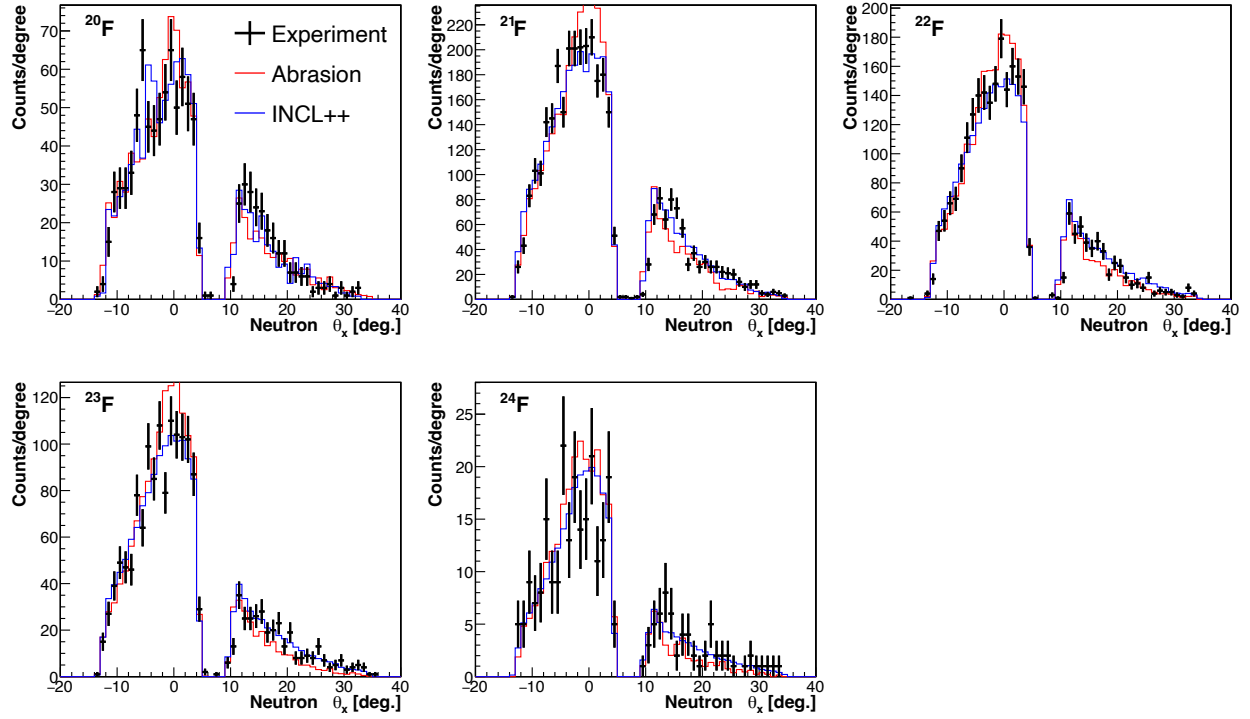


Figure A.18: Horizontal angular distributions (θ_x) for fluorine isotopes measured in the 3.15 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

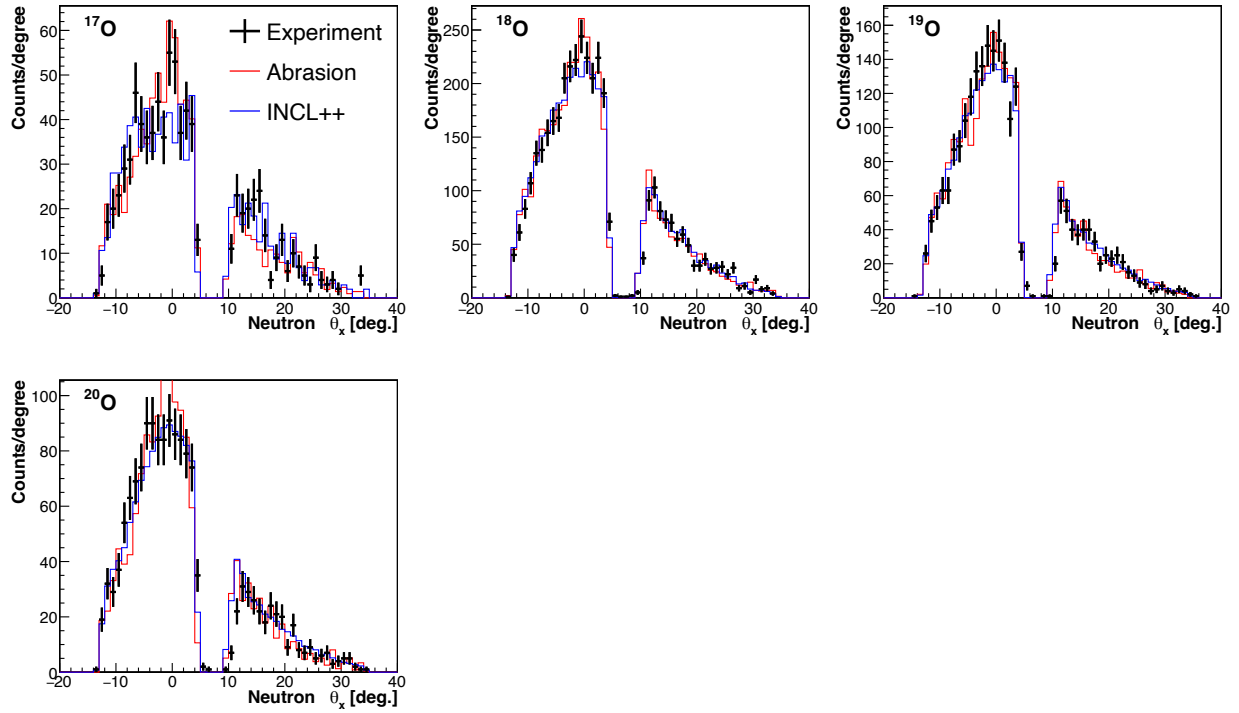


Figure A.19: Horizontal angular distributions (θ_x) for oxygen isotopes measured in the 2.97 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

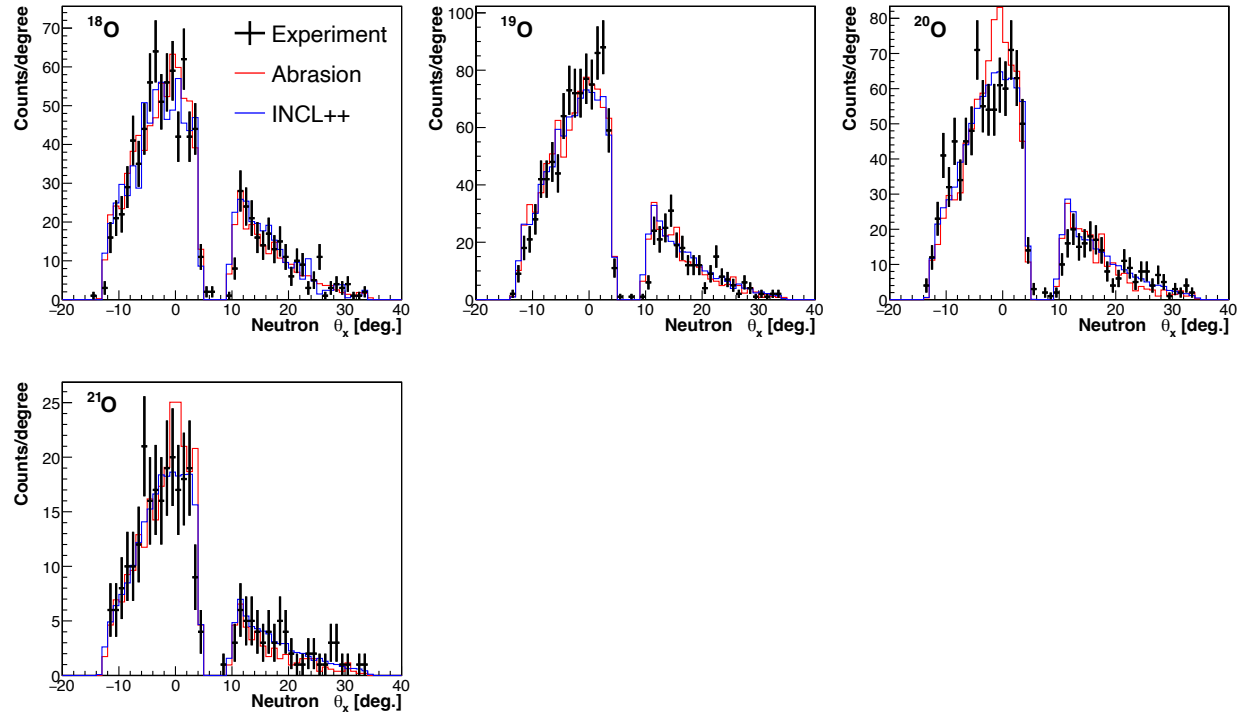


Figure A.20: Horizontal angular distributions (θ_x) for oxygen isotopes measured in the 3.15 Tm Sweeper magnet setting. Solid black circles represent experimental data, red histograms represent results from the Abrasion simulation, and blue histograms represent results from the INCL++ simulation.

APPENDIX B

NEUTRON INTERACTION MULTIPLICITIES

The measured and simulated neutron interaction multiplicity distributions are presented in this appendix for each isotope and Sweeper magnet setting in the figures below. Each simulated spectrum is normalized to the total number of measured fragment events for the corresponding isotope.

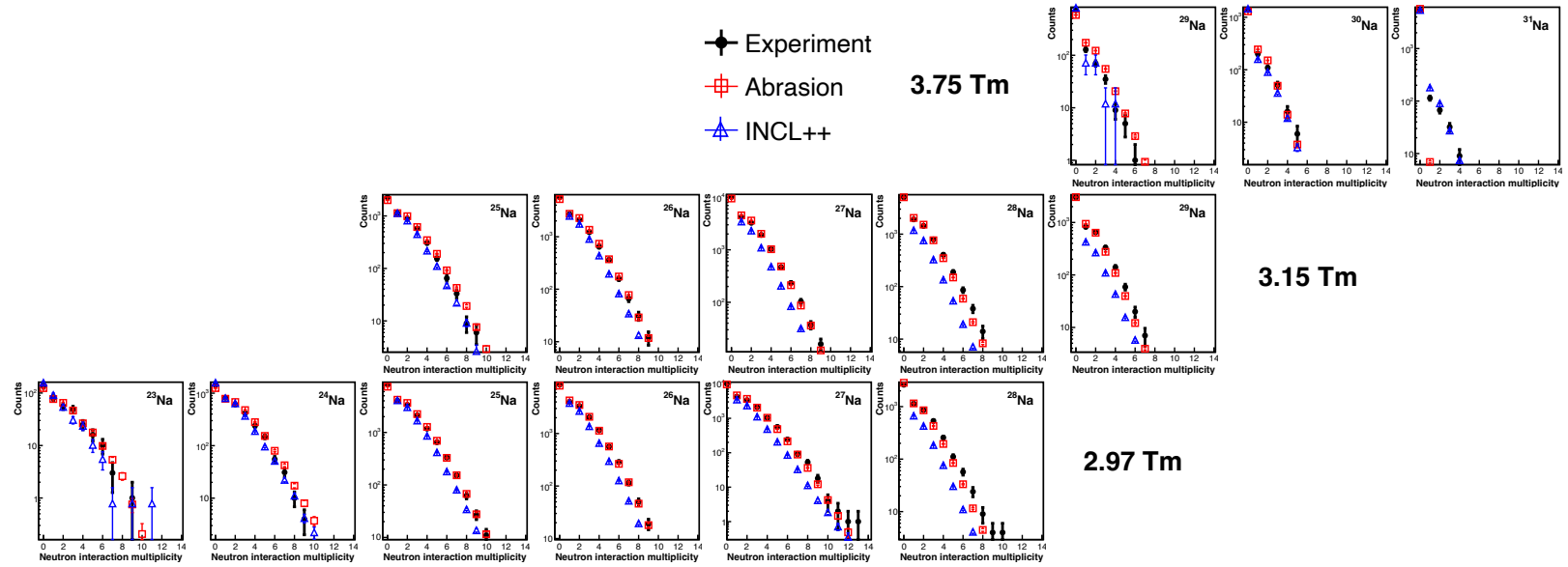


Figure B.1: Neutron hit multiplicity spectra for the sodium isotopes. Solid black circles represent experimental data, open red squares represent results from the Abrasion simulation, and open blue triangles represent results from the INCL++ simulation.

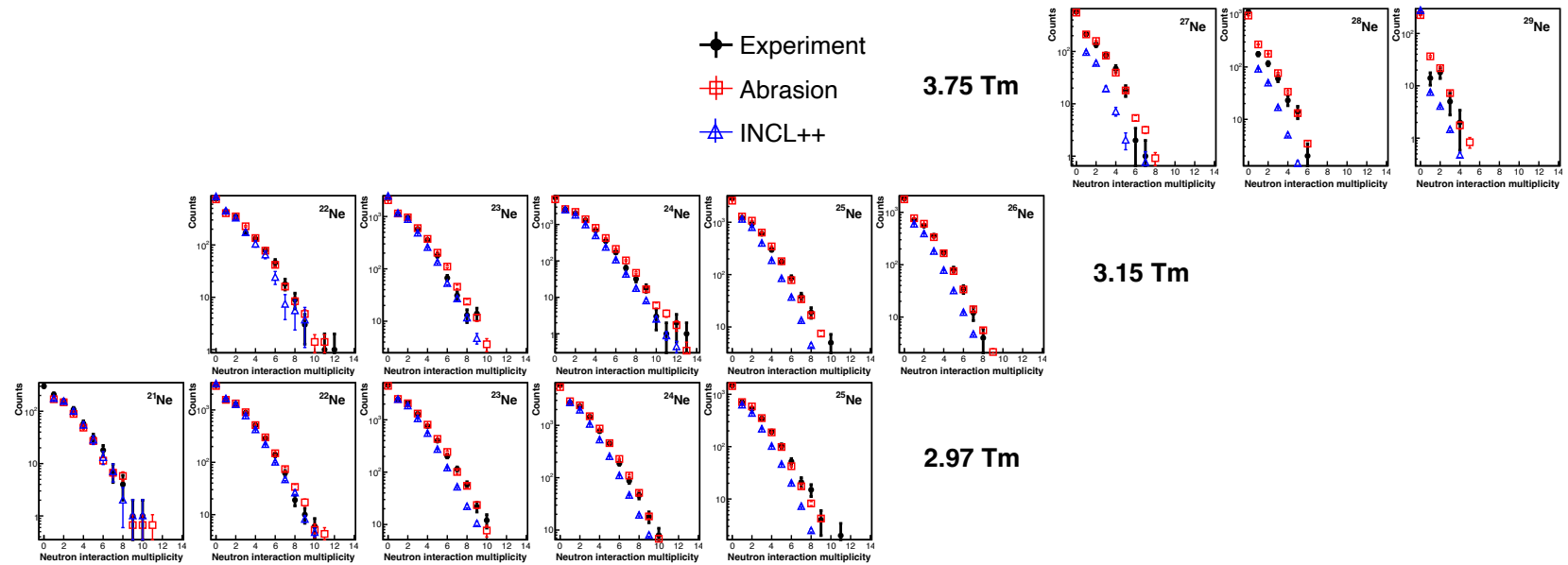


Figure B.2: Neutron hit multiplicity spectra for the neon isotopes. Solid black circles represent experimental data, open red squares represent results from the Abrasion simulation, and open blue triangles represent results from the INCL++ simulation.

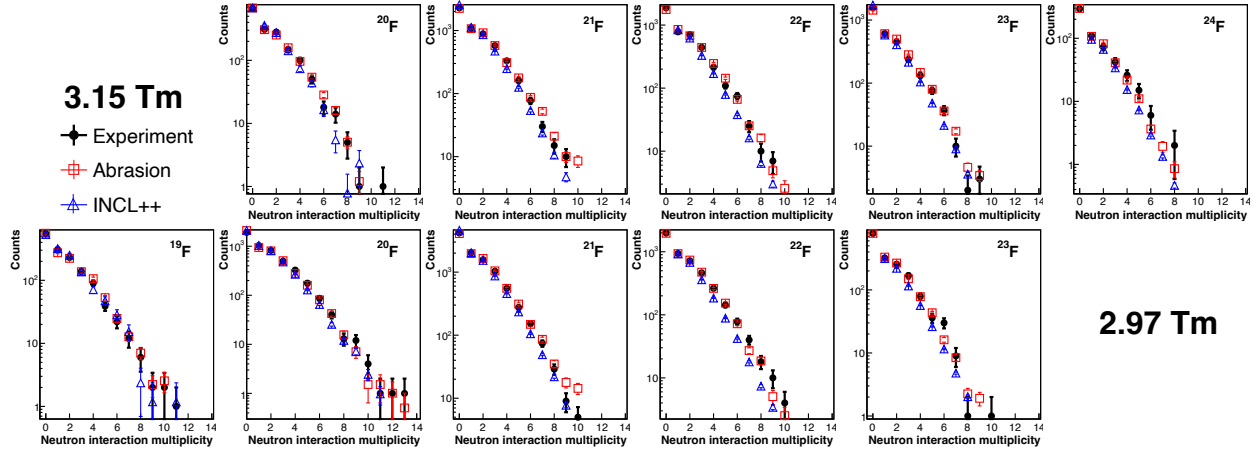


Figure B.3: Neutron hit multiplicity spectra for the fluorine isotopes. Solid black circles represent experimental data, open red squares represent results from the Abrasion simulation, and open blue triangles represent results from the INCL++ simulation.

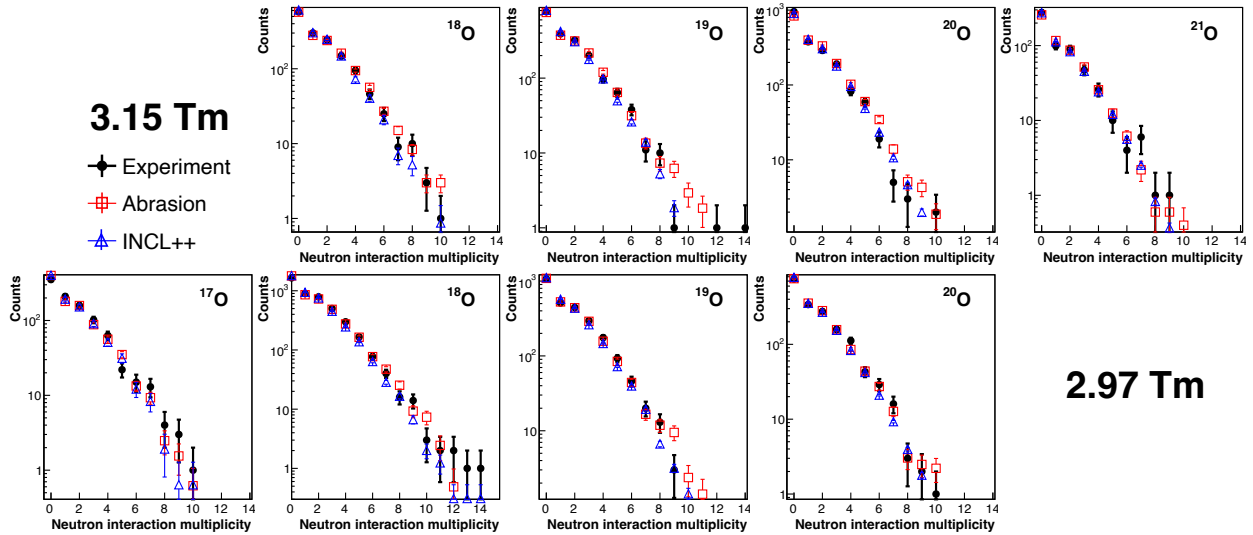


Figure B.4: Neutron hit multiplicity spectra for the oxygen isotopes. Solid black circles represent experimental data, open red squares represent results from the Abrasion simulation, and open blue triangles represent results from the INCL++ simulation.

APPENDIX C

NEUTRON COINCIDENCES-TO-TOTAL RATIO DATA

The reconstructed neutron coincidences-to-total (C/T) ratios obtained from both measured and simulated data are provided in this appendix for each isotope and Sweeper magnet setting within the tables below. The experimental ratios were calculated as the number of fragment events detected in coincidence with at least one neutron interaction in MoNA divided by the total number of detected fragment events for the corresponding isotope. The simulated ratios were determined in the same manner using the results from the Abrasion and INCL++ reaction-model calculations after propagation through the detector response in the GEANT4 simulation. The uncertainties listed in the tables are statistical and were calculated using binomial counting statistics. More details can be found in Section 4.2.6.

Table C.1: Neutron coincidences-to-total (C/T) ratios obtained using measured and simulated data for each isotope measured in the 2.97 Tm Sweeper magnet setting. The listed uncertainties are statistical.

Isotope	Experiment	Abrasion	INCL++
^{17}O	0.627 ± 0.0157	0.577 ± 0.00895	0.574 ± 0.0129
^{18}O	0.630 ± 0.00723	0.600 ± 0.00513	0.595 ± 0.00289
^{19}O	0.599 ± 0.00948	0.593 ± 0.00655	0.584 ± 0.00209
^{20}O	0.568 ± 0.0119	0.563 ± 0.00627	0.544 ± 0.00136
^{19}F	0.607 ± 0.0130	0.602 ± 0.00738	0.621 ± 0.0141
^{20}F	0.612 ± 0.00694	0.576 ± 0.00500	0.575 ± 0.00284
^{21}F	0.578 ± 0.00496	0.588 ± 0.00374	0.536 ± 0.00120
^{22}F	0.575 ± 0.00725	0.578 ± 0.00406	0.496 ± 0.00109
^{23}F	0.534 ± 0.0121	0.533 ± 0.00407	0.445 ± 0.000962
^{21}Ne	0.663 ± 0.0158	0.568 ± 0.00782	0.607 ± 0.0165
^{22}Ne	0.619 ± 0.00551	0.630 ± 0.00359	0.588 ± 0.00227
^{23}Ne	0.619 ± 0.00443	0.629 ± 0.00306	0.540 ± 0.00137
^{24}Ne	0.580 ± 0.00419	0.613 ± 0.00177	0.488 ± 0.000792
^{25}Ne	0.572 ± 0.00844	0.583 ± 0.00215	0.429 ± 0.000950
^{23}Na	0.640 ± 0.0248	0.670 ± 0.00636	0.581 ± 0.0226
^{24}Na	0.619 ± 0.00791	0.669 ± 0.00289	0.580 ± 0.00310
^{25}Na	0.593 ± 0.00347	0.629 ± 0.00136	0.517 ± 0.000982
^{26}Na	0.575 ± 0.00348	0.596 ± 0.00104	0.448 ± 0.000789
^{27}Na	0.537 ± 0.00337	0.559 ± 0.000707	0.356 ± 0.000613
^{28}Na	0.534 ± 0.00666	0.493 ± 0.000859	0.251 ± 0.000704

Table C.2: Neutron coincidences-to-total (C/T) ratios obtained using measured and simulated data for each isotope measured in the 3.15 Tm Sweeper magnet setting. The listed uncertainties are statistical.

Isotope	Experiment	Abrasion	INCL++
^{18}O	0.606 ± 0.0128	0.609 ± 0.00592	0.581 ± 0.00852
^{19}O	0.596 ± 0.0112	0.604 ± 0.00677	0.578 ± 0.00364
^{20}O	0.518 ± 0.0112	0.578 ± 0.00574	0.545 ± 0.00169
^{21}O	0.506 ± 0.0211	0.541 ± 0.00939	0.511 ± 0.00202
^{20}F	0.582 ± 0.0123	0.576 ± 0.00605	0.575 ± 0.0110
^{21}F	0.582 ± 0.00666	0.591 ± 0.00404	0.533 ± 0.00242
^{22}F	0.559 ± 0.00763	0.585 ± 0.00384	0.496 ± 0.00147
^{23}F	0.501 ± 0.00896	0.540 ± 0.00324	0.446 ± 0.00104
^{24}F	0.483 ± 0.0210	0.476 ± 0.00561	0.396 ± 0.00132
^{22}Ne	0.619 ± 0.00551	0.630 ± 0.00359	0.588 ± 0.00227
^{23}Ne	0.599 ± 0.00659	0.629 ± 0.00343	0.551 ± 0.00335
^{24}Ne	0.569 ± 0.00438	0.615 ± 0.00178	0.495 ± 0.00112
^{25}Ne	0.541 ± 0.00631	0.586 ± 0.00191	0.432 ± 0.00104
^{26}Ne	0.513 ± 0.00812	0.531 ± 0.00188	0.347 ± 0.000770
^{25}Na	0.583 ± 0.00669	0.632 ± 0.00161	0.516 ± 0.00333
^{26}Na	0.562 ± 0.00436	0.599 ± 0.00109	0.457 ± 0.00123
^{27}Na	0.526 ± 0.00340	0.559 ± 0.000685	0.357 ± 0.000683
^{28}Na	0.491 ± 0.00501	0.493 ± 0.000723	0.251 ± 0.000717
^{29}Na	0.403 ± 0.00690	0.400 ± 0.000684	0.173 ± 0.000682

Table C.3: Neutron coincidences-to-total (C/T) ratios obtained using measured and simulated data for each isotope measured in the 3.75 Tm Sweeper magnet setting. The listed uncertainties are statistical.

Isotope	Experiment	Abrasion	INCL++
^{27}Ne	0.468 ± 0.0152	0.485 ± 0.00405	0.175 ± 0.00588
^{28}Ne	0.256 ± 0.0111	0.375 ± 0.00303	0.109 ± 0.00106
^{29}Ne	0.134 ± 0.0199	0.234 ± 0.00520	0.0474 ± 0.000923
^{29}Na	0.256 ± 0.0140	0.395 ± 0.00122	0.173 ± 0.0420
^{30}Na	0.218 ± 0.00985	0.264 ± 0.000863	0.172 ± 0.00262
^{31}Na	0.0388 ± 0.00255	0.00231 ± 0.0000753	0.0540 ± 0.000390