PIONIC FUSION OF $^4\text{He} + ^{12}\text{C}$

A Dissertation

by

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Submitted to the Office of Graduate and Professional Studies of Texas A&M University in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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December 2018

Major Subject: Chemistry

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ABSTRACT

Pionic fusion is the process by which two nuclei collide, undergo complete fusion, and then de-excite solely by the emission of a pion. Previously measured pionic fusion cross sections are inconsistent with known mechanisms for pion production and suggest unknown collective processes might dominate production at low energies in heavy ion collisions. In this work, an experiment was developed to make the first coincident measurement of pionic fusion for a charged pion channel of a reaction for which there are no previous measurements.

The pionic fusion reaction \( ^4\text{He} (55 \text{ MeV/u}) + ^{12}\text{C} \rightarrow ^{16}\text{N} + \pi^+ \) was studied at the Texas A&M University Cyclotron Institute. The \( ^{16}\text{N} \) fusion residues were detected using a dE-E silicon telescope at the focal plane of the MARS spectrometer and the newly designed ParTI phoswich detector array was used to detect the charged pions. Fast-sampling digitizers recorded the waveform responses of the phoswiches which were used to identify the pions through fast vs. slow (dE-E) pulse shape discrimination and through the characteristic decay of the muon daughters of the implanted pions.

An energy calibration method for light charged particles including charged pions is developed for the ParTI phoswich detectors and the geometrical and particle identification efficiencies of the array are explored. The "muon decay trigger" which was implemented in the firmware of the on-board FPGA in the digitizers is discussed and its ability to increase the pion event selectivity is characterized. A detailed characterization of the transmission efficiency and particle identification capabilities at the focal plane of MARS is also given.

Cross sections are reported for all species detected at the focal plane of MARS and upper limits for the cross section of pionic fusion based on the measurement of \( ^{16}\text{N} \) in MARS and charged pions in the ParTI array are reported.
DEDICATION

To my wonderful wife, Christina, and my favorite person, Luke.
I would like to thank the staff at the Texas A&M University Cyclotron Institute for delivering the beams and maintaining the facility that made this work possible. I would also like to thank the Paul Scherrer Institute and, in particular, the πM1 group for their help and hospitality. I would like to thank all of the faculty, postdocs, graduate students, and undergraduate students that I have had the pleasure of working with. I would like to extend a special thanks to Sherry Yennello and Alan McIntosh for all of your aid and guidance. None of this would have been possible without all of you.

Thank you to my family and friends particularly my wife, Christina, who always knew this day would come... eventually.
CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supported by a dissertation committee consisting of Professors Sherry Yennello, Charles M. Folden, III and Joe Natowitz of the Department of Chemistry and Dr. Aldo Bonasera of the Department of Physics.

The analyses depicted in Section 4.3 were conducted in part by Emily Churchman of the Department of Physics at Texas Lutheran University.

All other work conducted for the dissertation was completed by the student independently.

Funding Sources

Graduate study was supported by the Robert A. Welch Foundation [Grant A-1266] and the U.S. Department of Energy [Grant DE-FG02-93ER40773].
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1. INTRODUCTION

1.1 Pionic Fusion Overview

Pionic fusion is the process by which two nuclei fuse during a collision and then de-excite by the exclusive emission of a pion. The final state of the system is composed of the fusion residue with the same total number of nucleons as the colliding system and a pion. The species of the fusion residue and the charge of the emitted pion satisfy charge conservation \([14]\). The process requires that nearly all of the available kinetic and potential energy in the colliding system be concentrated into just a few degrees of freedom - the rest mass and kinetic energy of the emitted pion. Thus, the energy of the emitted pion is limited by the energies of available, bound final states of the fusion residue \([7]\). The combination of limited available energy and the extreme coherence required in the process ensures that pionic fusion reactions are very rare. Pionic fusion has been observed in multiple reacting systems with reported cross sections ranging from approximately 100 nb to approximately 250 pb where the cross section is generally observed to decrease with increasing size of the reacting system \([7, 8, 9, 10, 15, 16, 17, 18, 5, 19, 20]\).

Figure 1.1 offers a schematic view of pionic fusion inside the larger scope of pion production \([1]\). One can consider all of the possible pion-producing reactions given a reacting system. The differential cross sections for each pion production channel can be given as a function of the kinetic energy of the emitted pion. When the pion kinetic energies are low (small compared to the total available energy in the system) the phase space is quite large and, consequently, the cross sections are large. As the kinetic energy of the emitted pion gets larger compared to the available energy in the system, the phase space and cross sections fall. Eventually, the kinetic energy of the emitted pion will require all of the available energy in the system and the reactions can be described as pionic fusion. In these cases, the kinetic energy of the pions is restricted to corresponding bound states in the fusion residue. As a practical matter, pionic fusion experiments are performed quite close to the absolute threshold of pion production. This drastically reduces the cross sections for
competing pion production reaction mechanisms.

Theoretical models for particle production in nuclear reactions are typically limited to cases of nucleon-nucleon interactions [21, 22]. The most traditional examples of particle production involve the reaction of two protons [23, 24] or reactions between complex nuclei in which the beam energy is high enough that particle creation can be explained by nucleon-nucleon collisions [21, 25, 26, 27]. Typically, the term “sub-threshold” is applied to pion production when the average center of mass energy of a nucleon-nucleon collision is below 140 MeV (280 MeV/nucleon beam energy) - the approximate rest mass of the charged pion. Sub-threshold pion production is a well-established phenomenon. Indeed, the possibility of creating pions below this threshold energy was recognized as early as 1947 [28]. In the last few decades it has become possible to perform very accurate production cross section measurements in near- or sub-threshold reactions [23, 29, 30]. These new data, particularly at deeply sub-threshold energies, suggest the need to advance the understanding of particle production beyond nucleon-nucleon processes to highly collective mechanisms.

In this field of near- and sub-threshold particle production in reactions of complex nuclei, those involving the exclusive creation of a pion, or pionic fusion, are of particular interest. As the lightest of the strongly interacting particles, pions represent the best hadron candidates for exclusive production due to the relatively low total energy threshold \(E_{CM} \approx 140 \text{ MeV}\) for charged pions) resulting in relatively high production cross sections compared to the heavier mesons [27]. Furthermore, studying exotic reactions involving pions can help to understand the strong force and nuclear structure [23, 31].

Historically, pion production has been described statistically using cascade models in which pions are created through \(\Delta\) and \(N^*\) resonances [32] provided there is enough energy to overcome the absolute energy threshold of producing a pion - its rest mass - in nucleon-nucleon collisions [27]. In the cases of pion production in reactions of complex nuclei the situation becomes less straightforward, particularly for sub-threshold reactions. Even in these cases, though, it is typically the case that the pion production is described in the context of nucleon-nucleon interactions within the
Figure 1.1: A schematic representation of pionic fusion reactions in the context of pion production reactions. The vertical axis is the differential cross section of pion production and the horizontal axis is the kinetic energy of the emitted pion. In this figure, pionic fusion is taking place in the “exclusive” region. Reproduced from [1], with the permission of AIP Publishing.
Nucleons inside of a nucleus can be approximated as a weakly interacting system of fermions, a Fermi gas. In such an approximation, protons and neutrons are able to move around quasi-freely inside the nuclear volume and fill two separate potential wells. The probability distribution for finding a fermion at a given energy takes the form of the Fermi-Dirac Distribution, Equation 1.1.

\[ f(E) = \frac{1}{e^{(E-E_F)/kT} + 1} \] (1.1)

Here, \( E_F \) is the Fermi energy, \( T \) is the temperature, and \( k \) is the Boltzmann constant. At temperature \( T = 0 \), the lowest energy states in the wells will be filled up to the Fermi energy and will have a maximum momentum of \( p_F \), the Fermi momentum. The fermions have a flat probability of having energies below \( E_F \) and have zero probability of having energy above \( E_F \). At nonzero temperatures, though, the step function character of the distribution changes such that at high temperature the distribution converges to a Boltzmann distribution. Figure 1.2 shows schematically how nonzero temperatures affect the probability distribution for \( T < T_F \). Importantly for subthreshold pion production, the probability distribution asymptotically approaches zero at high energies. There is a finite, nonzero probability of nucleons having energies in these high momentum tails of the distribution.

There have been attempts to reproduce production cross sections for sub-threshold pions by considering these extreme tails of the momentum distributions [34]. If one can sample arbitrarily high nuclei momenta then there will be some probability that the Fermi motion of two nucleons during a collision can result in much more energy than what the average energy per nucleon of the projectile nucleus would indicate. Thus, pions can be created in subthreshold reactions with the Fermi motion providing the extra energy. One encounters some consequences of employing this line of thinking. First, during attempts to model such a process it is often not possible to conserve energy (see ref. [29] for a review of sub-threshold particle production from nucleon-nucleon interactions). Second, as deeper sub-threshold production is considered, the necessary energies that must be sampled increase beyond physically meaningful energies of nucleons in...
bound nuclei. Still, these naïve methods based on sampling high momentum tails of nucleons approximated by the Fermi Gas Model proved to be quite successful for describing near- and sub-threshold pion production data as shown in Figure 1.3 [2].

The top three histograms in Figure 1.3 show experimental data for the energy spectra of pions produced in the sub-threshold reactions of $^{12}$C + $^{12}$C at 60, 74, and 84 MeV/nucleon. The bottom histogram in Figure 1.3 shows the experimental pion energy spectrum for the sub-threshold reaction of $^{40}$Ca + $^{40}$Ca at 44 MeV/nucleon. Model calculations which include the very high nucleon momentum tails of the distributions (solid lines) reproduce the experimental data much better than those which do not sample the high momentum tails (dashed lines). While the energies of the reactions shown in Figure 1.3 are far below 280 MeV/nucleon (our definition to this point of sub-threshold), they are still much higher than pionic fusion energies near the absolute pion production threshold (for $^{12}$C + $^{12}$C the absolute threshold is approximately 23 MeV/nucleon and for $^{40}$Ca + $^{40}$Ca the absolute threshold is approximately 7 MeV/nucleon). At these lower reaction energies, approaching the absolute threshold, application of the high momentum tails cannot reproduce reported pion production cross sections [35].

Figure 1.2: A schematic representation of the effect of nonzero temperature on the probability function for energies of fermions using Fermi-Dirac statistics.
Models based primarily on sampling the high momentum tails of nucleon momentum distributions have been largely discredited due to energy conservation constraints [14]. One of the more significant cases against these models was presented by Shyam and Knoll in ref. [3]. Their study showed that, from a shell model approach, one could not simply use the nucleons’ relative momentum to calculate the relative energy in a collision. Nucleons in shell model orbits have a momentum distribution but a fixed energy. By estimating available energies from harmonic oscillator wave functions instead of the more naïve Fermi gas model, they found that calculated cross sections significantly underestimate the experimental data even at bombarding energies of
Figure 1.4: Pion spectra resulting from the reaction of $^{12}\text{C} + ^{12}\text{C}$ at 85 MeV/nucleon at 90° laboratory angle (data from ref. [2]). The pair of curves labeled (a) represents results of the single nucleon-nucleon (NN) collision model using a standard harmonic oscillator shell model and the pair of curves labeled (b) represent results of the single NN collision model using the Fermi gas model. The solid and dashed lines represent the NN → d$\pi$ and the NN → NN$\pi$ channels, respectively. Reprinted from [3].

Further attempts to describe the sub-threshold mechanism for the production of pions have utilized collective or cooperative effects in the nuclear medium. Some of these models include the
mean field approach [36], decay from the compound nucleus [37], pionic bremsstrahlung [38], and explicitly cooperative statistical processes using two-body interactions [3]. While each of these methods has been able to reproduce data from cases of sub-threshold pion production, they each have their shortcomings. The pionic bremsstrahlung mechanism requires an ad hoc parameter that is related to the deceleration of nuclei during the collision. The mean field approach is technically collective in nature, but because of numerical difficulties the method is restricted to energies above 60 MeV/nucleon. The statistical decay of the compound nucleus through the pion channel is an intriguingly simple model, but it was only ever applied to data for neutral pion production and never gained traction in the field. The statistical process from ref. [3] explicitly accounts for the residual two-body interaction to create a situation in which several nucleons can pool their energies to create a pion in a quantum multiple collision model. This model was able to reproduce pion cross sections from experimental results, but much of the agreement was achieved by allowing the compound nucleus to fragment – a requirement that cannot be met in the most extreme case of pion production, pionic fusion.

The process of pionic fusion pushes pion production to its absolute limit, demanding a cooperative process that, in some measured cases, requires more than 95% of the total available energy in the system to create the pion. As a result the process has proven quite difficult to model and only a couple of attempts have adequately reproduced the data. Models based on clustering phenomena have proven to be capable of reproducing experimental data with reasonable accuracy [9, 15, 17, 19, 4, 16, 39, 40, 41]. Another model described in ref. [6] uses the Born approximation with respect to pion production and the sudden approximation for nuclear rearrangement.

The basic tenant of the clustering model from ref. [4] is the idea that cluster structure ($^6\text{Li} = ^4\text{He} + \text{d}$ or $^3\text{He} + \text{t}$, for instance) in the final state nucleus cooperates with the relative motion in the entrance channel to allow for the coherent production of pions. Some results of the calculation are shown in Figure 1.5 for the reaction of $^4\text{He} + ^3\text{He} \rightarrow ^7\text{Li} + \pi^+$ [4]. The data points are from ref. [5].

The pion production cross section in nanobarns per steradian is plotted as a function of the pion
Figure 1.5: A comparison of calculated pionic fusion cross sections [4] and measured cross sections for the reaction $^4\text{He}(^3\text{He}, \pi^+)\text{^7Li}$ at the incident energy of 88.8 MeV/nucleon. Solid and dashed curves are the calculated results from the cluster model and the shell model wave functions of $^7\text{Li}$, respectively. The solid dots with error bars are experimental data points from ref. [5]. $W_D$ is the strength of the imaginary part of the optical potential in the entrance channel. Reprinted with permission from American Physical Society.

emission angle in the center of mass of the reacting system in Figure 1.5. The solid lines are the results of the cluster model from ref. [4], the dashed lines are results from shell model calculations and the solid dots with error bars are experimental data from ref. [5]. From the figure, we again observe that the nucleon-nucleon single collision model greatly underestimates the production cross sections when the nucleons are forced into shell model orbits (dashed lines). In addition to the real interaction, the authors added a local imaginary potential given by $W_D(r)$ which has been used in previous distorted-wave Born-approximation analyses. The calculations in Figure 1.5 were carried out at $W_D(0) = 0$ and -25 MeV. The cluster model also underestimates the cross sections
slightly which the authors admit is likely due to the fact that they do not fully consider the two-body mechanisms, namely the s-wave and $\Delta$-intermediate state couplings. This cluster model has been used to predict some pionic fusion cross sections for reactions involving larger targets, but was limited to He projectiles.

The model presented in ref. [6] has been used to successfully reproduce pionic fusion data over the entire mass range of previously measured systems ($^3$He + $^3$He through $^{12}$C + $^{12}$C). The pionic fusion cross sections were calculated using a Born approximation with respect to pion production. Also, the sudden approximation was used for nuclear rearrangement. Energy, spin, momentum, and isospin conservations are satisfied at all steps in the calculation. The model accounts for the strong clustering correlation for $A = 7$ systems, the distortion of the entrance channel and the Pauli Exclusion Principle. Figure 1.6 shows some results of the model and experiments [9].

In Figure 1.6, the cross section for pion production scaled by $(m_\pi/k_\pi)^3$ is plotted as a function of the average of the sum of the projectile target and mass, $A_{avg} = (A_{proj} + A_{tgt})/2$. Here, the terms $m_\pi$ and $k_\pi$ are the pion mass and highest available momentum given by the difference between the available energy in the colliding system and the pion mass. The purpose for this scaling is to account for the fact that each of the experiments was performed at different energies above the absolute pion production threshold. It is shown that the model from ref. [6] reproduces the experimental data up through the reaction of $^{12}$C + $^{12}$C fairly well. However, there are very few data points for comparison and those data points that are similar between the model and experiment can be off by as much as an order of magnitude (as in the case of $^3$He + $^3$He). The model also predicts a roughly exponential drop off of the cross section with increasing average mass of the system. This phenomenon is expected simply by the assumption that cooperative processes will become more and more unlikely as the number of cooperating partners is increased. However, measurements of pionic fusion in higher mass systems and in systems with projectiles beyond $^3$He are needed in order to determine the true validity of the model.
Figure 1.6: Scaled pionic fusion cross sections as a function of the average of the sum of the target and projectile mass ($A_{\text{avg}} = (A_{\text{proj}} + A_{\text{tgt}})/2$). Terms $m_\pi$ and $k_\pi$ are the pion mass and highest available momentum given by the difference between the available energy in the colliding system and the pion mass. The closed circles are calculated results from the model described in ref. [6]. The open circles are measured results from [7, 8]. The cross is the measured result from ref. [9]. Reprinted from [9]

1.2 Previous Pionic Fusion Experiments

The first observation of pionic fusion was published in 1981 by Le Bornec, et al. [8]. At the time, there was very little investigation into exclusive pion production in systems more complex than two colliding protons. Throughout the 1970s, high-momentum-transfer reactions (for instance coherent (p,\pi) [24] or (p,d) [31]) were being very thoroughly investigated in the medium energy regime. However, the basic reaction mechanism involved was still unknown. In an attempt to shed some light on the situation, a program was developed to study coherent pion production using low energy $^3$He beams. The study produced the first results of the coherent reaction of $^3$He $+$ $^3$He $\rightarrow \pi^+ + \ ^6$Li.

The experiment was performed in the Orsay synchrocyclotron which produced $^3$He beams with
energies of 268.5 and 282 MeV. Reactions induced by the 282 MeV $^3$He beam, the beam energy which constitutes the majority of their statistics, represent a total available energy of about 17 MeV above the threshold for producing a pion and $^6$Li in its ground state. The beam was incident on a $^3$He target and the resulting pions were detected with a spectrometer. The experiment was able to identify pionic fusion events as well as analyze the final state of the compound nucleus, shown in Figure 1.7 [8].

Figure 1.7 shows the lab energy spectrum for pions at 20° in the lab frame. The kinetic energies of the pions correspond to the ground and near-ground states of $^6$Li. The angle-integrated total cross section for the production of the ground state was found to be 111 ± 11 nb. This practice of
observing pionic fusion through the detection of the emitted pions using a spectrometer remained
the technique of choice as investigations into the process began looking at larger systems. How-
ever, as the size of the targets increased, much smaller pionic fusion cross sections were found -
\(^6\text{Li}(^3\text{He},\pi^+)^9\text{Be}: \sigma \approx 150 \text{ pb/sr} [20], \(^7\text{Li}(^3\text{He},\pi^+)^{10}\text{Be}: \sigma \approx 60 \text{ pb/sr} [18], \(^{10}\text{B}(^3\text{He},\pi^+)^{13}\text{C}: \sigma \approx 95 \text{ pb/sr} [20], \text{ and } ^{12}\text{C}(^3\text{He},\pi^+)^{15}\text{N}: \sigma \approx 100 \text{ pb/sr} [18]. \text{ All of these cross sections are for reactions}
that result in the compound nucleus in its ground state.

There are a few important points to take away from the cross sections quoted above. First, these
studies each represent different energies above the coherent (pionic fusion) threshold ranging from
34 MeV to 83 MeV. Second, the cross sections for pionic fusion have been suppressed by at least
a factor of 100 for targets larger than \(^3\text{He}. \text{ However, there is very little difference in the cross}
sections among the larger targets. While this substantial reduction in cross section exists when
one moves from He targets to Li targets, it does not seem to be the case that the trend continues
downward in any significant manner. This observation bodes well for studies of pionic fusion of
heavy ion systems. Another important observation that we can make from these cross sections is
they are now low enough that the angular acceptance of spectrometers becomes an even bigger
problem. This makes the method of using a spectrometer to detect pions resulting from pionic
fusion events in more complex systems unrealistic.

In order to increase pionic fusion detection efficiency, researchers developed a method for
detecting the complementary fusion residue instead of the pion resulting from the pionic fusion event
[10]. These fusion recoils are emitted within a small forward cone since the only deflection off
of beam axis comes from the emission of a low energy pion and nearly all of the residues can be
accepted by a large solid angle spectrometer. They can then be identified with high efficiency and
events can be classified as pionic fusion based on the detection of these residues at the proper en-
ergy that contain all of the nucleons in the reacting system. For instance, any reaction of \(^{12}\text{C} + ^{12}\text{C}
near the pion production threshold which results in a mass 24 fusion residue is nearly guaranteed
to have cooled by the emission of a pion. This is certainly the case for \(^{24}\text{Na} \text{ or } ^{24}\text{Al residues since the neutron-to-proton ratio has changed from the original system. For residues in which the isospin}
is unchanged from the reacting system, $^{24}\text{Mg}$ in this example, radiative capture is also a plausible reaction mechanism. However, single photon emission events will produce a significantly different distribution of residue recoil energies due to the higher momentum transfer compared to pionic fusion and multiple high-energy photon emission has been shown to be orders of magnitude less probable than measured pionic fusion cross sections [7].

The first study to implement the method described above measured the reaction $^{12}\text{C}(^{3}\text{He},\pi^{+})^{15}\text{N}$ at 181.4 MeV beam energy; 19.0 MeV above the threshold for production of $^{15}\text{N}$ in its ground state [10]. The study was performed at the Indiana University cyclotron and residues were transported and focused into a gas proportional counter using the quadrupole-quadrupole-split-dipole (QQSD) magnetic spectrograph. Time of flight measurements were performed using a pair of Parallel Plate Avalanche Counters (PPACs) positioned 10 cm apart and located downstream of the QQSD. A flight path was determined using the angle and positions measured by the two PPACs. Using the magnetic rigidity of each ion, determined by its position on the PPACs, and the time of flight measurement through the spectrometer the ion’s mass to charge ratio was determined with a resolution of about 1%. The flight time between the two PPACs provided a second mass-to-charge determination and a second identification constraint. Some results of their study are shown in Figures 1.8(a) and (b).

The results in Figure 1.8 may contain up to 20% background produced primarily by incomplete separation of $^{13}\text{C}$ fragmentation products. As in the results from the Orsay experiment (Figure 1.7), we can see that there is a very high population of excited states in the fusion residue. However, unlike the results from Figure 1.7, there is very little population of the ground state. According to the authors, most of the yield corresponds to a group of unresolved excited states of the $^{15}\text{N}$ residues between 6.5 and 10.5 MeV. Above 10.5 MeV all known states of $^{15}\text{N}$ are unbound with very small gamma decay branching ratios [10]. The authors explain this result by noting that the radial angle, $\alpha$, was determined using the PPAC positions while the axial angle, $\phi$, was ignored since it could only be measured roughly in their setup. Therefore, residues with a large recoil in the transverse direction will be detected at smaller $\alpha$ values. These events will be incorrectly classified.
Figure 1.8: Pionic fusion results from the reaction $^{12}\text{C}(^{3}\text{He},\pi^{+})^{15}\text{N}$ using the fusion residue detection method. Solid lines: distribution of $^{15}\text{N}$ events by excitation energy in $^{15}\text{N}$ residues summed over all pion emission angles. The dashed line in (a) represents a fit to the data assuming the population of a single state at an excitation energy of 6.5 MeV. The dashed line in (b) represents a fit to the data assuming population of two states in the $^{15}\text{N}$ residues at energies of 6.5 and 8.5 MeV with relative populations of 0.7 and 0.3 respectively [10]. Reprinted with permission from American Physical Society.

as low momentum recoil events corresponding to low energy pion emissions and artificially high residue excitation energies. The authors conclude that nearly all of the events attributed to $E^{*} = 13\text{-}19$ MeV are due to this effect.

The discussion above demonstrates some of the difficulty in attempting a final state measurement of residues from pionic fusion using a spectrometer. In Figure 1.8(a) the dotted line represents a possible distribution for a single populated state around 7 MeV which tails off at higher energies. The dotted line in Figure 1.8(b) assumes the population of two excited states centered around 6.5
and 8.5 MeV in order to compare the results of ref. [10] to the results of ref. [18]. The dotted-line fits were normalized to include the same area as is under their respective solid lines. Ultimately, the angle-integrated cross section for the $^{12}\text{C}(^{3}\text{He},\pi^{+})^{15}\text{N}$ reaction was found to be $1.3 \pm 0.3 \text{ nb}$.

While the effects of increasing target size on pionic fusion were becoming better understood, the projectiles remained almost exclusively $^{3}\text{He}$. It was not until 1996 that a study was published by D. Horn et al. measuring the pionic fusion of two ions heavier than He [7]. The reactions studied were $^{12}\text{C}(^{12}\text{C},\pi^{+})^{24}\text{Na}$ and $^{12}\text{C}(^{12}\text{C},\pi^{0})^{24}\text{Mg}^{*}$. The pionic fusion events were selected based upon the detection of mass 24 residues using a heavy ion counter located downstream of the Q3D spectrometer at Chalk River’s TASCC facility. Until the publishing of this paper it was unknown whether or not reactions involving two heavy nuclei could achieve the coherence necessary for pionic fusion. The reaction was carried out only 6 MeV above the coherent threshold for $\pi^{+}$ and $\pi^{0}$ fusion. The $\pi^{-}$ channel is energetically forbidden at this bombarding energy. The results of the study are shown in Figure 1.9 and Table 1.1. Two different carbon targets were used, one thick (826 $\mu\text{g/cm}^{2}$) and one thin (486 $\mu\text{g/cm}^{2}$).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Counts</th>
<th>$\sigma_{\text{gross}}$(pb)</th>
<th>$\sigma_{\text{bkgd}}$(pb)</th>
<th>$\sigma_{\text{net}}$(pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{24}\text{Mg}(\text{thick})$</td>
<td>98</td>
<td>397(40)</td>
<td>166(25)</td>
<td>231(47)</td>
</tr>
<tr>
<td>$^{24}\text{Na}(\text{thick})$</td>
<td>68</td>
<td>353(43)</td>
<td>126(22)</td>
<td>227(48)</td>
</tr>
<tr>
<td>$^{24}\text{Mg}(\text{thin})$</td>
<td>58</td>
<td>329(43)</td>
<td>163(46)</td>
<td>166(63)</td>
</tr>
<tr>
<td>$^{24}\text{Na}(\text{thin})$</td>
<td>7</td>
<td>159(82)</td>
<td>136(38)</td>
<td>23(90)</td>
</tr>
<tr>
<td>$^{24}\text{Mg}(\text{subthreshold})$</td>
<td>14</td>
<td>279(90)</td>
<td>220(62)</td>
<td>59(109)</td>
</tr>
</tbody>
</table>

Table 1.1: Gross, background and background-subtracted cross sections for the $^{12}\text{C}(^{12}\text{C},\pi^{+})^{24}\text{Na}$ and $^{12}\text{C}(^{12}\text{C},\pi^{0})^{24}\text{Mg}^{*}$ reactions at 137 MeV center of mass beam energy with the thick and thin targets. Also listed is the sub-threshold measurement at 130 MeV center of mass beam energy.

Figure 1.9 shows the experimentally measured cross sections for producing mass 24 residues in the $^{12}\text{C} + ^{12}\text{C}$ reaction as a function of the recoil velocities of the residue as open squares or circles. The top panel shows the data for reactions producing $^{24}\text{Na}$ residues and the bottom panel shows the data for reactions producing $^{24}\text{Mg}$ residues. In both panels, the allowable recoil
velocity regions for each pionic fusion channel are shown using the double sided arrows. The gray area shown in the two plots corresponds to mass 24 residues produced by reactions on oxygen contamination in the target. This was measured using a metal MnO$_2$ target with the results scaled to match the contamination in the $^{12}$C target. This oxygen contamination accounts for most of the mass 24 residues measured outside the allowable region. Finally, the thin solid line in both panels is an independent background measurement based on $^{25}$Mg production which can only result from reactions on contaminant nuclei larger than $^{12}$C. The total cross sections for the two reactions are around 230 pb according to Table 1.1 - approximately an order of magnitude smaller than some cross sections for pionic fusion using He beams on heavy nuclei.

While the recoil residue detection method makes it possible to study pionic fusion in larger systems, it introduces an added difficulty of complicated background measurements. It also makes spectroscopic measurements of the final state more difficult as in ref. [10]. A study was performed by Joulaeizadeh et al. [9] in which the pionic fusion residues were detected using a spectrometer and photon decays of neutral pions were detected using a 4π detector array called the Plastic Ball (PB) [42]. This study was the first to measure the almost full pion angular distribution produced in pionic fusion reactions with a projectile heavier than a proton.

The reaction studied in ref. [9] is $^6$Li($^4$He,π$^0$)$^{10}$B$^+$ with a total center of mass energy about 10 MeV above the coherent pion production threshold. The total pionic fusion cross section for the above reaction was measured to be 6.8 ± 0.7 nb. This total cross section includes only two final states in the $^{10}$B system due to acceptances in the experimental system: E = 1.7402 MeV ($J^\pi = 0^+$, $l = 1$) and E = 5.1639 MeV ($J^\pi = 2^+$, $l = 1$).

1.3 Outline

In this work I will present the results of the measurement of the pionic fusion reaction $^4$He + $^{12}$C → $^{16}$N + π$^+$. The rest of this manuscript will be structured as follows: Chapter 2 will present the details of the experimental setup including the Momentum Achromat Spectrometer (MARS) and the newly designed and constructed Partial Truncated Icosahedron (ParTI) phoswich array. In Chapter 3, I will present the results of a Geant4 simulation of a ParTI phoswich, Gemini predictions
for residue cross sections at the focal plane of MARS, a final state pionic fusion model used to determine experimental parameters, and pionic fusion cross section predictions. In Chapter 4, I will present the results of the calibration and characterization experiments performed for the ParTI phoswiches and MARS. In Chapter 5, I will report the results of the pionic fusion experiment. Finally, in Chapter 6 I will give a brief summary of the results and conclusions.
Figure 1.9: Galilean-invariant cross sections as a function of velocity for thick target data. In the top panel the reaction is $^{12}\text{C}(^{12}\text{C},\pi^+)\text{Na}$ and the bottom panel shows data for the reaction $^{12}\text{C}(^{12}\text{C},\pi^0)\text{Mg}^*$, both at center of mass beam energy $E_{\text{cm}} = 137$ MeV. The square and circle data points show the measured pionic fusion cross sections for the respective reactions. Data are binned by the position on the spectrometer focal plane. The regions indicated by the double headed arrows denote the possible ranges of recoil velocities. The shaded regions represent the measured background from $^{12}\text{C} + ^{16}\text{O}$ reactions scaled to account for the oxygen contamination in the carbon target. The thin solid line is another measure of background based on $^{25}\text{Mg}$ production [7]. Reprinted with permission from American Physical Society.
2. EXPERIMENTAL

The pionic fusion reaction \( ^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{N} + \pi^+ \) was studied at the Texas A&M Cyclotron Institute. The Momentum Achromat Recoil Spectrometer (MARS) [43] was used for the detection of the \(^{16}\text{N} \) fusion residues and the Partial Truncated Icosahedron (ParTI) phoswich array [44] was designed and constructed for the detection of charged pions.

In this chapter, the overview of the experiment is presented in Section 2.1. In Section 2.2, the MARS spectrometer and the silicon stack detector at the focal plane will be discussed. In Section 2.3, the design and construction of the ParTI array and its phoswich charged particle detectors will be discussed. In Section 2.4, various beamline modifications and pionc fusion experiment components are discussed. In Section 2.5 I will discuss the electronics used in the pionic fusion experiment.

2.1 Overview

The K500 Superconducting Cyclotron at the Texas A&M University Cyclotron Institute was used to accelerate \(^4\text{He} \) to 55 MeV/nucleon which impinged upon self-supporting, isotopically enriched \(^{12}\text{C} \) targets in order to study the pionic fusion reaction \(^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{N} + \pi^+ \). The carbon targets were pyrolytic graphite films produced and delivered by Minteq [45]. The beam energy was chosen such that the total energy available in the colliding system would be just above the kinematic threshold of the pionic fusion process (the rest mass of the \( \pi^+ \), 139.5 MeV/c\(^2 \)) as calculated by Equation 2.1.

\[
E_{\text{Above threshold}} = Q_{\text{reaction}} + T_{\text{beam}} \left( \frac{A_{\text{target}}}{A_{\text{target}} + A_{\text{projectile}}} \right) - m_{\pi} \tag{2.1}
\]

Here, \( Q_{\text{reaction}} \) is the Q-value of the reaction, \( T_{\text{beam}} \) is the kinetic energy of the beam, \( A_{\text{target}} \) and \( A_{\text{projectile}} \) are the mass numbers of the target and projectile, respectively. The mass of the pion, \( m_{\pi}c^2 \) is included in the Q-value. Information regarding the reaction details including beam and target specifications, energy above the kinematic pionic fusion threshold, and fusion residue details
are presented in Table 2.1.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$^4\text{He} + ^{12}\text{C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4\text{He}$ Beam Charge State</td>
<td>$2^+$</td>
</tr>
<tr>
<td>Quoted Target Thickness</td>
<td>828 μg/cm² ± 10%</td>
</tr>
<tr>
<td>Target Purity</td>
<td>$&gt; 99.9% ^{12}\text{C}$</td>
</tr>
<tr>
<td>Pionic Fusion Residue</td>
<td>$^{16}\text{N}$</td>
</tr>
<tr>
<td>Center of Mass Velocity</td>
<td>0.086c</td>
</tr>
<tr>
<td>Energy Above Pionic Fusion Threshold</td>
<td>22.2 MeV</td>
</tr>
</tbody>
</table>

Table 2.1: Pionic fusion reaction information.

The experiment was performed in the MARS beam line. The MARS spectrometer was used to separate and focus the pionic fusion residues in order for them to be detected at the spectrometer focal plane using a silicon stack ΔE-E detector. The charged pions were detected using the ParTI phoswich array inside the MARS target chamber. Using this experimental setup, pionic fusion events can be identified through the detection of the pion in the ParTI array or the residue at the spectrometer focal plane independently, or as a coincidence in both detection instruments. During the experiment, the beam intensity was measured using a Faraday cup located inside the MARS target chamber.

2.2 Momentum Achromat Recoil Spectrometer (MARS)

MARS is a recoil mass spectrometer located at the Texas A&M University Cyclotron Institute. It is capable of operating over a broad energy range with high efficiency and good mass resolution. It can operate at 0° making it an extremely useful tool for the measurement of fusion reactions and reactions with inverse kinematics. Table 2.2 gives some of the characteristics of the spectrometer and Figure 2.1 shows a schematic of the instrument. A more complete description of the design specifications of MARS can be found in Ref. [43].

As previously stated, MARS was used to separate the pionic fusion residues and focus them onto a ΔE-E silicon stack located at the spectrometer focal plane. The $^4\text{He} + ^{12}\text{C}$ reactions will
Overall Length | 19 m
---|---
Magnets
| Quadrupoles | 20 cm diameter | 60 cm length
| Sextupoles | 20 cm diameter | 20 cm length
| Dipoles | Gap(cm) | Bend Angle | ρ(m) | Max Field (kG) |
| D1 | 5 | 35° | 1.116 | 16 |
| D2 | 10 | 35° | 1.116 | 16 |
| D3 | 13 | 0° - 25° | - | 6 |
Velocity Filter
| Length | 3 m
| Gap | 10 cm
| Max Voltage | 500 kV
| Max Magnetic Field | 1 kG
| Max Solid Angle | 9 msr
| Path Len Dispersion | 2 cm

Table 2.2: MARS specifications.

take place inside the target chamber and the reaction products that are inside the 9 msr acceptance of MARS will be dispersed according to their magnetic rigidities ($B\rho$) in dipole 1 (D1 from Figure 2.1). The equation for magnetic rigidity for the case of a charged particle moving perpendicularly to a magnetic field is given in Equation 2.2.

$$B\rho = \frac{p}{q}$$  \hspace{1cm} (2.2)

In Equation 2.2, $B$ is the strength of the magnetic field, $\rho$ is the bending radius of the charged particle in the magnetic field, $p$ is the magnitude of the particle’s momentum, and $q$ is the charge of the particle. When tuned for the proper $B\rho$ (approximately 0.61 T m in the case of $^{16}$N pionic fusion residues), the products of interest are transported down the center of the beam line while fragments with different rigidities are deflected off axis and lost as they strike the slits in the “coffin”. A second dipole (D2) operates complementary to D1 in order to create the desired momentum focus which gives the spectrometer its titular "momentum achromat" characteristic. Next, a Wien velocity filter provides a third level of separation by vertically dispersing the frag-
Figure 2.1: Schematic of the Momentum Achromat Recoil Spectrometer (MARS). Beam is delivered to the line from the right of the figure. The reaction takes place inside the target chamber and the reaction products within the 9 msr angular acceptance of MARS proceed through a series of quadrupole (Q) and dipole (D) magnets. A Wien velocity filter is located after the second dipole magnet for further product separation.

ments using competing magnetic and electric fields selected such that the species of interest at the velocity of interest will experience exactly canceling forces while other species will be deflected from beam center. After exiting the velocity filter, the particles are dispersed by a third dipole magnet (D3). This third dipole magnet disperses the fragments in the vertical direction according to their mass-to-charge ratio. After the D3 magnet, the particles arrive at the focal plane silicon stack which will be discussed in Section 2.2.1.

In order to perform the cross section measurement, an electron-suppressed Faraday cup was
installed directly behind the target ladder in the MARS target chamber for the purpose of monitoring the beam intensity. This cup was periodically inserted into the beam to get measurements of the absolute beam intensity on the target. This process cannot provide a continuous measure of beam intensity, however, since the cup blocks reaction products from entering MARS when it is in the line. During production runs, then, detector trigger rates were monitored to make a proportional measurement of the beam intensity which can be correlated to the absolute intensity of the beam. The Faraday cup will be described in greater detail in Section 2.4.2 and the beam intensity measurement will be discussed further in Section 5.1.

Following the process of separation, the particles at the magnetic rigidity of interest arrive at the focal plane silicon stack. The “ΔE” component of the detector is a Micron [46] X1(SS)-30 PSD type silicon detector. It has a 5 cm x 5 cm active area which is split into 16 vertical, position sensitive (resistive) strips. The nominal linear thickness of the detector is 30 μm. A 1 mm thick Micron MSX25 single element silicon, the “E” detector, is located directly behind the ΔE. See Appendix A for the Micron data sheets for the two detectors. The vertical position on the ΔE detector face is proportional to the mass-to-charge ratio of the particle (due to the combined effects of the velocity filter and D3). Using the total energy of particles at the focal plane and the vertical position, it is possible to produce an $E_{tot}$-Y particle identification plot as shown in Figure 2.2.

The particle separation capabilities of MARS are shown in Figure 2.2 for a reaction of $^{12}$C + $^{12}$C. The y-axis is the total energy deposited in the silicon stack and the x-axis is the vertical position of the particle on the ΔE detector which is monotonically related to the particle’s mass-to-charge ratio. Using the $E_{tot}$-Y plot will allow for the efficient identification of the mass, A, and charge, Q, of residues during the pionic fusion experiment. Isobars of the same charge state (for instance, $^{16}$O$^{7+}$ and $^{16}$N$^{7+}$), however, are not separable in this space. In order to identify residue proton numbers, Z, the relative energy loss in the ΔE strip silicon and the full E silicon can be used. As particles pass through the ΔE component silicon they deposit energy proportional to their proton number squared ($Z^2$). Thus, isobars with the same total energy can be distinguished by the amount of energy deposited in the transmission detector. The combination of these two
Figure 2.2: A particle identification plot produced at the focal plane of MARS. The y-axis is the energy deposited by the particle in ADC channels and the x-axis is the vertical position of the particle on the ΔE detector which is proportional to the particle’s mass-to-charge ratio. This figure was produced in the reaction of \(^{12}\text{C} + ^{12}\text{C}\) at 274.2 MeV and is presented as a demonstration of the particle identification capabilities of MARS. Located at approximately 10 mm is a column of spots corresponding to \(N = Z\) nuclei starting with deuterons and alphas at the very bottom and ending with \(^{22}\text{Na}\) at the very top. The large, very deformed spot at approximately 1600 channels is the beam, \(^{12}\text{C}\). To the left of the \(N = Z\) line is a curving band of spots corresponding to the \(N = Z + 1\) nuclei starting with \(^{13}\text{C}\) at approximately 1500 channels and ending with a few counts of \(^{25}\text{Mg}\).

Particle identification methods (\(E_{\text{tot}}-Y\) and \(\Delta E-E\)) will provide isotopic identification of residues at the focal plane of MARS. This capability is extremely important for the accurate measurement of residue cross sections. The exact process of particle identification and detector calibration will be discussed in Section 5.2.

Various MARS efficiencies were also measured over the course of this project. The transmission of particles at the central \(B_{\rho}\) (the magnetic rigidity that MARS is tuned for) was measured in a test experiment using an \(^{16}\text{O}^7+\) beam with lab-frame velocity equal to the center of mass velocity of the reacting system in the pionic fusion reaction as a surrogate for the pionic fusion residues of
Figure 2.3: Assembly configuration for the ∆E silicon detector provided by Micron and used for the pionic fusion experiment.

interest. A beam of $^{16}$N could not be used as it is unstable. The efficiency of MARS transmission for residues off of the central rigidity and the angular acceptance of MARS were also measured in order to produce the necessary high sensitivity measurement. The total measured transmission efficiency of MARS was compared with the efficiency predicted by the updated LISE++ [47] MARS simulation. Each of these investigations into the MARS efficiencies will be discussed in detail in Chapter 5.

2.2.1 The ∆E-E Silicon Stack

The ∆E-E silicon stack mounted at the focal plane of MARS is comprised of two silicon semiconductor devices arranged one behind the other. The first device is a 5 cm x 5 cm Design W with position sensitive metal on a Design X1 Ceramic produced by Micron Semiconductor Ltd. Figure 2.3 shows the assembly configuration for the device provided by Micron (serial number 2857-34). The detector is segmented into 16 resistive, position-sensitive strips on the front plane and has a single, non-resistive back plane.
A photograph of the $\Delta E$ silicon inside of its storage housing is shown in Figure 2.4. A second silicon was included in the order from Micron with identical specifications to the one shown in Figure 2.4 (serial number 3136-3) and has not yet seen beam in any capacity. Both devices were delivered as nominally 30 $\mu$m thick. However, during the pionic fusion experiment it was determined that the uniformity of the silicon thickness was not sufficient to produce particle identification from $\Delta E-E$. As a result, beam time was dedicated to scanning the area of the detector with an $^{17}$O beam. The energy loss of the beam in the $\Delta E$ was recorded as a function of position so that the thickness profile could be determined and a meaningful energy calibration could be obtained. More information regarding this process and the results are given in Section 5.2. No such investigation was done for the second silicon, but it should be assumed that it suffers from a similar non-uniformity in thickness.

The second silicon device in the silicon stack was a single area 5 cm x 5 cm device also provided by Micron (serial number 3145-9). According to the notation on the frame of the silicon, the thickness of the detector is 1038 $\mu$m. Unlike the $\Delta E$ detector, this device was not purchased new for the pionic fusion experiment.
The mount that was used for the silicon stack is the one that is routinely used to position silicon detectors at the focal plane of MARS. Two photographs of the silicon mount are shown in Figure 2.5. The $\Delta E$ detector is mounted on the face closest to the camera in Figure 2.5(a) and the $E$ is positioned behind it. The whole apparatus slides onto a standard target ladder and is manipulated vertically using a manual actuator arm in the MARS detector chamber.

Detector cabling for the $\Delta E$ silicon is connected via the 34-pin header and PCB seen in Figure 2.5(b). This is a standard installation in the mount as it is used for all X1 type strip silicons in the MARS detector chamber. Each of the 16 resistive strips of the detector has 1 side grounded through a $100 \, k\Omega$ resistor. Each of these sides are connected to a pin on one row (of 2) of the 34-pin header. Pins 18 - 25 and pins 27 - 34 (as numbered in Figure 2.3) are connected to the grounded sides of the strips. The pin labeled G/R goes directly to ground. Pins 1 - 8 and 10 - 17 are connected to the other side of each strip and the pin labeled "Rear" is connected to the back (unsegmented and non-resistive) plane. When ionizing radiation is incident on the detector, charge is liberated at the point of implantation and, on the resistive surface, the current will divide according to the ratio of resistances from the point of charge liberation through the two paths along the resistive strip to ground. By collecting the signal from one end of the resistive strip and comparing it to the signal collected off of the back plane it is possible to obtain position sensitivity along the strip dimension.

The new $\Delta E$ strip silicons described above were delivered with a mirrored pin configuration compared to the standard X1 designs. As a result, the silicon bias is applied to the ground (G/R) pin when the PCB that accompanies the mount is in its standard orientation. As a workaround, the PCB was removed from the mount and rotated $180^\circ$ as shown in Figure 2.5(b). During the experiment, the PCB was supported using strands of Mylar tape. As a result, strip signals for the pionic fusion experiment were being taken from the opposite physical side of the strip detector than is normally the case. This had no meaningful effect on the collected data though future runs using these strip silicons should employ a new PCB with the mirrored pin structure. For the $E$ detector, the cabling was connected directly to the posts coming off of the device assembly.

The $\Delta E$ silicon back plane was biased to $+12 \, V$ and the $E$ silicon was biased to $-80 \, V$ during
Figure 2.5: A photograph of the silicon stack mount from the front (a) and a photograph of the silicon stack mount from the side (b). The $\Delta E$ pin configuration required that the PCB which typically accompanies the mount when using standard X1 detectors be turned around to accommodate the new device as shown in figure (b).
the pionic fusion experiment. The path and logic for each of the 16 signals (14 strip sides, 1 $\Delta E$ back plane, and 1 E) is shown in the figures in Section 2.5.

2.3 The Partial Truncated Icosahedron (ParTI) Phoswich Array

The ParTI phoswich array was designed for use in the pionic fusion experiment for the purpose of identifying charged pions. In its complete configuration, it is comprised of 15 plastic/CsI(Tl) phoswiches arranged on the faces of a truncated icosahedron geometry and covers 19.7% of the solid angle. Unfortunately, during the pionic fusion experiment, the innermost 3 phoswiches were removed from the array in response to a sub-optimal beam tune. As a result, the ParTI configuration during the production runs in the pionic fusion experiment covered 15% of the solid angle. The target is positioned in the center of the truncated icosahedron shape and the distance from the target to the face of the phoswich detectors is 12.065 cm for pentagonal phoswich geometries and 11.76 cm for hexagonal phoswich geometries (phoswich geometries will be discussed more in Section 2.3.1). For the pionic fusion experiment, the ParTI array was mounted backward of the target position.

Each face of the array is an individual aluminum frame which holds a single phoswich detector. The frames are held together using two sets of aluminum tabs to create the truncated icosahedron geometry - one set for making the hexagon-hexagon connection and one set for the hexagon-pentagon connection. Two photographs of the populated detector array (one from the downstream direction and one from the upstream direction) are shown in Figure 2.6. Figure 2.6(a) was taken right before the array went into the beam line for the pionic fusion experiment and was taken from the upstream direction relative to the beam. Figure 2.6(b) was taken as the array was being mounted in the MARS target chamber and the camera is positioned just downstream of the target position.

The completely formed array is secured to its aluminum base and electronically isolated from the beam line by 3 plastic stands. The ParTI base was designed specifically to fit inside the asymmetric MARS target chamber and its shape partially aligns the array. Vertical alignment of the ParTI array is performed using 4 adjustable leveling feet on the ParTI base. The proceedure for
Figure 2.6: Two photographs of the ParTI array populated with its 15 phoswich detectors viewed from the upstream direction, (a), and from the downstream direction, (b).
inserting and aligning the ParTI array in the MARS target chamber is discussed in Appendix D. Solidworks drawings can be found for all ParTI array components in Appendix C.

2.3.1 The Phoswich Detectors

The term “phoswich” is an abbreviation of the phrase “phosphor sandwich” and describes a detector which is made up of two scintillating components with different characteristic scintillation times which are optically coupled together and to a single photo-sensitive unit. This configuration of detectors is beneficial for multiple reasons. Firstly, pulse shape discrimination techniques can be used to identify particle species. By coupling the two scintillators to the same photosensitive unit, the signal density can be reduced and the angular coverage of the detectors can be larger given a particular volume of usable space. The limited space in the MARS target chamber and the particle species of interest dictate that phoswich detectors are a good option.

There are 3 different geometries of phoswiches within the ParTI array. Twelve of the fifteen total detectors have the geometries of regular pentagons or hexagons corresponding to the faces of the truncated icosahedron shape. Each side of every regular polygon geometry is 3.81 cm. The other 3 units populate a single hexagonal face of the truncated icosahedron and are modified such that there is a 1.7 cm hole in the center of the face for the beam to pass through on the way to the target.

All phoswiches, regardless of geometry, have the same component construction. The first scintillating component is a 3 mm thick layer of EJ-212 scintillating plastic chosen for its fast rise and decay times (0.9 ns and 2.4 ns, respectively). A 1.5 cm thick CsI(Tl) crystal is optically coupled to the EJ-212 using BC-630 optical grease. There are multiple decay components associated with CsI(Tl) scintillators, however, the most prominent contributions have decay times on the order of 1 μs [48] which results in a scintillation response that minimally overlaps with the fast plastic response. After the CsI(Tl) crystal, a 2.54 cm thick Lucite light guide couples the polygon face to a 1924a Hamamatsu photomultiplier tube (PMT). A very thin layer of BC-630 silicone optical grease was applied to provide coupling in between each layer with the exception of the light guide-to-PMT coupling where RTV-615 was used for better structural stability. The front face of the
detector is covered with a layer of 420 $\mu$g/cm$^2$ aluminized Mylar to provide a uniformly thin and reflective barrier. The rest of the detector faces are covered with white teflon tape to provide a light-tight and diffusely reflective surface.

The EJ-212 plastic was ordered from Eljen Technologies [49] and was delivered pre-machined into the three desired geometries. These plastic components were also pre-polished. The CsI(Tl) crystals were purchased from Saint-Gobain [50] and were also delivered pre-machined into the necessary geometries. The CsI(Tl) crystals underwent some minor polishing in-house using progressively finer grit sandpapers and anhydrous ethanol. The Lucite light guides were machined in the Cyclotron Institute machine shop and underwent an extensive polishing process which included sand papers, polishing wheels, and commercial polishing products. A more detailed description of the polishing process for both the CsI(Tl) crystals and the plastic light guides is given in Appendix B.

During the pionic fusion experiment, each phoswich PMT cathode was biased to -1250 V. Each phoswich PMT was protected from stray magnetic fields produced by the spectrometer magnets using MuMetal sleeves purchased from the Magnetic Shield Corporation [51]. Each sleeve was attached to the phoswich wrapping using Torr Seal epoxy. Figure 2.7 shows a SolidWorks model for the assembled phoswich (a), a photograph of a pentagonal geometry phoswich before being wrapped (b), and a photograph of two wrapped phoswiches (c).

2.4 Beamline Modifications, Beam Monitors, and Pionic Fusion Experiment Components

The MARS line was not originally equipped to run the pionic fusion experiment when the measurement was proposed. As a result, some upgrades had to be made to the MARS target chamber and some complementary monitoring equipment had to be installed or utilized in the line. In this section, I will discuss these various beamline improvements and techniques.

2.4.1 The Z-Cube Vacuum Chamber

The installation of the ParTI array into the MARS target chamber was the first time that any complicated detector system had been positioned there. Often, the target chamber simply houses
Figure 2.7: (a) The SolidWorks phoswich construction. Moving up from the bottom are the EJ-212 plastic scintillator, the CsI(Tl) crystal scintillator, the Lucite light guide and the PMT. (b) A photograph of an unwrapped pentagonal geometry phoswich. (c) A photograph of two wrapped, finished phoswich detectors.
the target ladder on an actuator arm or the gas cell assembly for gas targets. Occasionally, Coulomb scattering detectors or Faraday cups are mounted in the target chamber for beam intensity measurements. Consequently, the chamber was not outfitted with the proper feedthroughs to accommodate an array like ParTI.

In order to get all the necessary bias and signal cabling to the ParTI array, a cube vacuum chamber was installed on the MARS target chamber. Each of the six sides of the cube are outfitted with ConFlat (CF) ports. Of those 6 ports, 5 are 20 cm CF and the remaining side is 17 cm CF. The smaller port mates with the existing port on the target chamber. Each of the larger ports on the cube can be used for feedthrough flanges. The cube is electrically isolated from the rest of the beamline by a plastic isolation ring. Figure 2.8 shows the SolidWorks model for the MARS target chamber with the cube vacuum chamber installed.

Currently, 3 of the 5 available 20 cm flanges are being used for feedthroughs. There are feedthroughs for 20x LEMOs, 10x BNCs, and 10x 34-pin headers. Two of the cube sides have blank flanges installed on them and can be modified in response to any future need. The 34-pin header feedthroughs conserve channel number (pin #1 on the outside of the chamber is pin #1 on the inside of the chamber) by utilizing a simple PCB with traced connections from pin to pin. A single board was used to house all 10 feedthroughs. A slot was cut into the 20 cm CF flange such that the board could sit inside. Then, Sure Fil J52 joint filler supplied by Dayton Superior [52] was used to fill in the slot and secure the board in the flange.

A structure was built to support the weight of the cube chamber while it is installed on the MARS target chamber. Shepherd Controls & Associates [53] supplied aluminum framing which was used to build a stand. On the top of the stand is a plastic plate which holds the chamber up and keeps it electrically isolated from the environment. Figure 2.9 shows a photograph of the cube chamber on its structural stand installed on the MARS target chamber.

### 2.4.2 The Target Chamber Faraday Cup

In order to obtain a direct measurement of the beam intensity at the target position, a Faraday cup was constructed and mounted directly behind the target position in the MARS target chamber.
The cup was made from an existing design which is being used in multiple locations in the Cyclotron Institute. The copper cup is electrically isolated from its aluminum housing and aluminum suppression ring using ceramic rings. The technical drawing for the electron-suppressed Faraday cup can be found in Appendix C. An aluminum mount was designed to attach the Faraday cup to an actuator arm. The mount also includes an attachable partial target ladder that hangs below the Faraday cup. This partial ladder has 3 target positions which can be used for degraders or stripper foils in future experiments. Figure 2.10 shows a photograph of the Faraday cup apparatus which is now a permanent installation in the MARS line.

The Faraday cup includes an electron suppression ring which was biased at -200 V during the
Figure 2.9: A photograph of the cube vacuum chamber installed on the MARS target chamber. The picture is taken looking approximately back toward the door into cave 2 and the entrance into MARS is on the right.
pionic fusion experiment. When the beam is incident on the Faraday cup, electrons are ejected from the copper cup. If these electrons are not accounted for, the reading from the Faraday cup will be artificially high as it will be affected both by the charge deposited by the incident beam and the lost electrons. By negatively biasing the suppression ring just outside the cup opening, electrons are pushed back into the copper cup instead of exiting. By doing this, a proper current reading can be made.

A Brookhaven Instruments Corporation model 1000c current integrator was used to measure the current coming from the Faraday cup. Previously, both of these current integrators have been mounted in the Cycotron Institute counting room and Faraday cup signals were routed into the room over patch panels in order to get beam intensity readings. While this arrangement can be useful for things like determining the relative intensities at different attenuation factors or an approximation of the intensity lost during the transport of the beam through the facility, the long stretches of cable in the patch panel introduced too much noise to get a measurement that is accurate enough for a high precision cross section. In order to reduce noise, the beam integrators were moved into Cave 2 during the experiment where the Faraday cup signals could be integrated after a minimal cable length.

The full scale range on the charge integrator can be adjusted between 0.02 nA and 0.02 A. Every second (for 1 second integration time), the integrator will produce a number of logic pulses between 0 and 1000 where 1000 pulses/second corresponds to the maximum current range. A SIS3820 scaler was used in the pionic fusion experiment to record the number of pulses from the integrator in 1 second intervals. Using the number of pulses generated and the scale setting on the integrator it is possible to calculate the total charge collected on the Faraday cup using Equation 2.3.

\[ Q_{\text{Integrated}} = \frac{N_{\text{pulses}}}{1000 \text{s}^{-1}} \times \text{Scale} \]  

In Equation 2.3, \( Q_{\text{Integrated}} \) is the integrated charge collected by the Faraday cup, \( N_{\text{pulses}} \) is the time-integrated number of pulses produced by the charge integrator, and \( \text{Scale} \) is the full scale
Figure 2.10: Two photographs of the Faraday cup apparatus which is now a permanent installation in the MARS target chamber. (a) The assembly as viewed from upstream. (b) The assembly as viewed from the side. A partial target ladder is mounted beneath the cup which can be used to insert degraders or stripper foils behind the targets in MARS.
range setting on the current integrator.

The current integrator was tested offline using a Keithley 261 picoampere current source. Currents between 300 nA and 100 pA were delivered to the integrator and the number of pulses it produced was monitored using a scaler counter. The full scale range was varied over the course of the testing to keep the reading near the center of the range. For all current inputs, the integrator was accurate to better than 1%. The linearity of the integrator was also tested at the 60 nA full scale setting (the setting for the pionic fusion experiment). The integrator was accurate to within 5 pulses in 1000 over the entire range between 0.5% and 100% of full scale.

2.4.3 Miniature Cameras for Beam Tuning

For typical MARS experiments using solid targets, beams from the cyclotrons are focused at the target position in the target chamber using a phosphor wedge viewer which can be seen through a viewing port on the chamber. When the ParTI array is in the chamber, however, the wedge viewer must be removed in order for ParTI to fit and the array occludes the viewing port such that the target ladder and everything upstream of it cannot be seen. In order to focus the beam in the chamber, therefore, it was necessary to put cameras inside the vacuum chamber.

Two model MC900 miniature (9.5 mm x 9.5 mm x 12 mm) 520 TVL CMOS cameras were installed directly downstream of the target position using the partial target ladder beneath the Faraday cup mount. Custom aluminum brackets were made so that the cameras could be attached to ball-and-socket assemblies that would allow the cameras to be positioned and aimed. The cameras were aimed back toward the target ladder to view a phosphor target. Copper tape was used to secure the cameras in the brackets and to thermally connect them to the aluminum to act as a heat sink. A halogen lamp was also installed on the camera mounting apparatus which could be turned on so that the inside of the chamber could be viewed when dark cloths were over the view ports. Power for the cameras and their video signals were transported through BNC connections on the cube vacuum chamber.

The cameras remained out of the beam as much as possible during the pionic fusion experiment and were only powered during beam tuning and troubleshooting. Even so, by the end of the exper-
Figure 2.11: A photograph of one of the miniature cameras which was mounted in the MARS target chamber to make tuning the beam onto the target position possible.

iment, degradation in the video quality from the cameras indicated that they had experienced some combination of radiation damage and overheating in vacuum. Figure 2.11 shows a photograph of one of the mini cameras used in the experiment.

2.4.4 The Target Heating Apparatus

The measurement of fusion residues to identify pionic fusion reactions is a very powerful technique because, given a fused system with $\geq 140$ MeV of excitation energy, there are only two reaction mechanisms which can result in a residue that has the same number of nucleons as the colliding system - pionic fusion or radiative capture (for residues that have the same charge as the reacting system). The major source of background for pionic fusion residues, therefore, is from reactions on heavier contaminants in the target or other materials in the beamline. In the case of the carbon foil used in this experiment, one of the largest contaminants in the target is oxygen from water that gets adsorbed on the surface of the foil. In order to minimize this background, the carbon target was heated under vacuum at approximately 125°C.

In order to heat the target ladder, two Athalon JC-type halogen lamps were slotted into an aluminum holder which was bolted onto the bottom of the ladder. Figure 2.12 shows a photograph of the aluminum holder attached to the target ladder with the lamps inside.
Figure 2.12: A photograph of the target heating lamps inside their aluminum holder bolted to the target ladder. This heating apparatus was used to heat the carbon targets for the pionic fusion experiment to reduce oxygen contamination due to water adsorbed on the foil’s surface.
While the lamps are operating under vacuum, the heat they produce is transferred to the target ladder through the aluminum holder. Voltage was applied to power the lamps using a Topward 6302D dual DC power supply. The voltage was varied between 6 V and 11 V to keep the temperature on the target ladder between 120°C and 130°C for 27 hours leading up to the pionic fusion experiment. While the lamps were heating the targets, a temperature probe was used to monitor the temperature on the ladder. A ring-type resistance temperature detector (RTD) was attached to the ladder next to the carbon target position. A Future Design Controls model FDC-C91 temperature controller was used to make the temperature reading. Both the probe and the controller were purchased from Dan Cox and Associates/ADI Instruments [54]. Macor ceramic was used to make a target frame on which the phosphor was mounted in order to thermally insulate it from the rest of the target ladder during heating.

2.5 Pionic Fusion Electronics

In this section I will discuss the hardware electronics, the signal logic, and triggering scheme implemented in the pionic fusion experiment. In Section 2.5.1, I will give the specifications for the Struck Innovative Systeme SIS3316 fast-sampling digitizer. In Section 2.5.2 I will discuss the signal paths and trigger logic implemented for the silicon stack at the MARS focal plane. In Section 2.5.3 I will describe the electronics, signal paths, and trigger logic implemented for the ParTI array. In Section 2.5.4, the signals from the arbitrary waveform generator, 50 Hz pulser and target chamber Faraday cup are discussed. Lastly, in Section 2.5.5 the trigger logic for the pionic fusion experiment and triggering capabilities are reported.

2.5.1 The SIS3316 Fast-Sampling Digitizer and the "Muon Decay Trigger"

The Struck Innovative Systeme SIS3316 is a VME fast-sampling digitizer with a programmable on-board FPGA [55]. Using its standard firmware, the SIS3316 is capable of performing the job of various analog electronics including ADCs, QDCs, TDCs, discriminators, shaping amplifiers, and signal logic units. Firmware can also be developed for the FPGA which gives the SIS3316 the potential to perform very specific, complicated functions. It’s versatility greatly simplified the
hardware electronics setup for the pionic fusion experiment and a “muon decay trigger” implemented in the firmware was instrumental in increasing the sensitivity of the ParTI phoswiches to charged pions.

The muon decay trigger is a modified version of a pile-up triggering functionality developed by a collaboration between Struck Innovative Systeme and the Cyclotron Institute (primarily Dr. Sara Wuenschel). When charged pions implant into the detectors, they will decay into charged muons with a mean lifetime of approximately 26 ns. Subsequently, the muon daughters of the pions will decay into electrons with a mean lifetime of 2.2 $\mu$s. Those electrons will deposit energy in the phoswiches which will create a characteristic pulse following the initial implantation pulse. The muon lifetime is long enough and the kinetic energy distribution of the decay electrons (peaked around 50 MeV [56]) is large enough that these second pulses can be separated from the implantation. By implementing the muon decay trigger functionality, the digitizer will produce a trigger if the internal CFD goes above threshold twice in a single digitization window.

The importance of the muon decay trigger lies in the reduction of the number of background events recorded. While beam is on target, the MARS target chamber is full of reaction products that are uninteresting in the context of measuring pionic fusion reactions. Even with the ParTI array positioned in the backward hemisphere with respect to the target, the large majority of incident radiation on the ParTI phoswiches is background. If one indiscriminately recorded events for every phoswich response the data acquisition system would be overwhelmed and the experimental live time would suffer significantly enough that a high sensitivity measurement would not be possible. By utilizing the muon decay trigger it is possible to selectively record events that have a characteristically pion-like second pulse following the implantation. The trigger was characterized in an experiment at the Paul Scherrer Institute (PSI) which will be discussed more in Section 4.3.

The detector responses for each of the 12 ParTI phoswiches were recorded using one SIS3316 module. The CFD pulse from the MARS silicon stack was also digitized in a second SIS3316 unit. Using the digitized phoswich waveforms, pulse shape analysis can be performed in order to obtain particle identification for light charged particles in the ParTI phoswiches. The two digitizers (the
one recording ParTI phoswich data and the one recording the MARS CFD pulse) are time synced such that relative timing between the two can be used to determine whether or not signals recorded at the MARS focal plane come from the same event as signals recorded in the ParTI phoswiches located in the MARS target chamber. The timing and event characterization between data collected at the MARS focal plane and in the ParTI array will be discussed in detail in Section 5.4. Table 2.3 reports the important SIS3316 settings used in the phoswich digitizer in the pionic fusion experiment.

### 2.5.2 MARS Silicon Stack Electronics

The silicon stack detector system at the focal plane of MARS consists of two silicon detector devices arranged back-to-back. The first, $\Delta E$ detector is a $5 \text{ cm} \times 5 \text{ cm}$ 16-strip detector. Each of the 16 strips is resistive along its length to provide position sensitivity along the direction of the strips as described in section 2.2.1. Only the middle 14 strips were used in the pionic fusion experiment and each strip produced 1 channel of data. The back plane of the $\Delta E$ detector and the second, $E$ detector also produced 1 channel each for a total of 16 channels of data associated with the silicon stack.

Each of the 14 strip signals was transported from the $\Delta E$ detector to the MARS detector chamber flange over a 34-pin header-to-LEMO “medusa” cable assembly. From the chamber, each signal went into one of the in-house pre-amplifiers permanently housed in the MARS focal plane electronics rack, then to a Caen 568 spectroscopy amplifier/shaper. From there, the shaped signals were sent into a Mesytec MADC-32 VME acquisition module to be read into the data stream. At every step in the path the signal was transported using coaxial cable. Figure 2.13 shows the path of each of the strip signals.
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<tr>
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<tr>
<td>SetInternalGate2Mask</td>
<td>0</td>
</tr>
<tr>
<td>EnableTrigger</td>
<td>false</td>
</tr>
<tr>
<td>SetExternalTrigger</td>
<td>true (from MARS)</td>
</tr>
<tr>
<td>SetExternalVeto</td>
<td>true</td>
</tr>
<tr>
<td>SetInternalFeedback</td>
<td>false</td>
</tr>
<tr>
<td>EnableHighEnergySuppress</td>
<td>false</td>
</tr>
<tr>
<td>SetPeakVal</td>
<td>9</td>
</tr>
<tr>
<td>SetGapVal</td>
<td>15</td>
</tr>
<tr>
<td>SetTau</td>
<td>3, 63</td>
</tr>
<tr>
<td>SetPreTriggerDelay</td>
<td>2000 bins (8 μs)</td>
</tr>
<tr>
<td>SetTriggerGateWindowLength</td>
<td>4000 bins (16 μs)</td>
</tr>
<tr>
<td>SetSampleLength</td>
<td>4000 bins (16 μs)</td>
</tr>
<tr>
<td>SetLemoOutTriggerEnableMask</td>
<td>0xffff</td>
</tr>
<tr>
<td>Input Range</td>
<td>-5 V - 0 V</td>
</tr>
<tr>
<td>Channel Thresholds</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 2.3: Firmware settings for the ParTI phoswich SIS3316 digitizer during production runs in the pionic fusion experiment as they were set in the frontend code.

The signal from the back plane of the ΔE silicon was recorded and also used to track the hit rate on the silicon stack at the MARS focal plane. The signal was transported out of the chamber on the same cable assembly as the 14 strip signals. Outside the chamber, the signal was amplified in one of the in-house pre-amplifiers, and then shaped and amplified with a Caen 568 Spectroscopy Amplifier. From the 568, the signal went to the Mesytec ADC. The fast output from the 568
amplifier for the back plane channel was discriminated using a constant fraction discriminator (CFD) and the discriminated signal was read into the data stream using two SIS3820 scalers, one raw and one inhibited using the computer veto. Figure 2.14 shows the path of the \( \Delta E \) back plane signal and the signal logic it produces. Coaxial cable was used to transport the signals over the whole path.

The signal from the E silicon was recorded in the data stream and also used in the triggering logic. From the detector, the signal was transported to the chamber flange on an independent coaxial cable with a LEMO connection. From the chamber, the signal followed the same path (pre-amplifier, amplifier, ADC) as the other data signals discussed above. Unlike the other signals, the E signal is split at the output of the pre-amplifier. This second signal is amplified in an Ortec 454 timing filter amplifier before entering a channel in the MARS SIS3316 digitizer where it is recorded for timing relative to the ParTI SIS3316. The standard internal CFD trigger is used for the channel. The trigger out of the digitizer is used in the master trigger logic which will be discussed in Section 2.5.5. The "User Input" (UI) LEMO input on the digitizer is used to deliver the external computer busy veto. As before, the signal is transported over coaxial cable throughout the process. Figure 2.15 shows the electronics path for the split E signals.
2.5.3 ParTI Array Electronics

The second major detector component of the pionic fusion experiment is the ParTI phoswich array located in the MARS target chamber. Each phoswich is read out using a Hamamatsu R-1924a photomultiplier tube (PMT). Each PMT is powered by its own channel from a Wiener PMT bias supply module. The bias voltage from the Wiener module was delivered to active base boards that were developed at the Cyclotron Institute for use with the same model PMTs in the NIMROD array [11]. These active base boards divided the -1250 V from the power supply into the appropriate proportions which were delivered to the cathode and dynodes of each PMTs. A circuit diagram for one channel of the active base boards is shown in Figure 2.16 and the values for each labeled component are listed in Table 2.4. A photograph of one of the active base boards is shown in Figure 2.17.

The PMT signal is collected from the anode pin. It is resistively coupled to ground through a 9 MΩ resistor in order to set the voltage baseline. The anode signal from the PMT is connected to a LEMO feedthrough on the chamber wall. From the chamber, the signal goes directly into
<table>
<thead>
<tr>
<th>Component Type</th>
<th>Component Label</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistor</td>
<td>R1</td>
<td>887 kΩ</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>220 kΩ</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>287 kΩ</td>
</tr>
<tr>
<td></td>
<td>R4</td>
<td>220 kΩ</td>
</tr>
<tr>
<td></td>
<td>R5</td>
<td>220 kΩ</td>
</tr>
<tr>
<td></td>
<td>R6</td>
<td>220 kΩ</td>
</tr>
<tr>
<td></td>
<td>R7</td>
<td>287 kΩ</td>
</tr>
<tr>
<td></td>
<td>R8</td>
<td>4530 nF</td>
</tr>
<tr>
<td></td>
<td>R9</td>
<td>4530 nF</td>
</tr>
<tr>
<td></td>
<td>R10</td>
<td>8450 nF</td>
</tr>
<tr>
<td></td>
<td>R11</td>
<td>8450 nF</td>
</tr>
<tr>
<td></td>
<td>Big</td>
<td>22000 nF</td>
</tr>
<tr>
<td>Capacitor</td>
<td>C1</td>
<td>47 nF</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>47 nF</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>47 nF</td>
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<tr>
<td></td>
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<td>1 nF</td>
</tr>
<tr>
<td></td>
<td>C5</td>
<td>1 nF</td>
</tr>
<tr>
<td></td>
<td>C6</td>
<td>47 nF</td>
</tr>
<tr>
<td></td>
<td>C7</td>
<td>47 nF</td>
</tr>
<tr>
<td></td>
<td>C8</td>
<td>1 nF</td>
</tr>
<tr>
<td></td>
<td>C9</td>
<td>47 nF</td>
</tr>
<tr>
<td></td>
<td>C10</td>
<td>0.1 µF</td>
</tr>
<tr>
<td>Power Supply Cable</td>
<td>X2</td>
<td>Power Supply Ground</td>
</tr>
<tr>
<td></td>
<td>X3</td>
<td>High Voltage</td>
</tr>
</tbody>
</table>

Table 2.4: Values for the circuit components for 1 channel of the active base boards for the R1924a PMTs.
Figure 2.16: Circuit diagram for the active base voltage divider used with the R-1924a Hamamatsu PMTs. These boards were developed at the Cyclotron Institute for use in the NIMROD array [11] and are ideally suited for use with the ParTI phoswiches. The component values are listed in Table 2.4.

the ParTI SIS3316 digitizer module. Information about the firmware settings for this digitizer was discussed in Section 2.5.1. The digitizer records the phoswich data and generates the trigger for the ParTI array using the muon decay trigger function. The trigger out (TO) from the MARS 3316 digitizer is routed into the trigger input (TI) for the ParTI 3316 so that the phoswiches are recorded whenever a residue is detected at the MARS focal plane. Like the MARS digitizer, the user input (UI) is used to veto the module using the computer busy. The electronics path for the phoswich signals is shown in Figure 2.18. The trigger out from the ParTI digitizer is used in the master trigger logic and will be discussed later in this chapter.

2.5.4 Arbitrary Waveform Generator, 50 Hz Pulser, and Faraday Cup Electronics

Besides the two major detector systems, there are 3 other signals that are being recorded in the data stream. The first of these was being generated by an Astronics model WX1282B arbitrary waveform generator (AWG) which is being used to create pion event-like waveform pulses. These pulses were being delivered to one channel of the ParTI SIS3316 digitizer at 3 Hz to be recorded.
The signals were also being discriminated and counted in the two (raw and live) SIS3820 scalers. The utility of the AWG was twofold. First, it provided a constant test of the muon decay trigger during the experiment. Second, by pulsing both the raw and live scalers the AWG provided a measure of the livetime in the experiment. The electronics diagram for the path of the AWG signals is shown in Figure 2.19. Logic pulses at 50 Hz were also used to provide a better measure of the live time during the experiment. Like the discriminated AWG pulses, the logic pulses were counted in the raw and live scalers.

The last signal source from the pionic fusion experiment is the Faraday cup which was mounted in the MARS target chamber just downstream of the target position. This cup was periodically inserted into the beam in order to get measurements of the beam intensity at the target position. The signal from the cup was transported out of the chamber through a BNC connector. Out of the chamber, the signal went directly into one of the Brookhaven Instruments Corporation current integrators. The logic output of the current integrator was counted in the raw and live scalers.
2.5.5 Master Trigger Logic

Because the pionic fusion experiment utilizes two very different detector systems with two very different triggering requirements, there are multiple possibilities for event triggering and the trigger logic must be designed such that the experiment is sensitive to all of them. The two trigger sources are the two SIS3316 digitizers (one for MARS and one for ParTI).

The trigger out from the MARS digitizer is duplicated in a fan-in/fan-out (FIFO) NIM module. One of the signals goes to a raw scaler and another goes to an inhibited scaler (both SIS3820 VME modules). Another signal goes to a Caen V259 VME bit register. A fourth duplicated signal goes to a Phillips Scientific 4-fold logic module where it is OR’ed with the ParTI digitizer trigger out in order to make the master trigger. The last MARS trigger copy is routed into the trigger input of the ParTI SIS3316 digitizer. This allows the ParTI array to be recorded whenever a particle is detected at the MARS focal plane. The trigger out from the ParTI digitizer is also duplicated in a FIFO. Again, two signals go to the two scalers, one signal goes to the bit register, and one signal goes to the logic module to be OR’ed with the MARS trigger.

The logic module output of the OR’ed combination of the two digitizer triggers creates the master trigger. One signal goes to a Lecroy 222 dual gate generator where it is used to make a 9

Figure 2.18: The electronics path for each phoswich signal and the beginning of the ParTI phoswich component of the master logic. The trigger out from the MARS digitizer is routed into the trigger in (TI) of the ParTI digitizer so that the phoswiches are read out when a residue is detected at the MARS focal plane.
\( \mu s \) gate which is fed into a SIS3100 VME controller to trigger the computer. The trigger for this controller type must be longer than the time between computer queries, 8 \( \mu s \), or there is a chance that the event will be missed. The busy signal from the controller is duplicated in a logic FIFO. Another master trigger copy is sent to each of the two scalers and a master trigger is sent to another logic unit channel where it is AND\('ed\) with the \( \overline{OUT} \) from the computer busy FIFO to make the starts for the ADC and bit register gates. The other outputs from the computer busy FIFO go to the UI inputs on both of the digitizers and to the live scaler to provide the vetoes.

An output from the ADC/bit register gate trigger is used to start a gate using a Lecroy 222 dual gate generator which was sent to the Mesytec ADC. A second output was used to start a gate using an Ortec 416 gate and delay generator which was sent to the bit register. An electronics diagram mapping all of the trigger logic paths is shown in Figure 2.20.

By configuring the trigger logic in the way described in Figure 2.20 and by centering the trigger location inside the time window of the ParTI SIS3316 using the pre-trigger delay, the pionic fusion experiment is sensitive to all of the event detection cases for a pionic fusion event. In the first case, a charged pion implants in one of the phoswiches and its decay triggers the muon decay trigger, but
the residue is not detected at the MARS focal plane. In the ParTI SIS3316 the trigger location (the decay pulse) is centered in the time window and the preceding 8 $\mu$s of the window are available to record the prior implantation. In this case, an unnecessary gate is delivered to the Mesytec ADC which will see only baseline. Conversely, in the case that the charged pion is missed but the pionic fusion residue is detected at the MARS focal plane, a gate is provided to the Mesytec ADC which will record the silicon stack response and all of the ParTI phoswiches will be recorded. The trigger for the phoswiches in this case will come after any particle implantations corresponding to the same event as the residue in MARS. Again, though, the pre-trigger delay ensures that even those implantation responses will be recorded.

In the case that a coincident measurement is made, the charged pion is detected in a phoswich and a trigger is produced. The pion implantation is recorded in the pre-trigger delay and an ADC gate is delivered to the Mesytec ADC early since the residue flight time through MARS (approximately 800 ns) is much longer than the pion flight time from target to phoswich. The ADC gate, however, is 10 $\mu$s wide which is more than long enough to catch the silicon stack response peaks even when they are delayed by many hundreds of nanoseconds.

It is also possible to have the case where a charged pion implants in a ParTI phoswich but does not pass the conditions of the muon decay trigger (the decay happens before the internal CFD can reset, the decay peak is too small, the decay is longer than the flight time of the residue through MARS, etc.) and the event is triggered by the pionic fusion residue at the MARS focal plane. In such a case, the Mesytec ADC will be provided with an appropriate gate and all of the ParTI phoswiches will be recorded. The response from the implantation from the pion event will have begun before the trigger arrived and will be recorded in the pre-trigger delay region of the digitizer window. The pulse from the muon decay (which did not fire the muon decay trigger) can come any time in the digitization window after the implantation (> 8 $\mu$s).

While the multitude of different detection cases can vary the position of the detector responses in relation to their respective gates and digitization windows in complicated ways, the pionic fusion experiment was sensitive in all cases. The bit register data was used to sort out detection classi-
fications event-by-event. This is particularly important for events with data in the MARS silicon stack and in the ParTI array as proper timing can only be achieved if the relative time between the trigger and the detector response can be accounted for.
Figure 2.20: The electronics diagram for the pionic fusion experiment trigger logic.
3. SIMULATIONS AND MODELS

This section will describe the simulation and modeling efforts made over the course of the pionic fusion project. In Section 3.1, the Geant4 [57] simulation of the ParTI phoswiches will be discussed. In Section 3.2, a Gemini [58] simulation of the excited $^{16}$O compound nuclei is described. This will be used to compare the residue results with the measured cross sections at the MARS focal plane. In Section 3.3, a Monte Carlo model for the pionic fusion final states is described. This code was used to inform many aspects of the pionic fusion experiment including to predict the effects of the energy loss of residues in the target, determine the geometrical efficiency of the ParTI array, and determine the angular efficiency and distribution of pionic fusion residues entering MARS. Lastly, in Section 3.4, a theoretical attempt to predict the pionic fusion cross section is described.

3.1 The Geant4 Phoswich Simulation

Before the ParTI phoswiches were constructed, their proposed designs were simulated using the Geant4 particle-through-matter interaction software [57]. These simulations were used to inform the construction of the detectors components, the thicknesses of those components and the geometries. Most importantly, though, the Geant4 simulations were able to characterize the charged pion identification capabilities of the phoswiches. In this chapter, the simulation will be discussed and the predicted phoswich pion detection capabilities will be reported.

Prior to constructing any physical phoswiches, Geant4 simulations were used to determine the optimal material components. Various scintillating plastics and inorganic scintillators (including CsI(Tl), NaI(Tl), and CaF$_2$(Eu)) were considered for the 2 components. Ultimately, EJ-212 scintillating plastic and CsI(Tl) were the two chosen components due to a combination of their desired scintillation characteristics, cost, and ease to work with. See Section 2.3.1 for a detailed description of the detector construction. Only the Geant4 simulation for this final iteration of phoswiches will be detailed in this section.
Table 3.1 notes all of the physics processes implemented by the simulation and for which particle types they apply. Table 3.2 reports all of the important phoswich material characteristics used in the simulation. Citations are provided for values where applicable.

The two most prominent scintillation components in CsI(Tl) are used in the simulation - a faster component with a decay time of 600 ns and a slower component with a decay time of 1000 ns [59]. Unfortunately, Eljen Technology has not calculated optical parameters for their EJ-212 scintillating plastic. For the purposes of the Geant4 simulation, then, the parameters for BC400 scintillating plastic from Saint-Gobain were used instead. Polished dielectric metal exterior surfaces were used to simulate the effects of the reflective wrapping on the crystals and the light guide.

The geometric construction of the Geant4 phoswich is identical to the physical construction of the hexagonal geometry which is described in detail in Section 2.3.1. Figure 3.1 shows the geometrical construction of the Geant phoswich inside the Geant environment. In front (the farthest left in the figure) is the thin EJ-212 plastic component followed by the thicker CsI(Tl) crystal followed by the light guide and ending in the cylindrical photomultiplier tube (PMT).

In each Geant phoswich event a single particle is fired into the front face of the simulated phoswich. The identity of the particle was selected at random from 10 possible species: neutron, $\gamma$, proton, deuteron, triton, $^3$He, $^6$Li, $\alpha$, $\pi^+$, $\pi^-$. The energies of the particles in the Geant4 simulation were also randomized over reasonable ranges based on the particle type and the scintillator thicknesses. The angle of trajectory with respect to the face of the detector was also randomized on an event-by-event basis with a maximum simulated angle corresponding to the distance from the center of the phoswich to the corners. This accounts for the range of possible energy losses due to the different effective thicknesses of the phoswich components as a function of incident angle.

After entering the detector material, the particles deposit energy and the scintillators produce photons according to the Geant4 physics processes listed in Table 3.1. If a photon arrives at the front surface of the PMT, it is counted and its time of arrival is recorded. The time spectrum of these collected photons creates the simulated waveform response, an example of which is shown in Figure 3.2 for an $\alpha$ primary event. The vertical axis is the number of photons collected and the
Figure 3.1: The geometrical construction of the Geant4 phoswich inside the simulation environment viewed from the side. Particles enter the detector from the left.
<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Physics Processes</th>
</tr>
</thead>
</table>
| $\gamma$     | G4PhotoElectricEffect  
|              | G4ComptonScattering  
|              | G4GammaConversion    
|              | G4GammaConversionToMuons |
| e$^-$        | G4MultipleScattering  
|              | G4eIonisation        
|              | G4eBremsstrahlung    |
| e$^+$        | G4MultipleScattering  
|              | G4eIonisation        
|              | G4eBremsstrahlung    
|              | G4ePlusAnnihilation  |
| proton       | G4NuclearStopping   
|              | G4hMultipleScattering 
|              | G4hIonisation        
|              | G4hBremsstrahlung    
|              | G4hPairProduction    |
| neutron      | G4HadronElasticProcess 
|              | G4NeutronInelasticProcess 
|              | G4HadronCaptureProcess 
|              | G4HadronFissionProcess |
| $\pi^-/\pi^+$| G4NuclearStopping   
|              | G4hMultipleScattering 
|              | G4hIonisation        
|              | G4hBremsstrahlung    
|              | G4hPairProduction    
|              | G4PionMinus(Plus)InelasticProcess 
|              | G4HadronElasticProcess |
| $\mu^+$      | G4MuMultipleScattering 
|              | G4MuIonisation       
|              | G4MuBremsstrahlung   
|              | G4MuPairProduction   |
| $\mu^-$      | G4MuMultipleScattering 
|              | G4MuIonisation       
|              | G4MuBremsstrahlung   
|              | G4MuPairProduction   
|              | G4MuonMinusCaptureAtRest |
| Generic Ion  | G4hMultipleScattering 
|              | G4ionIonisation      |

Table 3.1: All of the physics processes that were utilized within the Geant4 simulation of the ParTI phoswiches organized by the particles that they were applied to.
<table>
<thead>
<tr>
<th>Scintillators</th>
<th>EJ-212</th>
<th>CsI(Tl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Characteristic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>1.023 g/cm$^3$ [49]</td>
<td>4.51 g/cm$^3$ [59]</td>
</tr>
<tr>
<td>Birks Constant</td>
<td>0.0862 mm/MeV [60]</td>
<td>0.0071 mm/MeV [61]</td>
</tr>
<tr>
<td>Mean Excitation Energy</td>
<td>64.7 eV [62]</td>
<td>553.1 eV [63]</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>1.58 [64]</td>
<td>1.79 [59]</td>
</tr>
<tr>
<td>Absorption length</td>
<td>160 cm [64]</td>
<td>35 cm</td>
</tr>
<tr>
<td>Scintillation Yield</td>
<td>10000 photons/MeV [64]</td>
<td>54000 photons/MeV [59]</td>
</tr>
<tr>
<td>Decay Constant</td>
<td>2.4 ns [49]</td>
<td>630 ns, 1000 ns [59]</td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Guide</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td></td>
<td>1.185 g/cm$^3$</td>
</tr>
<tr>
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<td>1.4914</td>
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<tr>
<td>Exterior surfaces</td>
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</tr>
<tr>
<td>Type and finish</td>
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<td>polished dielectric metal</td>
</tr>
</tbody>
</table>

Table 3.2: The important material values used in the Geant4 simulation of the ParTI phoswiches. Citations for the values are provided where applicable. Decay times for the two most prominent scintillation components for CsI(Tl) were included, as the table suggests.

The horizontal axis is the time (in ns) since first photon arrival.

Figure 3.2 shows the regions of the fast and slow integrations overlaid on the waveform. The fast integration region is 28 ns long and encompasses the sharp peak produced by the fast plastic. The slow integration region begins 24 ns after the end of the fast region and is 400 ns wide. These pulse shape discrimination (PSD) gates are consistent with the gates used in the analysis of the data collected by the physical detectors. The two integrations can be used to produce the fast vs. slow particle identification (PID) plot shown in Figure 3.3 where the vertical axis is the integration of the implantation pulse inside the fast gate and the horizontal axis is the integration of the implantation pulse inside the slow gate. This figure contains the predicted phoswich responses to each of the 10 particle species mentioned above. The charged particles lose energy (thus producing more scintillation photons) as they pass through the plastic layer of the phoswich proportional to their mass number and their proton number squared, $Z^2$. Thus, the PID lines for the charged particles have large separations in the fast integration dimension between elemental species and much smaller separations between isotopes of the same element. The neutral particles...
Figure 3.2: An example Geant phoswich response waveform created by an incident α particle. The vertical axis is the number of photons collected and the horizontal axis is the time since first photon arrival in ns. The red shaded area shows the region of the fast integration and the green area shows the region of the slow integration.
do not deposit energy constantly as they pass through a material. Instead, these particles deposit their energy in discrete events with the detector material nuclei. In the case of $\gamma$ particles, their probability of reacting on a target nucleus increases with $Z^2$. The CsI(Tl) crystal layer is made up of much higher $Z$ nuclei than the plastic which explains why the $\gamma$ events are in the lowest fast vs. slow PID structure - they are not depositing energy in the plastic. Neutron primary events are also most likely to interact with the CsI(Tl) layer since it is considerably thicker than the plastic layer providing more potential interaction points.
The charged pion PID line (red points in Figure 3.3) contains events from both $\pi^+$ and $\pi^-$ primary events. The pion events are clearly separated from the neutron (blue) and $\gamma$ (green) events inside the neutron/$\gamma$/cosmic line below and from the proton line above. Thus, Geant4 predicts that the ParTI phoswiches will be sensitive to charged pions and capable of efficiently identifying them. Furthermore, the simulation indicates that if one records the entire phoswich response waveform, there is a second charged pion identification method that can be utilized for $\pi^+$ primary events.

After implantation in the detector material (or possibly in flight on the way to the detector), the $\pi^+$ particle with a mean lifetime of 26 ns will quickly decay into a $\mu^+ + \nu_\mu$. This 2-body decay results in 4.12 MeV of kinetic energy for the $\mu^+$, the phoswich response for which is difficult to separate from the implantation response with which it is overlapping. That $\mu^+$ is likely to have also stopped in the detector material (unless it was produced close to an outside wall of the detector) and will subsequently undergo a decay into $e^+ + \nu_e + \bar{\nu}_\mu$ with a mean lifetime of 2.2 $\mu$s. This will produce a scintillation response from the stopping of the $e^+$. Since it is a 3-body decay, the positron will have a distribution of possible kinetic energies which, for this decay, is peaked around 50 MeV [65]. These positrons have enough energy that they are likely to leave the detector before completely stopping. The energy deposited on their way out and their long mean lifetime compared to the scintillation components of the phoswich, though, make the resulting phoswich response identifiable. Figure 3.4 shows an example of one of these $\pi^+$ primary events. Unlike in the waveform in Figure 3.2, there is a second peak from the $\mu^+$ decay which is clearly visible. Using this characteristic shape of the phoswich response, then, can be a second method of identification for $\pi^+$ events. This method cannot be efficiently used to identify $\pi^-$ primary events as the capture lifetime of the $\mu^-$ on the nuclei in the detector material is much shorter than the decay lifetime [66].

3.2 Gemini Predictions for Fusion Residues at the MARS Focal Plane

MARS is being used in the pionic fusion experimental effort to separate and focus $^{16}\text{N}$ fragments from the reaction of $^4\text{He} + ^{12}\text{C}$ as they can be used to identify the pionic fusion reaction events that produces a $\pi^+$ as described in Chapter 1. Along with the pionic fusion residues, MARS
Figure 3.4: An example Geant phoswich response waveform created by an incident $\pi^+$ particle. The vertical axis is the number of photons collected and the horizontal axis is the time since first photon arrival in ns. The second pulse is the detector response to the $\mu^+$ daughter’s decay and its presence in the waveform can be used to identify the $\pi^+$ primary.
is collecting other fragments with similar magnetic rigidity, $B\rho$. With this information, cross sections can be produced for all species that can be identified. Gemini statistical deexcitation code [58] has been used to produce fragment yields which can be compared to the measured cross sections.

The Gemini code predicts compound nuclei decays by sequential binary breakups. A Monte Carlo technique is used to follow the decay chains of individual compound nuclei until a point is reached where the products are unable to decay further [67]. At each step in this process, all possible binary divisions from light particle or $\gamma$ emission through symmetric division are considered. Decay widths for the emission of light fragments are calculated using the Hauser-Feshbach formalism [68] and widths corresponding to heavier fragments are calculated using the transition state formalism of Moretto [69].

In total, 57 million $^{16}$O deexcitations each with 162 MeV of total excitation energy (the proper energy for complete fusion of the $^4$He + $^{12}$C reaction studied) were analyzed. The set of deexcitations included 8 million events each of integer spin values between $L = 0\hbar$ and $L = 7\hbar$. The $7\hbar$ spin is the maximum allowable spin for complete fusion of the system according to [70]. Some of the results of the calculation are shown in Figure 3.5.

All panels in Figure 3.5 are inclusive over all spins. Panel (a) is the event multiplicity distribution including $\gamma$ particles predicted by Gemini over all spin values. Panel (b) is the distribution of fragment mass numbers and panel (c) is the distribution of fragment proton numbers. In each of these first 3 panels, $\gamma$s are included. Panel (d) is the center of mass velocity distribution for $^7$Li fragments where the horizontal axis is in units of c. MARS will filter each particle type by magnetic rigidity, accepting only a small window of its velocity distribution for any given setting. First, though, the effect of the limited acceptance of the spectrometer will be accounted for. Each fragment velocity is returned from Gemini in the center of mass frame. Because the reactions of interest are complete fusions, each fragment is boosted into the lab frame using the center of mass velocity in the z direction. The new lab trajectory is then tested to see if it enters the 5 cm x 5 cm MARS entrance slits which are positioned 31.115 cm from the target position. The filtering effect of the MARS entrance on the $^7$Li velocity distribution is shown in Figure 3.6.
Figure 3.5: Diagnostic plots for the Gemini calculations of the statistical deexcitation of $^{16}$O. (a) The event multiplicity is the number of total fragments resulting from the deexcitation including $\gamma$ particles. (b) The distribution of fragment mass numbers resulting from the deexcitations. (c) The distribution of fragment proton numbers resulting from the deexcitations. (d) The center of mass velocity distribution of $^7$Li fragments produced by the Gemini deexcitations.
Figure 3.6: The distribution of $^7$Li lab velocities in units of c produced by the Gemini simulation after accounting for the angular acceptance of the MARS entrance.

The comparison of Figure 3.6 to Figure 3.5 (d) demonstrates the high angular selectivity of MARS. For all particles that make it into the spectrometer, their rigidities are required to be within 3\% of one of the central MARS $B_\rho$ settings where data was taken during the experiment. This rigidity acceptance of $\frac{\Delta B_\rho}{B_\rho} = 3\%$ is approximately the acceptance window found in the analysis of the MARS $B_\rho$ efficiency which will be discussed in Section 5.2.4. Figure 3.7 shows the velocity distributions for the $^7$Li fragments inside of each $B_\rho$ window.

This process of filtering the particles by their trajectories and rigidities which has been demonstrated in Figures 3.5 through 3.7 for $^7$Li was performed for each particle type identified at the back of MARS in the pionic fusion experiment. Figure 3.8 shows the yields in counts for each of these
Figure 3.7: Each figure shows the velocity distribution in units of $c$ of $^7\text{Li}$ fragments produced by Gemini that make it through the MARS entrance and the MARS $B\rho$ filters. Each panel corresponds to one of the $B\rho$ settings for MARS that was used in the pionic fusion experiment and each panel is labeled with its corresponding central $B\rho$. 
particle types for each of the rigidity settings. These yields will be compared to the experimentally measured cross sections in Section 5.2.5. It is important to note that Gemini does not predict the production of the pionic fusion residues of interest as the model does not include a mechanism for their production.

3.3 The Pionic Fusion Final State Model

In order to better understand many of the various geometrical and momentum dependent facets of the experimental setup, a Monte Carlo simulation code was written which generates final states of pionic fusion reactions. There is no treatment of the system before or during the reaction. Instead, for each event a pion is created with energy sampled from a flat distribution between 0 MeV and the energy above the pionic fusion threshold in the system, 22.24 MeV. The angle of the pion emission with respect to the beam axis, $\theta$, is randomly sampled from a $\cos^2\theta$ distribution which has been reported to be the shape of the angular distribution of pion emission in pionic fusion reactions [7]. Lastly, $\phi$ is sampled randomly from a flat distribution between 0 and $2\pi$.

Once the pion has been created, a trajectory is made for the $^{16}$N residue which conserves momentum. Both velocity vectors are then boosted into the lab frame using the center of mass velocity of the reacting system. The residue is then given a charge state either +7, +6 or +5 according to the charge state distribution predicted in LISE++ [47] (76%, 22%, and 2%, respectively). Given this information, it is possible to begin predicting the experimental parameters and determining the effects of the experimental efficiencies.

3.3.1 Residue Energy Distribution and MARS Implications

The first consideration with respect to using MARS to identify the $^{16}$N residues is the ability to separate those particles from the beam. If the residue $B_\rho$ is near the beam rigidity there will be significant contamination from beam particles at the spectrometer focal plane. This can damage detectors, swamp useful data and limit the usable beam intensity, all of which potentially limit the experimental sensitivity. Figure 3.9 shows the $B_\rho$ spectrum with the three particle types of interest shown - $\pi^+$ pionic fusion pions (black), $^{16}$N residues at the 3 different charge states (blue), and the
Figure 3.8: The yield in counts of fragments produced in the Gemini simulation. Each panel corresponds to one of the MARS $B_\rho$ settings. Only fragment types that were identified at the MARS focal plane in the pionic fusion experiment and that had a non-zero yield from Gemini are shown.
Figure 3.9: The magnetic rigidity spectrum for the three species of interest in the pionic fusion reactions. The $B\rho$ spectrum for emitted pions is shown in black, the spectrum for the $^{16}$N residues is in blue and the location of the beam rigidity is in red. The vertical axis is the yield in counts and the horizontal axis is the magnetic rigidity in T m.

$\alpha$ beam at 55 MeV/nucleon (red). The vertical axis is the yield in counts and the horizontal axis is the magnetic rigidity in T m. There is 1 pion and 1 residue created in each of the 500,000 pionic fusion events generated. The height of the $B\rho$ bin corresponding to the beam is not meaningful. From this spectrum it is clear to see that the $\alpha$ beam is well separated from all of the 3 residue charge state distributions. It is also the case that, while MARS is tuned for detecting the residues, there is no chance of also collecting the pions as the rigidity distributions are also well separated.

Focusing just on the pionic fusion residues with charge state 7+ (the most populated charge
state according to LISE++), one can examine the energy window of interest for most efficiently measuring pionic fusion. Figure 3.10 (a) shows this energy distribution. The vertical axis, again, is the yield in counts and the horizontal axis is the kinetic energy of the residue entering MARS in MeV. The double peaked phenomenon in the distribution is a result of the $\cos^2 \theta$ emission distribution of the pions. These relatively low energy nitrogen fragments, however, can lose an appreciable amount of energy as they travel through the carbon target. Furthermore, the amount of energy lost will depend on how deep into the target the fusion reaction occurs.

To explore this effect, the implementation of the Stopping and Range of Ions in Matter (SRIM) [71] code inside ROOT was used. For each event, the effective thickness of the carbon target that the residue passes through is determined randomly with a minimum thickness of 0 $\mu$g/cm$^2$ (fusion at the very downstream face of the target) to a maximum of 830 $\mu$g/cm$^2$ (fusion at the very upstream face). The thickness of 830 $\mu$g/cm$^2$ is the nominal thickness of the carbon targets. The simulation has also been run with the measured carbon target thickness of 894 $\mu$g/cm$^2$ determined in Section 5.1.1 and the results are consistent with those shown in this section. The energy lost by the $\alpha$ beam in the carbon target was not accounted for as the high energy $\alpha$’s lose a negligible amount of energy in the thin carbon foil. Figure 3.10 (b) shows the energy spectrum of the 7+ pionic fusion residues after the energy lost in the target is accounted for.

Figure 3.10 (b) was used to determine the MARS $B_\rho$ settings which were used in the pionic fusion experiment. Data was collected at 6 windows with central $B_\rho$s of 0.5363 T m, 0.554 T m, 0.5829 T m, 0.6073 T m, 0.6304 T m and 0.6657 T m. The middle 4 windows are all within the allowable energy distribution shown in Figure 3.10 (b) and the two outside windows were used to perform the background subtraction. This is discussed in more detail in Section 5.2.5.

### 3.3.2 MARS Angular Acceptance

The next experimental parameter that was determined using the final state model is the pionic fusion residue detection efficiency associated with the limited angular acceptance of MARS. The entrance of the spectrometer is a slit system directly in front of the first MARS quadrupole magnets (labeled "Slit 1" in Figure 2.1). During the pionic fusion experiment, these slits were opened to
Figure 3.10: (a) The energy distribution in the lab frame for pionic fusion residues in the 7+ charge state considering only the center of mass of the reacting system and conservation of momentum with the complementary created pion. The vertical axis is the yield in counts and the horizontal axis is the kinetic energy in MeV. (b) The energy distribution for the same set of pionic fusion residues after the energy lost in the target has been accounted for.

create a 5 cm x 5 cm opening. The trajectories of the residues produced in the final state generator can be tested to determine the likelihood that these particle will make it into MARS.

In order to make the model as close an approximation as possible, the approximate shape of the beam on the target was accounted for. This was done by changing the position where each event is generated. In the x-direction (where the beam defines the z-direction), the position was randomly sampled from a gaussian with a FWHM of 8 mm centered at 0 (the center of the 16 mm diameter carbon target). The position in the y-direction was sampled from a Gaussian distribution with a FWHM of 3 mm also centered at 0. Figure 3.11 shows the simulated shape of the beam spot used in the model.

It is also the case that the beam is not perfectly parallel as it enters the target chamber. As a result, there is some angular range of the beam particles’ trajectories with respect to the face of the target. This effect was accounted for by sampling a Gaussian distribution with a FWHM of 1.5° which was used to adjust the trajectory of the center of mass of the system. This Gaussian width was determined by the known effect of deliberately changing the angle of incidence of the beam in
Figure 3.11: The shape of the simulated beam spot on the 16 mm diameter carbon target. The position in $x$ is sampled from a Gaussian distribution with a FWHM of 8 mm and the $y$ position is sampled from a Gaussian with a FWHM of 3 mm. This beam shape is a good approximation of the experimental beam shape in the pionic fusion experiment.

MARS. There is functionality with MARS to adjust this angle with respect to the target, however, the current state of the beam line prevents the angle from being adjusted more than 1.5°. The $\phi$ angle for the center of mass of the system was also randomized between 0 and $2\pi$.

Lastly, the effects of the angular straggling of the residues in the target material was investigated. TRIM calculations were made for $^{16}$N residues across the allowable energy range passing through various thicknesses of carbon up to the full thickness. In even the most extreme case (the lowest allowable energy through the full target), though, the average angular straggling pre-
dicted by TRIM was around 0.006°. This effect is negligible with respect to the MARS angular acceptance.

After all experimental considerations were made, the resulting trajectories were tested to see if they would be inside the spectrometer entrance slits which are located 31.115 cm ± 0.3175 cm from the target position at the center of the target chamber. The angular efficiency of MARS is then defined as the fraction of total simulated residues that are accepted over the total produced. The model found that for the $^{16}\text{N}$ residues of interest, the MARS angular efficiency is 99.88% with an uncertainty of 0.01%. The uncertainty was determined using the measurement error of the distance from the target to the slits.

### 3.3.3 Geometrical Efficiency of the ParTI Array

The ParTI array was also simulated in the final state model in order to determine its geometrical characteristics. First, the corners of each of the hexagonal and pentagonal detector faces are imported into the code. There is optionality in the simulation to declare whether each detector position is populated or not which allows for multiple ParTI array configurations to be explored. Figure 3.12 shows the 3D render of the ParTI array faces in their standard configuration with the central detectors populated viewed from directly downstream. Each line is the edge of a detector’s active area. The space between the faces is the aluminum framework. In the simulation, the central detector face with the hole to allow the beam through is a single active area while, in actuality, it is made up of 3 partial hexagonal phoswiches as described in Section 2.3.1. In order to account for the reduced active area due to the aluminum framing within that cell, the probability of that detector recording a hit within its active area is reduced by 6.79%. This corresponds to the fraction of the area in the physical detector that is occupied by aluminum. In order to account for the hole in the central face, all particles within that angular range are automatically counted as missed.

On an event-by-event basis, the emitted pions are boosted into the lab frame and their trajectories are analyzed to determine if they will strike one of the ParTI phoswiches. The intersection point of the pion trajectory with the plane defined by each detector face is found. Then, for a hexagonal phoswich, 6 triangles (5 for a pentagonal phoswich) are defined each having 1 vertex.
Figure 3.12: A 3D render of the faces of the ParTI array phoswiches for the ParTI array in its normal configuration with the central face populated. The view is from the perspective of the target looking directly upstream.
Figure 3.13: (a) An example of a pion hitting a hexagonal phoswich where the intersection of the pion’s trajectory and the plane of the detector face is shown as the blue point and the green lines are drawn from each detector corner to the intersection point. (b) An example of a miss where, again, the intersection point is shown as a blue point and the red lines are drawn from each detector corner to it.

as the intersection point with the plane and the other two vertices as each permutation of adjacent corners of the detector. Heron’s formula for calculating the area of a triangle given the length of its sides is used to determine the areas of the 6 (or 5, for pentagonal detectors) triangles. The sum of all of the triangle areas is then calculated and compared to the area of the face of the detector. If the sum of the triangle areas is consistent with the area of the detector face, then the particle intersected the detector’s plane within its active area - that detector was hit. If the sum of the triangle areas is larger than the area of the detector face then the pion missed that detector and the process repeats for the next detector in the array. Figure 3.13 (a) shows an example of a particle that hits a hexagonal detector and (b) shows an example of a miss on that detector. In both cases the calculated lines that make the generated triangles are shown.

With the ParTI detector faces implemented in the final state model a few of the array characteristics can be determined. First, an isotropic distribution of trajectories was generated and filtered
using the process described above in order to determine the solid angle coverage of the normal configuration of the ParTI array. This was found to be 20% of $4\pi$. Next, the trajectories of the final state pions were filtered in order to determine the geometrical efficiency for pionic fusion events. This was found to be 21.6%. During the pionic fusion experiment, the 3 phoswiches which fill the central detector frame were removed in order to facilitate beam tuning. This reduced the solid angle coverage to 18.4% of $4\pi$ and the pion detection efficiency to 13.2%. Figure 3.14 shows the 3D render of the ParTI array with the center detectors installed with the pion hit pattern for each detector included following a 500,000 event simulation.

3.4 Statistical Model for Pionic Fusion through Pion Emission from a Compound Nucleus

In Chapter 1, a general overview of the history of the effort to model deeply subthreshold pion production processes and predict cross sections was presented. Many early efforts employed entirely statistical methods using Fermi Gas Model approximations of nuclei in an attempt to reproduce available data. One of these attempts was quite successful in reproducing inclusive pion production production results [37, 35]. In this case, the creation of the pion is entirely statistical and it is governed only by the available phase space. This same methodology will be applied to the $^4$He + $^{12}$C → $^{16}$N + $\pi^+$ reaction to predict pion production cross sections which can be compared with the results of the experiment in Chapter 5.

The foundation of the analysis in ref. [37] is statistical emission according to Weisskopf systems [72]. The probability per unit time of a nucleus, $A$, with $E_A$ excitation energy emitting a particle with mass $m$ and kinetic energy $e$ is given by Equation 3.1.

$$W_{if}(e)de = \frac{\rho(U)}{\rho(E)} \left[ (2S + 1) \frac{m}{\pi^2} \right] \sigma_{fi}(e)ede$$  (3.1)

Here, $\rho(U)$ is the level density of the residue after the evaporation, $\rho(E)$ is the level density of the compound nucleus, $S$ is the intrinsic particle spin, and $\sigma_{fi}$ is the inverse cross section for the formation of the compound nucleus. The level densities of the compound and residual nuclei are calculated using the entropy for each case as $\rho(U) = exp(S_{residue})$ and $\rho(E) = exp(S_{CN})$. The
Figure 3.14: The same 3D render of the faces of the ParTI array phoswiches from Figure 3.12 with the pion hit patterns for each detector included.
entropy per nucleon in the two systems is calculated with the density fixed at 0.15 nucleons/fm$^3$ and using the parameterization in Equation 3.2 [72].

\[ S/N = (aE/N)^{1/2} + b \]  

(3.2)

where

\[ a = 0.188, \quad b = 0.238, \quad \text{For } 8.75 \leq E/N \text{ [MeV]} \]

\[ a = 0.240, \quad b = 0.063, \quad \text{For } 3 \leq E/N < 8.75 \text{ [MeV]} \]

\[ a = 0.256, \quad b = 0.039, \quad \text{For } 0.5 \leq E/N < 3 \text{ [MeV]} \]

The inverse cross sections for the creation of the compound nuclei were calculated as geometrical cross sections in the cases of the proton, neutron, and alpha emissions. In the cases of the pion emissions, since the absorption is not geometric due to the large wavelength of the pion, the inverse cross sections were calculated using the parameterization given in Equation 3.3. Here, $\Gamma = 160$ MeV and describes the width of the $\Delta$ resonance and $E_0$ is the rest mass of the pion being emitted.

\[ \sigma = \frac{a (\Gamma/2)}{(E - E_0)^2 + (\Gamma/2)^2} \]  

(3.3)

The term $a$ is a fit parameter which is obtained from pion-nucleus interaction data from ref. [12]. This paper gives $\pi^+$ reaction cross sections on Li, C, Al, and Fe nuclei at various energies. For each of the target nuclei, the differential cross sections are fit with Equation 3.3 and the value of $a$ is extracted. Then, $a$ is parameterized as a function of the mass number of the target nucleus in order to determine the value of $a$ for the case of interest, $A = 16$. Figure 3.15 shows the $\pi^+$-nucleus interaction differential cross sections for 4 different target nuclei. The horizontal axis is the kinetic energy of the pion and the vertical axis is the differential cross section in mb. The red curves are fits to the 4 sets of data using the form of Equation 3.3. This parameterization of the interaction cross section is only doing a fair job of reproducing the measured data. For the purposes of this calculation, though, this first-order approximation of the cross sections is sufficient and has been
Figure 3.15: The data from ref. [12] for pion interaction cross sections on Li, C, Al, and Fe targets with fits of the form of Equation 3.3 overlaid in red. The vertical axis is the differential cross section in mb and the horizontal axis is the pion kinetic energy.

used successfully. Indeed, extraction of the $a$ parameter from the carbon target data returns the same reported value in ref. [37], 285 mb. Figure 3.16 shows the result of the $a$ parameterization. The vertical axis is the extracted value of $a$ in mb and the horizontal axis is the mass number of the target nucleus. A second order polynomial fit to the data is shown overlaid on the figure. Using this fit, the value of $a$ for $A = 16$ is found to be 355 mb.

Now, for every energy, $e$, from 0 to the total excitation energy the decay rates for protons, neutrons, alphas, $\pi^+$, $\pi^-$, and $\pi^0$ are calculated. The reaction Q-values are accounted for in the determination of the total excitation energy of the compound nucleus in each case. Figure 3.17
Figure 3.16: The parameterization of the value $a$ from Equation 3.3 from fitting the data in ref. [12]. The vertical axis is the extracted $a$ values for 4 target nuclei whose identities are noted next to each point and the horizontal axis is the mass number of the target nuclei. The red curve is a second order fit to the data.
Figure 3.17: The differential decay rates calculated for protons, neutrons, alphas, and the three pion channels using Equation 3.1. The vertical axis is the calculated decay rate and the horizontal axis is the kinetic energy of the emitted particle in MeV.

shows the differential decay rates calculated for each particle type as a function of their kinetic energies. Notice that the range of possible kinetic energies for the pion channels is much lower than the ranges for the nucleon and alpha channels. This truncation is the consequence of the available energy needing to account for the pion mass before kinetic energy is imparted to the particle. The decay rates for protons and neutrons are nearly identical.

The differential decay rates calculated in Equation 3.1 can then be used to predict the differential cross sections for each particle emission using Equation 3.4.
\[ d\sigma/d\epsilon = \sigma_0 \frac{\sum_j W_{ij}(\epsilon)}{\int W_{ij}(\epsilon_j) d\epsilon_j} \quad (3.4) \]

For a given particle emission at a given energy, then, the cross section is ratio of its production rate to the summed rate of all other emission possibilities and then scaled by \( \sigma_0 \) which is the cross section to form a compound nucleus in the entrance channel. For the case of the reaction being measured, \( \sigma_0 \) was calculated using the summation of partial waves up to the maximum angular momentum for fusion in the system, \( 7\hbar \) [70]. Equations 3.5 and 3.6 show how this summation was performed where \( l \) is the angular momentum, \( \lambda \) is the reduced wavelength, \( E_k \) is the kinetic energy of the projectile, and \( T_l \) takes the value 1 for \( l = 0 - 7 \) and the value 0 for all other angular momenta. This calculation results in a cross section for compound nucleus formation in the reaction of interest of 46.1 mb. Figure 3.18 shows the predicted differential cross sections for each considered particle type as a function of its kinetic energy.

\[ \sigma = \pi \lambda^2 \sum_{l=0}^{\infty} (2l + 1) T_l \quad (3.5) \]

\[ \lambda = \frac{\hbar c}{[E_k (E_k + 2m_0c^2)]^{1/2}} \quad (3.6) \]

The cross sections shown in Figure 3.18 only include the first stage of deexcitation. These proton, neutron and alpha results can be compared to the results of the Gemini simulation described in Section 3.2 as a check for consistency. Only the Gemini simulations with 0 spin will be used for the comparison since no spin is included in the statistical model. The differential cross sections are calculated from the Gemini results using equation 3.7. The value of \( \sigma_0 \) is the same cross section for the production of the compound nucleus in Equation 3.4, \( N_i(\epsilon) \) is the yield of particle \( i \) with energy between \( \epsilon \) and \( \epsilon + d\epsilon \), and \( N_{\text{events}} \) is the number of simulated events.

\[ d\sigma/d\epsilon = \frac{\sigma_0 N_i(\epsilon)}{N_{\text{events}}} \quad (3.7) \]
Figure 3.18: The differential cross sections calculated for protons, neutrons, alphas, and the three pion channels using Equation 3.4. The vertical axis is the calculated cross section and the horizontal axis is the kinetic energy of the emitted particle in MeV.
Figure 3.19 shows this comparison of the statistical model (full circles) and Gemini results (histograms). The difference between the two types of results can largely be attributed to two contributing factors. First, the Gemini results are inclusive over all stages of the compound nucleus deexcitation where this statistical model only considers the first deexcitation. Simulating the total deexcitation significantly increases the cross section for the production of low energy particles as the highly excited compound nuclei will almost certainly deexcite through a chain of lower energy emissions. Second, the deviation in the slope of the tails of the distributions is a result of the different assumptions made in the models with respect to densities of states. For a given excitation energy, then, the corresponding temperature will vary between the Gemini and Fermi Gas Model frameworks. A third, smaller, factor in the differing cross section predictions is the fact that the Gemini simulation has many more deexcitation channels than just the proton, neutron, and alpha channels used in the above analysis (the pion channels, in this respect, are negligible). Given these known differences, the cross sections predicted by the two models are consistent enough to verify the general utility of the statistical model.

By integrating over the range of possible pion kinetic energies, the total predicted pion cross sections are calculated for each pion channel. According to the statistical model, then, the predicted cross sections for the subthreshold production of $\pi^+$, $\pi^-$, and $\pi^0$ are 40.6 pb, 13.3 pb, and 627.7 pb, respectively. The predicted cross section for the neutral pion production is significantly larger because the Q-value of the $\pi^0$-producing reaction is the largest of the 3 channels. Also, the rest mass of $\pi^0$ is approximately 5 MeV smaller than the charged pions which means that, for a given compound nucleus excitation energy, the available phase space for the neutral pion is larger.

In order to be a fair comparison to the measured pionic fusion results, however, only the events which result in bound fusion residues should be considered when determining the predicted cross sections. For instance, considering the $^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{N} + \pi^+$ reaction, the highest nucleon bound state of the fusion residue is at 3.35 MeV. Therefore, only the region of differential cross sections which leave less than that much excitation energy in the residue will contribute. This reduces the prediction of the experimentally accessible part of the $\pi^+$ cross section to 0.19 pb.
Figure 3.19: A comparison of the differential cross sections predicted by the statistical model (full circles) and the Gemini simulation (histograms).
Figure 3.20: A comparison of previous pionic fusion measurement cross sections (black) and predictions from the statistical model (red) presented in this section. (a) The vertical axis is the total cross section in nb for the pion channel in the experimental measurement and the horizontal axis is $A_{tot}$, the total number of nucleons in the reacting system. (b) The vertical axis is the cross section in nb and the horizontal axis is the available energy above the pion production threshold. Two predictions for the $^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{N} + \pi^+$ cross section are shown in blue in both panels. The open circle is the inclusive $\pi^+$ production and the closed circle is the experimentally comparable prediction which requires the fusion residue to be left in a particle bound state.

This statistical model can be used to make predictions for some previous pionic fusion cross section measurements as well. The two panels in Figure 3.20 show the experimental results from previous pionic fusion experiments (black) and the corresponding statistical predictions (red) using the model described above. The vertical axis in both cases is the total cross section in barns for the pion channel in the experimental measurement and the horizontal axis is $A_{tot}$, the total number of nucleons in the reacting system, in panel (a) and the total available energy above the pion production threshold in MeV in panel (b).

The comparison of the previous pionic fusion measurements to the predictions of the statistical model demonstrate the canonical motivation for hypothesizing a collective mechanism for deeply subthreshold pion production. In all cases, the purely statistical model underestimates the reported pion production cross sections by at least an order of magnitude. In general, the statistical prediction is closer to reproducing the experimental result as the available energy above the pion
production threshold increases. In Section 5, the results of the $^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{N} + \pi^+$ experiment will be compared to the statistical model’s prediction for the cross section of that reaction shown in blue in Figure 3.20. The open blue circle shows the predicted cross section for inclusive pion production in the first stage of the deexcitation and the closed circle shows the prediction for the cross section of creating the $^{16}\text{N}$ in a particle bound state such that it can be detected in the pionic fusion experiment.

The statistical prediction for this reaction is the only one that has been modified such that only the subset of pion emission events that result in a particle bound residue contribute to the cross section. A proper accounting of this effect in the other cases will change the result of the statistical prediction relative to the measured result in different ways depending on the specifics of the experiment (but can only ever decrease the predicted cross section). For instance, in the case of the data for pionic fusion of $^3\text{He} + ^3\text{He}$ (the point at $A_{\text{tot}} = 6$ in Figure 3.20(a)) this consideration will have no effect on the result since the pions were measured. Thus, there is no limitation on measuring the bound residue. Rather than potentially wrongly making assumptions about the detection capabilities of these various experiments, the statistical predictions for pion production in these other experiments remains the inclusive predictions. As previously stated, it is already clear that the statistical model is greatly underpredicting the reported cross sections.

One final test of the statistical deexcitation code can be performed by examining how well the model predicts pion production cross sections for reactions with higher excitation energy. In general, as the excitation energy increases statistical treatments of pion production are better able to reproduce the data. To make this test, the first stage deexcitation code from this section can be used to predict the cross sections for pion production in $^{12}\text{C} + ^{12}\text{C}$ reactions. These predictions can be compared to production cross sections reported for pionic fusion [7] and for inclusive subthreshold production at higher bombarding energies [12]. Figure 3.21 shows the result of this comparison. The horizontal axis is the total $^{12}\text{C}$ beam energy in MeV and the vertical axis is the reported cross section for pion production. In the case of the lowest energy (pionic fusion) measurement, the pion channel is $\pi^0$ while the pion channel is $\pi^+$ in the other 3 cases.
Figure 3.21: Pion production predictions from the first stage statistical deexcitation model (red) and reported pion production cross sections from refs. [7, 12] (black). The horizontal axis is the total $^{12}$C beam energy in MeV and the vertical axis is the reported cross section for pion production. The first point at 274.2 MeV beam energy is a coherent cross section for $\pi^0$ production and the three other measurements are inclusive $\pi^+$ production cross sections.
The statistical model is closer to reproducing the experimental results in the cases with higher beam energy than in the pionic fusion case. However, the statistical predictions begin to plateau faster than the data such that the agreement gets worse as the bombarding energy increases from around 700 MeV to around 1000 MeV. This is not consistent with the expected result. A possible explanation for this divergence is the fact that the statistical model being used is only accounting for the first stage of the deexcitation. This is a good approximation at low bombarding energies as the extreme limitation in available energy means that after the first deexcitation there is a very small chance that there will be enough energy remaining to emit a pion. At much higher excitation energies (like in the cases of the 3 highest bombarding energies in Figure 3.21), however, the subsequent emissions can play a much larger role.

A second version of the statistical deexcitation model was developed which considers the first and second stages of deexcitation through pion emission in order to confirm that our model is consistent with the known cross section behavior at higher excitation energy. The first stage of the deexcitation is performed exactly as in the original model. Next, the production cross sections for all particles are updated by the probability they are emitted following a proton in the first stage. This is accomplished by looping over the possible range of emission energies of the proton in the first step and for each of those emission energies, calculating the Weisskopf decay rates of protons, neutrons, alphas and the 3 pion channels at energies between 0 and the remaining excitation energy. The cross section for the emission of each particle type with a given energy in the second stage after a proton emission is then given by Equation 3.8.

$$\sigma_{2nd,i} = \sum_{j,e} \sigma_{1st,j,e} \left( \frac{W_{i,e}}{W_{tot,e}} \right)$$  (3.8)

In Equation 3.8, $\sigma_{2nd,i}$ is the total cross section for production of species $i$ in the second stage of deexcitation, $\sigma_{1st,j,e}$ is the production cross section for species $j$ with energy $e$ in the first stage of the deexcitation, $W_{i,e}$ is the total emission rate of species $i$ in the second stage, and $W_{tot,e}$ is the total emission rate in the second stage. Effectively, the cross section for emission of a particle in the second stage given a particular first stage emission is the probability of emitting that particle...
times the cross section of that first stage emission. The total cross section for production of species $i$ in the first 2 stages, then, is given by $\sigma_{tot,i} = \sigma_{1st,i} + \sigma_{2nd,i}$. Figure 3.22 shows the result of this 2-stage emission calculation compared to the same $^{12}$C + $^{12}$C pion production data shown in Figure 3.21.

The predicted cross section for pion production has increased in all cases in Figure 3.22 compared to the predictions in Figure 3.21. As expected, the higher energy reactions have seen a greater contribution to their total pion production cross sections compared to the lowest energy
point whose difference is negligible. Furthermore, after considering the second stage of the deexcitation the model predictions are better reproducing the data as the bombarding energy increases over the whole range of bombarding energies. While it is true that by considering the contributions from subsequent emissions one could even better reproduce the experimental data, the results in Figure 3.22 are enough to indicate that the statistical model presented in this section is behaving as expected.
4. CALIBRATION AND CHARACTERIZATION EXPERIMENTS

In addition to the pionic fusion production run, three separate calibration/characterization experiments were performed. First, the MARS transport efficiency for pionic fusion residues of interest was measured using a $^{16}\text{O}$ beam at the center-of-mass velocity of the pionic fusion system. The experiment and results are discussed in Section 4.1. The second calibration experiment involved transporting secondary beams of light charged particles to representative phoswich detectors mounted at the focal plane of MARS. In doing so, the detector responses for known energies of known species could be used as a calibration template for the ParTI array in the pionic fusion experiment. The results of the ParTI calibration experiment are reported in Section 4.2. For the third experiment discussed in this chapter, 3 of the ParTI phoswiches were taken to the Paul Scherrer Institute (PSI) in Switzerland where charged pion beams were scattered into them to characterize the responses. This experiment is discussed in Section 4.3.

4.1 The Determination of the MARS Transport Efficiency

The MARS spectrometer is made up of a collection of dipole and quadrupole magnets whose field strengths are set in order to optimize the transportation of a particular species with a particular velocity to the spectrometer focal plane. An experiment was performed in which a $^{16}\text{O}^{7+}$ beam at 3.5 MeV/u ($B\rho = 0.6073$ T m after the 2 $\mu$m stripper foil) was transported through the spectrometer and the magnet settings were adjusted to optimize the rate of beam particles on a silicon detector at the focal plane. These settings were recorded and were used to set the magnet settings for each of the MARS tunes in the pionic fusion experiment by scaling the magnet currents by the ratio of $B\rho$s according to Equation 4.1.

$$I_{\text{new}} = \frac{B\rho_{\text{new}}}{B\rho_{\text{opt}}} I_{\text{opt}}$$ (4.1)

In Equation 4.1, $I_{\text{new}}$ is the new magnet current setting, $I_{\text{opt}}$ is the magnet current setting for the optimal MARS tune, $B\rho_{\text{new}}$ is the desired rigidity, and $B\rho_{\text{opt}}$ is the rigidity of the beam for
which the optimal setting was found. This scaling of the magnet currents was performed for each magnet in MARS each time the rigidity was changed in the pionic fusion experiment. The optimal settings for each MARS magnet that were found in the optimization experiment are given in Table 4.1.

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Current Setting (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MARSBLD1</td>
<td>-406.2</td>
</tr>
<tr>
<td>Q1</td>
<td>-65.8</td>
</tr>
<tr>
<td>Q2</td>
<td>31.1</td>
</tr>
<tr>
<td>D1-2</td>
<td>255.0</td>
</tr>
<tr>
<td>D1Trim</td>
<td>-0.32</td>
</tr>
<tr>
<td>Q3</td>
<td>14.6</td>
</tr>
<tr>
<td>Q4</td>
<td>-26.0</td>
</tr>
<tr>
<td>Q5</td>
<td>42.0</td>
</tr>
<tr>
<td>D3</td>
<td>63.6</td>
</tr>
<tr>
<td>EXB Filter</td>
<td>440.80</td>
</tr>
<tr>
<td>EXB Dials</td>
<td>52</td>
</tr>
</tbody>
</table>

Table 4.1: The MARS magnet current settings for the optimized tune with the 3.4 MeV/u $^{16}$O$^{7+}$ beam. These settings were used to arrive at the settings for each tune in the pionic fusion experiment.

During the MARS optimization experiment discussed above, the $^{16}$O$^{7+}$ charge state was made by stripping a $^{16}$O$^{2+}$ beam using Mylar foils. Over the course of the experiment, the stripper foils degraded such that a determination of the transport efficiency could not be made. To make that measurement, another $^{16}$O$^{7+}$ beam at 3.4 MeV/u was transported through MARS. Two silicon detectors were used to make the measurement - one mounted at the focal plane of MARS and one mounted in the target chamber on the target ladder. MARS was tuned with the same settings from Table 4.1 for the rigidity of 0.6073 T m. The transport efficiency was measured by counting the beam rate on the silicon in the target chamber and then removing it to transport the beam through MARS and counting the rate at the focal plane detector. The rates were recorded using a SIS3820 scaler. The results of that measurement are shown in Figure 4.1.
Figure 4.1: The rate of $^{16}\text{O}^{7+}$ beam particles on the silicon mounted in the MARS target chamber (black) and the silicon mounted at the MARS focal plane (red) as a function of time. The transport efficiency of MARS is the ratio of the rate at the focal plane to the rate in the target chamber.

Figure 4.1 demonstrates the process of counting the beam rate alternating between the target chamber and the focal plane as a function of time. The black histogram shows the rate counted in the target chamber and the red histogram shows the rate counted at the focal plane. The transport efficiency is calculated as the ratio of particles that are transported through MARS (the rate at the focal plane detector) to particles entering MARS (the rate in the target chamber). It is clear from Figure 4.1, however, that there is some fluctuation in the intensity of the beam being delivered to MARS which is causing significant variation in the successive measurements. This fluctuating beam intensity must be accounted for before a good measurement of the transport efficiency can be made.

In order to make the correction for the fluctuations in the beam intensity being delivered to the target chamber, the average count rates at both detector positions were determined by fitting the time spectrum of each histogram with a 0-order polynomial. The rates at the focal plane detector were then scaled by the ratio of the average rate in the target chamber to the average rate at the focal plane.
Figure 4.2: Correcting the counting rates in the MARS transport experiment for the beam intensity instability. The rate at the MARS focal plane detector is scaled up by the ratio of the average rate in the target chamber to the average rate at the focal plane. The whole time spectrum is then fit with a 8-order polynomial to approximate the beam intensity in the target chamber as a function of time.

plane. This gives an approximation of the beam intensity in the target chamber during the times when the target chamber silicon was not seeing beam. From here, a 8-order polynomial was used to fit the whole time spectrum made up of the rate on the target chamber silicon and the scaled focal plane rate. This polynomial fit is an approximation of the continuous form of the beam intensity being delivered to MARS. Figure 4.2 shows this whole time spectrum with the scaled rates at the focal plane and the polynomial fit.

Now with the polynomial approximation of the beam rate in the target chamber, a ratio can be taken of the integrated rate on the detector at the focal plane (not scaled) and the integration of the polynomial over the same time period. In this way, each group of measurements at the focal plane can be used to make a ratio measurement of the transport efficiency. Table 4.2 shows the results of the transport efficiency measurement. The focal plane and target chamber rates are the number of beam particles per second counted on the respective silicon detectors. The uncertainties on each of
Table 4.2: Results of the MARS transport experiment and analysis. Each “Ratio” is one of the measurements of the transport efficiency given by the ratio of event rate at the MARS focal plane to the rate in the target chamber given by the approximation in Figure 4.2. Uncertainties are discussed in the text.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Focal Plane Rate (particles/s)</th>
<th>Target Chamber Rate (particles/s)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24.06 ± 0.47</td>
<td>96.15 ± 0.93</td>
<td>0.2503 ± 0.0055</td>
</tr>
<tr>
<td>2</td>
<td>23.07 ± 0.46</td>
<td>86.63 ± 0.89</td>
<td>0.2663 ± 0.0060</td>
</tr>
<tr>
<td>3</td>
<td>19.84 ± 0.42</td>
<td>75.47 ± 0.83</td>
<td>0.2629 ± 0.0063</td>
</tr>
<tr>
<td>4</td>
<td>20.76 ± 0.43</td>
<td>77.84 ± 0.84</td>
<td>0.2667 ± 0.0062</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.2616 ± 0.0041</td>
</tr>
</tbody>
</table>

The average ratio reported in Table 4.2 is the measured transport efficiency of MARS given the experimental settings for particles of interest at the energy which MARS is tuned for. The statistical uncertainty in this analysis is added in quadrature with the uncertainty in the determination of the 0-order polynomial described above. Ultimately, the transport efficiency and its uncertainty was determined to be 0.2616 ± 0.008. This will be used in the calculation of the cross section of particles in Section 5.2. The uncertainty in each rate measurement is the statistical uncertainty calculated as $\sqrt{N_{110}}$ where $N$ is the total counts in the respective 110 second runs. The uncertainty in each ratio measurement was calculated using the two statistical uncertainties and Equation 4.2. The average ratio is the geometric average of the 4 ratio measurements and the uncertainty in that average is given by Equation 4.3 which is the equation for the calculation of the uncertainty of an average for a small data set.

$$\sigma_{Ratio} = \sqrt{\left(\frac{\sigma_{MARSRate}}{Rate_{MARS}}\right)^2 + \left(\frac{\sigma_{TgtRate}}{Rate_{Tgt}}\right)^2}$$

$$\sigma_{Avg} = \frac{Range}{2\sqrt{N}}$$

In Equations 4.2 and 4.3, $\sigma_i$ is the uncertainty in measurement $i$, $Rate_i$ is the rate on detector $i$ from Table 4.2, $N$ is the number of efficiency ratio measurements (4), and $Range$ is the difference
between the highest and lowest measurement of the ratio efficiency.

This measurement of just over 26% for the transport efficiency through MARS is lower than expected. At the end of the transport efficiency experiment, the LISE++ MARS implementation was used to determine the MARS magnet settings for the residues of interest. Those LISE++ settings were different than those which were determined in the optimization run. Some data were collected at these settings in order to compare the quality of the two methods for arriving at MARS magnet settings. Not enough data were collected to do the analysis described above for the settings of interest, but a naive comparison of the rates at the two detectors with the LISE++ settings indicated that the transport efficiency is at least as high as 50% and could be as high as 70%. Unfortunately, the updated MARS LISE++ simulation was not available at the time the optimization experiment was performed and the transport efficiency experiment was performed after the pionic fusion data had been taken.

As was seen in the transport efficiency experiment, the beam intensity being delivered from the cyclotron was likely not constant during the MARS optimization experiment. Thus, the attempt to vary the MARS magnet settings in order to maximize the rate of the direct beam at the focal plane was likely undermined by the time dependent rate of particles entering the spectrometer. This is likely the reason that the settings ended up sub-optimal. In the future, the LISE++ MARS magnet current settings should be used for any tune barring an extremely rigorous optimization procedure.

### 4.2 The Phoswich Calibration Template using Secondary Beams from MARS

The construction of the Partial Truncated Icosahedron (ParTI) phoswiches and the orientation of the array (all discussed in more detail in Section 2.3) were selected to be optimal for detecting charged pions in the pionic fusion experiment. These details, though, would make it impossible to calibrate the ParTI pionic fusion data in a normal fashion. Because the rate of background charged particles forward of the target would be too high given the beam intensity, the ParTI array was oriented in the backward hemisphere relative to the target. This meant that it would not be possible to scatter beams of known energy into the phoswiches to provide calibration points. Also, since the phoswiches needed to be sensitive to pions which are very minimally ionizing charged...
particles, the $\Delta E$ phoswich component (the scintillating plastic) needed to be sufficiently thick to get a measurable energy deposition. As a result, there were no available radioactive sources which could provide calibration points in both detector components.

In order to perform the calibration of the pionic fusion ParTI data, then, a method was developed [73] based on a similar method [74] which utilized a calibration template for the phoswich detectors using data collected in a separate experiment. In that experiment, representative phoswiches (1 hexagonal geometry and 1 pentagonal geometry) were mounted at the focal plane of the MARS spectrometer and secondary beams of light charged particles were transported through MARS and incident on the phoswiches. Because each of these particle beams was a known species at a known energy, the detector responses to each type can be used to produce Z-dependent energy calibrations for the phoswiches. Then, using a scaling method that will be discussed later in this section, it is possible to use these secondary beam phoswich calibrations to calibrate the phoswich data in the pionic fusion experiment.

For this experiment, a $^{16}\text{O}$ beam at 3.9 MeV/nucleon was incident on a $^9\text{Be}$ production target located in the MARS target chamber. Fragments from the reaction near the beam axis entered the MARS spectrometer and those near the selected magnetic rigidity were transported to the focal plane where the phoswich detectors were mounted. In the rest of this section, the pulse shape discrimination (PSD) particle identification (PID) capabilities of the ParTI array will be demonstrated and the technique for calibrating the array will be described. What follows are results of beam experiments in which the phoswich data was collected using the Struck Innovative Systeme (SIS) 3316 VME digitizer to record the full waveform response of the detectors.

4.2.1 Fast vs. Slow PID

To perform the PSD, the phoswich response waveforms are analyzed and the area under the waveform is integrated inside two regions corresponding to the fast plastic scintillation response and the slower CsI(Tl) scintillation response. The fast integration region begins with the first bin above a software threshold and spans 7 bins (28 ns), encompassing the sharp peak corresponding to the fast plastic response. The slow integration regions begins 6 bins (24 ns) after the end of the
Figure 4.3: A representative phoswich detector response for a charged particle event. The red highlighted region corresponds to the fast (28 ns width) integration region and the green highlighted region corresponds to the slow (400 ns width) integration region.

fast region and spans 100 bins (400 ns). Figure 4.3 shows a representative phoswich waveform response produced by a charged particle event with fast and slow integration regions highlighted. Because the number of photons produced by each scintillating component is proportional to the energy deposited in the material, a Fast vs. Slow Integration analysis for phoswich detectors is an approximation of a $\Delta$E-E analysis and can similarly produce particle identification lines based on relative energy loss in the two materials.

Figure 4.4 shows the fast vs. slow particle identification plot for a representative hexagonal geometry phoswich (a) and a representative pentagonal geometry phoswich (b) produced in the secondary beam experiment. In each case, the neutron/gamma/cosmic (NGC) line extends from approximately (0,0) and is the first region of note in the figure. The next area with structure (as one moves upward) is a band corresponding to protons which is not used in the following analysis as they do not originate from reactions on the target and, thus, are uncorrelated to the tune of the spectrometer. Above this is a series of spots corresponding to secondary beams of deuterons with $B_\rho = 1.0$ T m, 1.2 T m, 1.3 T m, 1.4 T m and 1.5 T m. While the protons are not useful for this analysis, the separation between the proton band and the band of deuteron spots is representative of the isotopic resolution of protons and deuterons in the ParTI phoswiches. Furthermore, while not
available in this data set, the resolution of tritons from deuterons is of comparable quality. Above the deuterons are 4 spots corresponding to $\alpha$ secondary beams with $B_\rho = 1.2$ T m, 1.3 T m, 1.4 T m and 1.5 T m. Finally, above the $\alpha$ spots are 2 spots corresponding to $^6$Li secondary beams with $B_\rho = 1.4$ T m and 1.5 T m. Spanning the vertical range of the plot is a band of data to the left of the secondary beam data. This “punch-in” line is populated by charged particles which do not have enough energy to punch into the CsI(Tl) scintillator, depositing all of their energy in the fast plastic.

The phoswich calibration process follows generally the technique outlined in ref. [74]. Figure 4.5 (a) shows the first step in this process for the data from the hexagonal phoswich. The NGC line and the punch-in line are fit with first- and second-order polynomials, respectively. The intersection of the two fit lines is a point which corresponds to the electronic channel offset in the fast and slow integrations.

The NGC line is populated by events that only deposit energy in the CsI(Tl) crystal which, in $\Delta E$-$E$ space, corresponds to a horizontal line at $\Delta E = 0$. In fast vs. slow space, though, the line is clearly sloped. The reason for this is that although the CsI(Tl) scintillation has a much slower decay (and rise) it still begins at the moment of charged particle interaction. Because of this, there will be some nonzero integration of the slow signal inside the fast integration region. Similarly, the punch-in line corresponds to events which deposit no energy in the CsI(Tl) crystal, but the punch-in line is not vertical at slow integration = 0 because, while the plastic scintillation has a very fast decay, large energies deposited in the fast plastic can produce nonzero contributions in the slow integration region. In order to move from integration space to energy space it is important to correct for these phenomena and the nonzero location of the intersection discussed in the paragraph above. Each data point, therefore, undergoes the transformation given by Equation 4.4 and 4.5 where $F$ and $S$ refer to the fast and slow integrations, $(S_0, F_0)$ is the intersection point, and $M_{NGC}$ is the slope of the NGC fit line. The values of $a_1$ and $a_2$ are the coefficients of the first and second order terms in the polynomial fit of the punch-in line after the fast vs. slow space has been inverted to produce a fit line with an equation for slow as a function of fast.
Figure 4.4: (a) Results of secondary beam calibration data for a hexagonal phoswich at the focal plane of the MARS spectrometer. (b) Results for the pentagonal phoswich in the same experiment. In both panels the vertical axis is the waveform integration inside the fast integration region in ADC channels and the horizontal axis is the waveform integration inside the slow integration region in ADC channels as shown in Figure 4.3.
\[ F' = (F - F_0) - (S - S_0) M_{NGC} \]  \hspace{1cm} (4.4)

\[ S' = (S - S_0) - (F - F_0)^2 a_2 - (F - F_0) a_1 \]  \hspace{1cm} (4.5)

The results of this transformation are shown in Figure 4.5 (b). The NGC line is now horizontal at fast integration = 0 and the punch-in line is vertical at slow integration = 0. Data from secondary beam species have shifted but remain qualitatively the same as described above.

### 4.2.2 The Energy Calibration Template

The data in this form can now be calibrated into energy space using The Stopping and Range of Ions in Matter (SRIM) [75] energy loss calculations for the known particles at known energies through the scintillating components of the phoswich. The spots corresponding to the secondary beams in Figure 4.5 (b) are projected onto the fast and slow integration axes and fit with Gaussians to extract the center in each dimension. All of the spot center locations are then used to calibrate the phoswiches using the deposited energies in each component calculated from SRIM. A different calibration is produced for each proton number, Z, for the plastic ΔE component as the charge density of the incoming particles is clearly affecting the scintillation response [74]. Figure 4.6 shows the energy calibrations for the plastic and CsI(Tl) components in the hexagonal geometry and Figure 4.7 gives the calibrations for the pentagonal geometry.

The calibrations shown in Figures 4.6 and 4.7 produced by these secondary beams provide the calibration templates for the phoswiches in other experiments. The data which is to be calibrated using the templates will first be corrected for the NGC and punch-in lines and then transformed using Equations 4.4 and 4.5. Then the data in each detector is scaled to match the template in Figure 4.5 (b) or the comparable template for the pentagonal phoswiches. This scaling is necessary to account for differences in the voltages applied to the PMTs in different experiments and differences in the intrinsic gains of different PMT units. This process of applying the phoswich calibration templates to other data sets is discussed in Section 5.3 for the pionic fusion data. The
Figure 4.5: (a) Results of secondary beam calibration data for a hexagonal phoswich at the focal plane of the MARS spectrometer with a first-order polynomial fit for the NGC line and a second-order fit for the punch-in line overlaid on the data. (b) The same phoswich data after it has been corrected for the slow component contribution in the fast integration and vice-versa using Equations 4.4 and 4.5. In both panels the vertical axis is the waveform integration inside the fast integration region and the horizontal axis is the waveform integration inside the slow integration region as shown in Figure 4.3.
Figure 4.6: Energy calibrations for the plastic and CsI(Tl) ($\Delta E$ and $E$) components of the hexagonal geometry ParTI phoswich. In all figures, the vertical axes are the gate integrations of the waveforms, fast or slow, in ADC channels. The horizontal axes are the energies deposited in the respective components in MeV as calculated using SRIM. (a) The $\Delta E$ calibration for $Z = 1$ particles. (b) The $\Delta E$ calibration for $Z = 2$ particles. (c) the $\Delta E$ calibration for $Z = 3$ particles. (d) The $E$ calibration using all of the secondary beam species and energies. All error bars are the $\sigma$ widths of the gaussian fits to the 1D projections of Figure 4.5(b) as described in the text and where they are not visible they are smaller than the points.
Figure 4.7: Energy calibrations for the plastic and CsI(Tl) ($\Delta E$ and E) components of the pentagonal geometry ParTI phoswich. In all figures, the vertical axes are the gate integrations of the waveforms, fast or slow, in ADC channels. The horizontal axes are the energies deposited in the respective components in MeV as calculated using SRIM. (a) The $\Delta E$ calibration for $Z = 1$ particles. (b) The $\Delta E$ calibration for $Z = 2$ particles. (c) The $\Delta E$ calibration for $Z = 3$ particles. (d) The E calibration using all of the secondary beam species and energies. All error bars are the $\sigma$ widths of the gaussian fits to the 1D projections of Figure 4.5(b) as described in the text and where they are not visible they are smaller than the points.
parameters for all of the calibrations are given in Table 4.3. These calibrations are applicable for future experiments with the ParTI phoswiches provided the physical construction remains the same and the same gate widths and positions are used.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Calibration</th>
<th>slope (channels/MeV)</th>
<th>intercept (channels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexagonal</td>
<td>$Z = 1 \Delta E$</td>
<td>914 ± 54</td>
<td>4810 ± 597</td>
</tr>
<tr>
<td></td>
<td>$Z = 2 \Delta E$</td>
<td>316 ± 38</td>
<td>20304 ± 1622</td>
</tr>
<tr>
<td></td>
<td>$Z = 3 \Delta E$</td>
<td>181 ± 75</td>
<td>27884 ± 7245</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>1932 ± 32</td>
<td>-1248 ± 1222</td>
</tr>
<tr>
<td>Pentagonal</td>
<td>$Z = 1 \Delta E$</td>
<td>534 ± 27</td>
<td>1995 ± 287</td>
</tr>
<tr>
<td></td>
<td>$Z = 2 \Delta E$</td>
<td>154 ± 16</td>
<td>13405 ± 717</td>
</tr>
<tr>
<td></td>
<td>$Z = 3 \Delta E$</td>
<td>54 ± 28</td>
<td>22625 ± 2782</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>1064 ± 16</td>
<td>-326 ± 606</td>
</tr>
</tbody>
</table>

Table 4.3: The calibration line parameters for the hexagonal and pentagonal ParTI phoswiches.

4.3 The Characterization of Phoswich Responses to Incident Charged Pion Beams

The Partial Truncated Icosahedron (ParTI) phoswiches were designed to be able to detect low energy charged pions from pionic fusion reactions. In order to demonstrate this capability it was necessary to characterize the phoswich responses using a significant number of pion primary events. For this, beams approaching the pion production threshold (280 MeV/nucleon) are required. However, the Cyclotron Institute’s K500 cyclotron can only reach 60 MeV/nucleon for certain light ions. The decision was made to transport 4 of the ParTI phoswiches (2 pentagonal and 2 hexagonal geometries) to the Paul Scherrer Institute (PSI) in Switzerland where beams of $\pi^+$, $\pi^-$ and protons were scattered into them. One of the pentagonal phoswiches was damaged during the experiment so the analysis of the PSI data will only include the three detectors that worked throughout. The facility’s $\pi M1$ beam line was used for the experiment and a series of copper degraders were used to access the pion and proton energy ranges of interest. Figure 4.8 shows the layout of the $\pi M1$ beam line.

At the PSI facility, the High Intensity Proton Accelerator (HIPA) consists of a 870 keV pre
Figure 4.8: The layout of the πM1 beam line at the Paul Scherrer Institute. The primary pion beam is delivered from the bottom left of the figure onto a carbon target and the πM1 entrance is 22° off of the primary beam axis.
injector, a 72 MeV cyclotron injector and a 590 MeV Ring Cyclotron and is used to deliver a 1.3 MW proton beam to the facility. That proton beam is impinged on a carbon target in the primary beam line. The \( \pi M1 \) line siphons charged particles at 22° off of beam center and uses a two stage separator to deliver secondary beams to the end of the \( \pi M1 \) experimental area. The copper degrader system was placed directly at the end of the line and the phoswiches were positioned approximately 4 feet behind the degraders inside dark boxes. Each phoswich PMT was supplied -1250 V and the phoswich signals were digitized using the SIS3316 digitizers discussed in Section 2.5.1. Figure 4.9 shows a photograph of the experimental setup inside the \( \pi M1 \) area.

### 4.3.1 Pion Identification Using Fast vs. Slow Pulse Shape Discrimination

Figure 4.10 shows the data from the \( \pi^+ \) (a) and \( \pi^- \) (b) beams collected by one of the phoswiches. This data is representative of the other two working phoswiches. In both panels of Figure 4.10, the data for the proton beams are also included. As before, the vertical axis is the integrated area under the recorded waveform inside the fast integration region and the horizontal axis is the area...
Figure 4.10: Data for proton and $\pi^+$ beams (a), and protons and $\pi^-$ beams (b) from the PSI experiment using the muon decay trigger. In both cases, the vertical axis is the integrated waveform inside the fast integration region and the horizontal axis is the integrated waveform inside the slow integration region as given by Figure 4.3. Moving upward from 0 on the fast integration axis is the NGC line, a region corresponding to positron (electron) events in panel a (b), the line for the corresponding species of charged pion, the line corresponding to protons and, finally, the line corresponding to deuterons.

inside the slow integration region (as shown in figure 4.3). Moving up from 0 on the fast integration axis one can identify, first, the NGC line extending from approximately (0,0). Next is a region populated by the phoswich response for positrons and electrons (in the cases of the $\pi^+$ and $\pi^-$ beams, respectively). Moving upward once more, one finds an area in each plot corresponding to charged pions. Considerably farther up the fast integration axis is the line for protons and, just above it, a more weakly populated line for deuterons. In both charged pion cases, the pion events populate well-defined PID lines which are separated from the NGC line and the proton line. The three relevant particle identification lines - pion ($\pi$), proton (p), and deuterons (d) - are labeled.

The data from Figure 4.10 was taken using the muon decay trigger in the cases of both beams. The muon decay trigger is discussed in further detail in the following subsection and in Section 2.5.1.
4.3.2 The Muon Decay Trigger

In order to perform the pionic fusion measurement for which the ParTI array was designed, it needs to be sensitive to a very small pion production cross section while subjected to incident rates of other charged particles many orders of magnitude higher. In order to accomplish this, a non-standard trigger was implemented in the SIS3316 firmware which would selectively trigger on pion-like events. The “muon decay trigger” uses the internal constant fraction discriminator (CFD) function of the module but does not trigger the data acquisition until the second instance of the waveform crossing threshold inside a trigger window. Following a $\pi^+$ implantation in a phoswich, the daughter $\mu^+$ will decay and deposit energy in the detector. This second energy deposition will create a second pulse in the phoswich waveform response which will potentially satisfy the muon decay trigger. The result of using the decay trigger is a significant reduction of triggers by background events and an increased acquisition live time.

The quality of the muon decay trigger was investigated during the PSI pion beam experiment. In Figure 4.11, data collected with a $\pi^+$ beam using the SIS3316 standard CFD trigger is shown in panel (a). As before, the vertical axis is the fast integration and the horizontal axis is the slow integration. The prominent spot at approximately fast = 2500 and slow = 20000 is the phoswich response for the $\pi^+$ beam. In panel (b), the muon decay trigger is implemented for the same beam. Immediately it can be seen that that implementation of the muon decay trigger has increased the ratio of events in the charged pion region to events in background regions. In order to measure this effect, events populating the center region of the pion spot (inside the solid box) were integrated and divided by an integration of background events from the positron region (inside the dashed box) of the same size. The ratio of pions to background triggers increases from 0.11 in the data from panel (a)) to 1.0 in the data from panel (b) - an increase in the selectivity of nearly an order of magnitude. This result is representative of the effect of the muon decay trigger for all 3 working detectors. The effectiveness of the muon decay trigger depends upon many factors including the CFD threshold, PMT gain and the region of the fast vs. slow space that is being investigated.
4.3.3 Analysis of the Characteristic Waveforms Produced in Pion Events

As discussed in Section 4.3.2, the muon daughters of the $\pi^+$ primary events will decay into positrons which will deposit energy in the scintillator components and produce a muon decay pulse. This results in a characteristic, 2-peaked waveform. An example of one of these characteristic phoswich responses recorded by the SIS3316 for a $\pi^+$ event can be seen in Figure 4.12. The initial sharp peak is the plastic response to the charged particle depositing energy as it travels through and the following slower component tail corresponds to the CsI(Tl) component response to the implantation. Some time later, there is a second CsI(Tl) response corresponding to a potential muon daughter decay. The time between the initial implantation into the detector and the muon-like decay pulse is defined as $\Delta t$.

An event-by-event analysis of these $\Delta t$s can show that the particle identification (PID) line discussed in Section 4.3.1 is truly due to incident particles of interest. By the time the low energy pions arrive at the phoswich positions, many of them have already decayed in flight to muons.
Figure 4.12: An example of a characteristic waveform for a $\pi^+$ primary event collected by the SIS3316 digitizer in the PSI experiment. The initial sharp peak is the plastic response to the incident charged particle and the following, slower decaying component is the response from the CsI(Tl). The second peak around 8000 ns is a muon decay-like response. The time between the initial implantation and the second pulse is defined as $\Delta t$.

(the pion lifetime is 26 ns). Therefore, the PID line is expected to be populated by muon and pion primary events. The energy resolution of the phoswiches, though, is not sufficient to separate pions from muons as they have the same charge and their masses only differ by approximately 35 MeV. As a result, all events within the PID line will be considered in the following analysis without any further discrimination between pion and muon primary implantations.

The locations of the two pulses (the implantation and the muon decay) within the digitization time window must be identified before $\Delta t$ can be determined. The time location of the implantation is defined as the first bin in the 4000 bin time window which crosses a software threshold. The software threshold is set to 200 channels above baseline which is large enough to ignore noise fluc-
tualations preceding the implantation and small enough to identify all real events of interest. Since the implantation pulse will always have a fast component rising from baseline, this process of looking for the first bin above baseline is a successful method of locating the start of the implantation pulse.

The muon decay pulse, in general, is more difficult to locate with precision. It frequently does not have a fast component which means there is often not a sharp rise from baseline. Therefore, a simple software threshold can be difficult to implement. Also, the location of the muon decay pulse moves around relative to the implantation pulse and is frequently riding on top of the fall of the implantation response (as is the case in Figure 4.12). This further complicates the process of finding its location by effectively varying the baseline relative to the pulse. As another example of its utility, though, the muon decay trigger largely solves both issues. Because it is this second pulse that triggers the acquisition, the location of the second peak is always approximately in the same place in the digitization window. Therefore, the time location of the second peak is defined as this trigger location, 1972 bins, in every case.

The next step in the analysis is to draw software gates around the PID line for each detector. Figure 4.13 shows the fast vs. slow PID space for one of the hexagonal phoswiches with two software gates overlaid. The solid gate is drawn around the pion PID line and the dashed gate is drawn in a background region. Events inside of the background gate are likely primarily to be detector responses to incident positrons and gammas which are followed by a pileup event that triggers the muon decay trigger. Events in this region are not expected to include pion or muon primaries. The data shown in Figure 4.13 is representative for all phoswiches in the analysis.

For all of the events inside of these graphical cuts, the time between each implantation and muon decay-like pulse, $\Delta t$, is determined. The distributions of $\Delta t$ for events inside the pion/muon gate produce the histograms in Figure 4.14 panels (a), (c), and (e). Panels (b), (d), and (f) show the $\Delta t$ distribution for events inside the background gates. Each of the 3 rows corresponds to one of the 3 phoswiches in the experiment. Each one of the histograms is a measurement of the decay curve associated with the incident particle species (or, possibly, multiple particle species) inside

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Figure 4.13: The fast vs. slow PID plot from a representative phoswich for the $\pi^+$ data from the PSI experiment. The graphical software cuts are shown overlaid for the pion/muon PID region (solid line) and the background region (dashed line). Events inside the pion/muon gate are expected to be responses to incident pions and muons. Events in the background region are not expected to be pion or muon primaries.
of the PID line or background area. Beyond the requirement that all analyzed events must have produced detector responses that meet the muon decay trigger criteria, all events in this analysis have a \( \Delta t \) of at least 1000 ns. The reason for this restriction is that if the decay pulse follows the implantation pulse too quickly, the fast vs. slow pulse shape discrimination PID is compromised. This is also the reason that each of the decay curves in Figure 4.14 does not extend to \( \Delta t = 0 \).

For each of the decay curves in Figure 4.14, an exponential fit of the form of Equation 4.6 can be implemented. Here, the exponential term is describing the decay characteristics of the particles inside the PID gates and the constant offset, \( a_0 \), is allowing the fit to account for a flat background. The term \( \lambda \) is the decay constant. The red curves overlaid in Figure 4.14 represent these fits for each of the phoswiches. In each pion/muon panel, next to each fit line is the value of \( \tau \) extracted from the fit of the decay curve where \( \tau = 1/\lambda \).

\[
N = N_0 e^{-\lambda t} + a_0
\]  

(4.6)

It is clear from the comparison of the pion/muon line PID gate panels to the background gate panels in Figure 4.14 that the particles populating the pion/muon line are decaying after implantation and those particles in the background region are not. There is some systematic uncertainty in the analysis due to the fact that some of the primary particles from panels a, c, and e are pions and some are muons. However, because the pion lifetime is so short compared to the muon lifetime and because the analysis is ignoring \( \Delta t \)s shorter than 1000 ns (more than 10 pion average lifetimes) this effect is very small. Indeed, the mean lifetimes calculated from the decay constants in Figure 4.14 are all within 1\% of the known value for \( \tau_{\mu^+} \), 2197 ns.

There is a periodic spike structure to the decay curves from Figure 4.14 which is visible in the lowest \( \Delta t \) region shown in each of the pion/muon PID panels. This phenomenon is stronger for the region where the two peaks are separated by less than 1000 ns. The origin of this phenomenon is unknown. It does not appear to be an effect of the muon decay trigger as data taken with the SIS3316’s standard trigger also shows the same structure. The analysis has also been done using a software CFD to locate the implant and decay pulses. This method which no longer
Figure 4.14: (a, c, e) Decay curves for events inside of the pion/muon PID software cuts with the exponential fits of the form in Equation 4.6 overlaid in red. The extracted mean lifetime, $\tau$, from each of the fits is given in all 3 cases. (b, d, f) The same $\Delta t$ analysis for events inside the background gates.
assumes knowledge of one of the peak locations (the trigger location) also results in the peaked
phenomenon. This implies that it is not due to imprecision regarding the trigger’s location in the
digitized window. The period of the spikes (around 150 ns) is not consistent with the PSI cyclotron
RF frequency of 50 MHz so it does not seem plausible that this is caused by true pile up from
events in a subsequent beam burst. Ultimately, a precision measurement of the muon lifetime was
not the purpose of this exercise and the spike structure has not affected the ability to confirm the
presence of muon decays in the appropriate PID gate.

Based on the PSI experiment results, the ParTI phoswiches are behaving as expected with re-
spect to the response to charged pions and muons. The pion beams are producing a well-defined
PID line in the fast vs. slow space which is separated nicely from other charged particle lines and
the neutron/γ/cosmic line. And, when gating on that line, the waveforms display the characteristic
decay attributes that are expected for $\mu^+$. This process exemplifies the power of the phoswich
design when combined with the SIS3316 digitizers for low energy charged pion detection applica-
tions.

The analysis described in this section has only been applied to the data collected from the $\pi^+$
beams during the PSI experiment. The prospect of applying this analysis to the $\pi^-$ beams is com-
plicated by two factors. First, the population of negative pions and muons in the secondary beams
at PSI are about a factor of two lower than for positive charged pions and muons at 115 MeV/c
momentum [76]. This results in fewer statistics for the negative particle data. More importantly,
though, after the $\mu^-$ daughters are stopped in the detector material, there is a high probability that
they will be captured on the detector nuclei. The mean lifetime for negative muon capture on Cs
nuclei is 87.8 ns and the lifetime for muon capture on I nuclei is 86.1 ns [77]. In both cases, these
capture lifetimes are much shorter than the mean lifetime of the muon. As a result, in these capture
cases, there will be no second pulse corresponding to the muon decay. For these reasons, a decay
curve analysis was not performed on the data from the $\pi^-$ beams.
5. DATA ANALYSIS AND RESULTS

The primary result of this work, a measurement of the cross section of the pionic fusion reaction $^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{N} + \pi^+$, will be presented in this section along with the analysis of the data. The cross section is defined by the thin target approximation for reaction cross sections, Equation 5.1, where $\sigma$ is the measured cross section in barns, $I$ is the time-integrated beam intensity on target, $t$ is the areal density of the target in nuclei/cm$^2$, and $N$ is the number of observed reactions of the type in question.

$$\sigma = \frac{N}{It}$$

Cross section analyses for the pionic fusion reaction were measured using data from the number of $^{16}\text{N}$ fusion residues measured in MARS and from detected pions measured in the ParTI array. Also, cross sections of other fusion residues detected in MARS will be compared to the results of a Gemini [58] simulation of the deexcitation of the fused $^{16}\text{O}$ system. In Section 5.1 the process for determining the target areal density, $t$ and the process for determining the integrated beam particles on target, $I$, are discussed. In Section 5.2, all aspects of the MARS component of the pionic fusion experiment will be discussed including the calibration of the MARS detectors, particle identification (PID), the determination of detection efficiencies, and the measured cross sections. In Section 5.3, all aspects of the ParTI component of the experiment will be discussed including the calibration of the data using the calibration templates from Section 4.2, charged pion detection efficiencies, and the measured cross section for pionic fusion. Section 5.4 will discuss the coincidence capabilities of the MARS/ParTI pionic fusion experiment. Section 5.5 describes the analysis of the ParTI-triggered events and the identification of pion events that did not come in coincidence with a MARS residue. Lastly, Section 5.6 will briefly discuss the data set with respect to other pionic fusion channels of the $^4\text{He} + ^{12}\text{C}$ reaction.
5.1 The Beam Intensity and Target Thickness Measurements

In order to make a measurement of reaction cross sections, it is necessary to know the thickness of the target and the number of beam particles incident on the target during the irradiation. This section will describe the analyses that result in the determination of these two values.

5.1.1 Target Thickness Measurement

The target thickness measurement was performed using a 53 MeV $^{16}$O beam. The beam was transported through the MARS spectrometer and beam particles were detected using the same silicon stack detectors as were used during the pionic fusion measurement. Data was taken with two different targets in the beam path and with a blank frame. The energy differences between the blank frame data and the data collected while each target was in the beam path is due to the energy lost by the beam in each target. From these energy losses, the target thickness can be determined. Figure 5.1 shows the results of this process for the experimental $^{12}$C target and a gold target which was mounted on the target ladder for the purpose of producing fragments for the calibration of the ParTI phoswiches.

In Figure 5.1, each of the energy distributions corresponds to the $^{16}$O particle energies detected at the MARS focal plane while the respective targets were in the beam path. The horizontal axis is the measured energy in MeV calibrated using the method described later in Section 5.2. The y-axis is the yield normalized such that the maximum bin is 1. Each of these energy distributions is fit with a gaussian to find the centers. The "Transport of Ions in Matter" (TRIM) [75] software was used to determine the thickness of each target given the energy lost in each case compared to the energy in the blank frame data. The gaussian centroids, energy lost in the target, and calculated target thicknesses are reported in Table 5.1. The uncertainties on the target thicknesses are determined by the uncertainty in the gaussian centroids given by $\frac{\sigma}{\sqrt{N}}$ where $\sigma$ is the width and $N$ is the number of measurements and the intrinsic uncertainties in the TRIM calculation [13]. The thickness uncertainty is not symmetric given a symmetric uncertainty in the amount of energy deposited. This is because charged particles deposit energy non-linearly as a function of their energy.
For the beam through the thin carbon target, though, the difference between the two limits of the error bars is negligible and the number quoted in Table 5.1 is the larger of the two.

### 5.1.2 Measuring and Monitoring Beam Intensity

During pionic fusion production runs, the beam intensity was periodically measured by inserting a Faraday cup into the beam directly downstream of the target location inside the MARS target chamber. The current on the cup was integrated using a Brookhaven Instruments Corporation cur-
## Table 5.1: The first column notes the targets in the beam for the measurement. The second column has the centroids of the Gaussian fits of the different data sets in Figure 5.1 and the uncertainties are given by the quadrature sum of the statistical uncertainty and the intrinsic errors from the SRIM calculation [13]. The third column is the energy lost by the beam in the target (the energy difference between the Blank centroid and the target centroid). The last column is the measured thickness of the target given the energy lost in the target calculated using TRIM.

<table>
<thead>
<tr>
<th>Target</th>
<th>Centroid (MeV)</th>
<th>Energy Lost in Target (MeV)</th>
<th>Target Thickness (μg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank</td>
<td>53.017 ± 0.004</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Carbon</td>
<td>48.158 ± 0.005</td>
<td>4.86 ± 0.23</td>
<td>894 ± 18</td>
</tr>
<tr>
<td>Gold</td>
<td>42.809 ± 0.010</td>
<td>10.208 ± 0.37</td>
<td>5150 ± 100</td>
</tr>
</tbody>
</table>

rent integrator. More details about the Faraday cup and the current integrator were given in Section 2.4. Figure 5.2 shows the integrated current in nC over each 10 second scaler event calculated from the output of the beam integrator using Equation 2.3 for all measurements taken while MARS was tuned for 0.5829 T m. This is qualitatively similar to data taken during the other 5 $B_\rho$ tunes of MARS during the pionic fusion experiment. During the runs where the Faraday cup is in the beam path the measured intensity is non-zero.

It has been observed that the beam intensity delivered from the K500 cyclotron fluctuates significantly even over time scales of a few minutes (an example of this has been demonstrated in Section 4.1). It is necessary, therefore, to continuously monitor the beam intensity during the pionic fusion production runs. While the Faraday cup was in the beam path, however, no meaningful data could be collected as no residues were entering MARS. In order to continuously monitor the beam intensity, then, the CFD scaler rate from the $\Delta E$ silicon at the MARS focal plane was used as a proportional measurement of the beam intensity. Figure 5.3 shows the scaler rate from the $\Delta E$ silicon as a function of the scaler event number.

In Figure 5.3 the times with relatively high intensity are directly following peaks of the beam. In the time following each beam peak, the beam intensity steadily falls off until the beam is peaked again. The short gaps in the MARS CFD rate corresponds to scaler events for data taken with the target chamber Faraday cup in the path of the beam (the non-zero spikes in Figure 5.2). During these times, there are no particles being delivered to the MARS focal plane. In order to complete
Figure 5.2: The measured beam intensity on the target chamber Faraday cup in nC as a function of the scaler event number (each scaler event is 10 seconds in length). This represents all of the target chamber Faraday cup data collected during the pionic fusion production runs when MARS was tuned for 0.5829 T m. The long stretches of zero intensity correspond to the times where the Faraday cup is removed from the beam path and data is being collected at the MARS focal plane.

The continuous measurement, the recorded MARS CFD rates from Figure 5.3 can be correlated to the intensity of beam on target in Figure 5.2. The analysis will compare the particle rate at the MARS focal plane in the time directly before and after the Faraday cup is inserted into the beam path to the beam intensity measured by the cup in the target chamber.

Each time production mode is switched over to Faraday cup mode can be used to make a calibration point for correlating the MARS rate to the beam intensity on target. Similarly, each time Faraday cup mode is switched to production mode can also be used to make a calibration point. When a switch from production running to Faraday cup data occurs, the average beam intensity in nC of the first 5 Faraday cup scaler events (ignoring the first scaler event of the run
Figure 5.3: The scaler rate from the CFD from the MARS $\Delta$E focal plane detector as a function of the scaler event number. Data covers all of the pionic fusion production runs across all 6 $B_\rho$ settings of MARS. The short gaps in the data correspond to times when the target chamber Faraday cup was inn the path of the beam.

as it is sometimes an incomplete event) is compared to the average rate at the MARS focal plane over the previous 5 scaler events (ignoring the last 2 scaler events in the run for the same reason). Similarly, when the experiment returns to production runs, the average of the first 5 MARS scaler rates (ignoring the first) can be compared to the last 5 Faraday cup scaler events (ignoring the last 2). Each calibration point can be plotted as the average beam intensity integration from the Faraday cup vs. the average MARS focal plane rate. The result of this analysis is shown in Figure 5.4. In the cases where the beam was peaked in between a switch between production and Faraday cup runs, that data point was not used in the calibration and does not appear in Figure 5.4.

The vertical error bars in Figure 5.4 represent an uncertainty of 10% in the current measured by the Faraday cup. This uncertainty in the measured beam intensity was estimated based on the
Figure 5.4: The results of the calibration of the event rate at the MARS focal plane to the beam intensity at the target position measured on the Faraday cup. Each calibration point comes from one instance of switching from production runs to a Faraday cup run or visa versa as described in the text. This figure includes data from all of the MARS $B$ tunes. The vertical axis the integrated beam intensity in nC measured by the Faraday cup per 10 second scaler event. The horizontal axis is the integrated scaler rate on the MARS $\Delta E$ focal plane detector per 10 second scaler event. The vertical error bars represent an uncertainty of 10% in the current measured by the Faraday cup. The horizontal error bars are statistical uncertainties. The red line is a linear fit to the data representing the calibration that will be used for the determination of the cross sections. The black lines were calculated using the ROOT fit parameter errors and represent the uncertainty in the calibration.

uncertainty reported in [78]. This is a conservative estimate of the true uncertainty as one of the largest sources of uncertainty was mitigated by moving the charge integrators into the experimental cave for the pionic fusion experiment. The horizontal error bars represent the statistical uncertainty from the MARS $\Delta E$ scaler rate. The red line in Figure 5.4 is a linear fit of the data and represents
the calibration of the scaler rate at the MARS focal plane to the beam intensity at the target position. The black lines were calculated using the ROOT fit parameter errors and represent the uncertainty in the calibration. This analysis was also performed separately on the data from each MARS $B_\rho$ setting but there was no indication that the calibration was changing with transported particle energies.

5.2 Residues at the MARS Focal Plane

Pionic fusion events can be identified by the detection of the pionic fusion residues as discussed in Chapter 1. In this section, the process for calibrating and analyzing the MARS focal plane data will be discussed and the cross section results will be reported.

5.2.1 Position Calibration of the MARS $\Delta E$ Strip Detector

A beam of $^{16}$O (the same beam used in the determination of the target thickness from Section 5.1.1) was used to calibrated the position of the $\Delta E$ silicon detector at the MARS target plane. First, the beam was defocused in the x dimension so that each of the strips (the central 14 were collecting data) was being hit with beam. Then, the slit located directly upstream of the MARS detector chamber ("Slit 4" in Figure 2.1) was closed to a 1 mm gap. That gap was moved vertically such that its center was located at -6 mm, 0 mm, and 6 mm. The signals are taken from one side of each resistive strip. Figure 5.5 shows the raw position calibration data for strip 8. This is representative of the data on each strip.

In Figure 5.5, the vertical axis is the yield in counts and the horizontal axis is the ratio of the signal measured on the strip in ADC channels to the signal measured in ADC channels from the $\Delta E$ silicon back plane. Each of the three peaks corresponds to events collected while the MARS slits were centered at one of the three positions. For each strip, the three peaks are fit with Gaussians in order to find their centers. Then, the peak centers are calibrated using the known position locations from the slits and assuming a parallel beam at the focal plane. The calibrations are linear for all strips. Figure 5.6 shows the same data for strip 8 from Figure 5.5 after it has been position-calibrated. The vertical axis is the yield in counts and the horizontal axis is the vertical
Figure 5.5: The raw position calibration data for strip 8 of the ΔE MARS focal plane detector. The vertical axis is the yield in counts and on the horizontal axis is the ratio of the signal measured in ADC channels on the strip to the signal measured in ADC channels off the back plane of the ΔE silicon. The three peaks correspond to the slit positions at ± 6 mm and 0 mm.

position along the strip in mm where 0 mm is located at the center of the strip. Table 5.2 reports the slope and intercept of all the linear position calibrations, 1 for each strip collecting data during the experiment.

5.2.2 MARS Silicon Stack Energy Calibration

Using a two-layer silicon stack at the focal plane of MARS allows for particle identification (PID) in two ways - ΔE vs. Y-position and ΔE vs. E, where ΔE is the energy lost in the strip silicon and E is the energy deposited in the second silicon. Figure 5.7 shows an example of what
was being monitored online during the experiment. Figure 5.7(a) shows the raw $\Delta E$ vs Y-position for the data collected at the MARS focal plane at $B\rho = 0.5829$ T m magnet settings. The vertical axis is the energy deposited in the $\Delta E$ silicon in channels and the horizontal axis is the calibrated Y-position in units of 0.1 mm. Data from all strips are included in the plot. The expectation is to see horizontal spots corresponding to each residue species incident on the detector. Clearly, the raw data is not behaving in this way. Similarly, Figure 5.7(b) is not providing useful PID spots. The vertical axis is the energy deposited in the $\Delta E$ silicon and the horizontal axis is the energy deposited in the second silicon. Again, data from all strips is included in this plot. The expectation
Table 5.2: The slopes and intercepts for the position calibration of each strip of the MARS ∆E focal plane detector. Strips 0 and 15 were not being read out in the experiment.

is that there will be a well-defined spot corresponding to each residue species. In Figure 5.7(b), though, the spots are not well defined.

A correction must be applied to the data shown in these two plots before moving forward with the analysis of the MARS residues. The non-uniformity of the particle spots makes the data too ambiguous to perform PID and the shifting energies within each particle region makes it impossible to make an energy calibration. It was determined that the most likely reason for the condition of the data was a significant non-uniformity in the thickness of the ∆E silicon. In order to address this, 1 day was dedicated to scanning the surface of the ∆E silicon with an $^{17}$O beam at 4 MeV/nucleon. The results of that scan are shown in Figure 5.8 as ∆E vs. Y-position plots for each of the strips analyzed in the experiment (note: not all strips on the detector were analyzed in the experiment). In each case, the vertical axis is the energy deposited in the ∆E silicon and the horizontal axis is the Y-position along the respective strip. Multiple beam spots can be seen in each figure as the beam was moved across the length of the strip in steps.

For a uniformly thick detector, the band of data should be a horizontal line across the length
Figure 5.7: Two PID figures for the MARS silicon stack data when the spectrometer was tuned for $B_\rho = 0.5829$ T m. (a) The $\Delta E$ vs. Y-position plot. The vertical axis is the energy deposited in the $\Delta E$ silicon in ADC channel number and the horizontal axis is the Y-position along the resistive strip in units of 0.1 mm. (b) The $\Delta E$ vs. E plot for the MARS silicon stack. The vertical axis is the energy deposited in the $\Delta E$ silicon in ADC channel number and the horizontal axis is the energy deposited in the second silicon in ADC channel number.

of each strip and the value of that line should be consistent from strip to strip. The non-linear band of data for each strip and the shifting values from strip to strip confirm that the detector has a significant non-uniformity in its thickness across its face. Indeed, along a single strip the energy deposited in the thinnest region can be as low as 50% of the energy deposited in the thickest region. In order to move forward with the analysis, the beam data in each strip was fit with a 9th order polynomial shown in each figure as the red line. There is no expected analytic form for the non-uniformity of the detector thickness and so the order of the polynomial was selected to be as high as necessary to reproduce the shape.

To perform the energy calibration, two locations were chosen on the detector. Those positions were chosen to be 0 mm on strip 8 and -13.5 mm on strip 8 and data within 0.5 mm on either side of these were considered. Both positions were chosen to be on strip 8 because the pionic fusion data was focused on strip 8 for all $B_\rho$ tunes resulting in strip 8 having the best statistics. The vertical position at -13.5 mm was chosen because it is the approximate location of the center of the
Figure 5.8: The results of the beam scan of the $\Delta E$ silicon at the focal plane of MARS using an $^{17}$O beam. Each histogram corresponds to the data collected on one of the vertical resistive strips (labeled on each histogram) and in each case the vertical axis is the energy deposited in the $\Delta E$ silicon in ADC channel number and the horizontal axis is the vertical position along the resistive strip in 0.1 mm. The red curve in each figure is the 9th order polynomial fit to the data.
$^{7}$Li residue spot which is the most populated species in the data.

Within the position range of -13 mm to -14 mm, the energy deposited in the $\Delta E$ for each event was used to fill a histogram for each MARS $B\rho$ tune. Figure 5.9 shows one of these histograms for the data taken when MARS was tuned for 0.5829 T m. Each group of data in the figure corresponds to a different particle type. The peak corresponding to the $^{7}$Li spot is fit with a Gaussian, the red curve on the figure. The other 3 peaks do not have enough statistics to be useful in this analysis. A similar process is performed for the other 5 $B\rho$ settings and for the energy deposited in the E silicon. Each of these peaked distributions corresponds to incident $^{7}$Li fragments at 1 of 6 known energies (a different energy for each $B\rho$ setting). Importantly, all of these incident particles hit the $\Delta E$ detector in a concentrated region on the detector face and, consequently, all sampled approximately the same silicon thickness. These 6 Gaussian centers can now provide 6 calibration points for the $\Delta E$ energy.

A 7th calibration point comes from the energy deposited in the $\Delta E$ silicon by the $^{17}$O beam that was used to scan the detector face. The energy of the beam is known and the energy deposited at -13.5 mm can be found by solving the 9th order polynomial from Figure 5.8. The 8th, and last, $\Delta E$ calibration point is obtained from the energy deposited by the $^{17}$O beam at the 0 mm position on strip 8, also from the polynomial. Next, TRIM calculations are performed for the energy lost in various silicon thicknesses by the 6 incident energies of $^{7}$Li particles and the incident $^{17}$O beam energy. The resulting data is used to parameterize the energy lost by each particle type as a function of the silicon thickness.

At this point, the only information necessary to obtain a $\Delta E$ calibration is the thickness of the $\Delta E$ silicon at the two selected positions. The space of possible thicknesses at these two positions was explored, and for every pair of possible silicon thicknesses the calculated energy losses for each of the lithium energies and the $^{17}$O beam are determined using the TRIM parameterizations. Those energy losses are compared to the Gaussian centers and the solutions of the 9th order polynomials to make an 8-point energy calibration for the $\Delta E$ silicon.

A calibration is made for the E silicon as well using the residual energies of the 6 lithium spots.
Figure 5.9: The distribution of energies deposited in the $\Delta E$ silicon by particles hitting strip 8 between -13 mm and -14 mm for the data collected when MARS was tuned for $B_\rho = 0.5829$ T m. The vertical axis is the yield in counts and the horizontal axis is the deposited energy in channel number. Each group of events is labeled with the species it corresponds to. The red curve is a Gaussian fit of the peak corresponding to the $^7\text{Li}$ spot.

and the two oxygen beam spots as 8 calibration points for the E. Each of the spots on each of the strips during the $^{17}\text{O}$ scan from Figure 5.8 can also be used as a calibration point by using the $\Delta E$ calibration that was previously found. The $\Delta E$ calibration can be used to determine the energy deposited by the oxygen beam in the first silicon and the residual energy can be calibrated to the centroids of the 1-D $E$ energy distributions.

The two energy calibrations have associated $\chi^2$ values returned by the root fitting procedure. Each is divided by the degrees of freedom for the fit and the two resulting $\frac{\chi^2}{N_{DF}}$ are added in
Figure 5.10: The $\chi^2/\text{NDF}$ results for the $\Delta E$ silicon calibrations produced by varying the two position thicknesses. The vertical axis is the sampled thickness in $\mu$m at the 0 mm position on strip 8 and the horizontal axis is the sampled thickness in $\mu$m at the -13.5 mm position on strip 8. The z axis is the $\chi^2$ result of the energy calibration at the corresponding sampled thicknesses.

This entire process is repeated for a range of silicon thickness pairs. The pair which produces the smallest summed $\chi^2$ is determined to be representative of the actual silicon position thicknesses and the proper energy calibrations. Figure 5.10 shows the $\chi^2$ results over the space of the sampled silicon thicknesses.

The vertical axis on Figure 5.10 is the sampled silicon thickness in $\mu$m at the 0 mm position on strip 8 and the horizontal axis is the sampled silicon thickness in $\mu$m at the -13.5 mm position on strip 8. The z-axis is the value of the summed $\chi^2$s of the $\Delta E$ and E calibrations as described above.
The minimum $\chi^2$ is reached when the 0 mm position is 21.2 $\mu$m thick and the -13.5 mm position is 19.5 $\mu$m thick. The energy calibrations that correspond to this pair of thickness are shown in Figure 5.11.

![Energy calibrations for the $\Delta E$ detector (a) and the E detector (b).](image)

**Figure 5.11:** The energy calibrations for the $\Delta E$ detector (a) and the E detector (b). In both panels, the vertical axis is the energy deposited in the detector in channel number and the horizontal axis is the calculated energy deposited in MeV. The vertical error bars are the Gaussian widths from the respective distributions.

The vertical axes in both plots in Figure 5.11 is the energy deposited in the respective detector in ADC channels and the horizontal axes are the calculated energies deposited in the respective detector in MeV. The vertical error bars are the Gaussian widths, $\sigma$s, for each calibration peak. Using the proper calibration it is also possible to map the thickness at every point on the $\Delta E$ detector using the data collected in the $^{17}$O scan. The 9th order polynomial is used to find the energy deposited at various positions in ADC channels. The $\Delta E$ calibration is used to find the energy deposited in MeV and then SRIM is used to find the thickness of the silicon at that point using the known incident energy of the beam and the lost energy. The results of that analysis can be seen in Figure 5.12. The x- and y-axes correspond to the spatial dimensions of the $\Delta E$ silicon detector. On the x-axis is the strip number that the particle hit. On the y-axis is the distance along
Figure 5.12: The thickness profile of the $\Delta$E detector at the focal plane of MARS. The y-axis is the position along the resistive strips in units of 0.1 mm and the x-axis is the position in the x direction in strip number. The z-axis is the thickness of the detector in $\mu$m.

the resistive strip in units of 0.1 mm. On the z-axis is the thickness of the silicon at each position in $\mu$m.

With the detector calibrations complete and the thickness profile of the $\Delta$E detector characterized, it is now possible to do PID at the MARS focal plane. Figure 5.13 contains all of the data collected at the MARS focal plane for all $\Delta$E detector strips when the spectrometer was tuned for 0.5829 T m. On the vertical axis is the total energy (sum of the energy deposited in the $\Delta$E and the E) of the particle in MeV and on the horizontal axis is the Y-position on the $\Delta$E detector. By moving to the $E_{tot}$ vs. Y-position PID space, the ambiguity caused by the $\Delta$E thickness variation is
Figure 5.13: The $E_{\text{tot}}$ vs. Y-Position PID histogram for the MARS focal plane data at $B \rho = 0.5829$ Tm settings. The vertical axis is the sum of the energies deposited in the $\Delta E$ and E detectors at the MARS focal plane in MeV. The horizontal axis is the Y-Position in 0.1 mm measured on the resistive strips of the $\Delta E$ detector. Each group of events is labeled with the mass and charge state of the particles it corresponds to.

circumvented. It is clear to see the well-separated spots corresponding to different particle species. The mass and charge identities of the various spots are labeled in the figure. The events below the $^7$Li spot are produced by scattered $^4$He beam particles. The disadvantage of moving to the $E_{\text{tot}}$ vs. Y-position PID space is a loss of Z identification as isobars with the same charge state will be indistinguishable. The process for obtaining the Z identification will be discussed in the following section.
5.2.3 Particle Identification at the MARS focal plane

With a calibrated silicon stack and Figure 5.13 it is possible to perform PID on the data at the focal plane of MARS by drawing software gates around each spot of data. While gates could be drawn manually for the most populated spots, the goal of the experiment is to identify high mass pionic fusion residues which are located in a region of the $E_{tot}$ vs. Y-Position space that does not have clear spots of data. In order to produce meaningful gates for arbitrarily large residues, then, the gate positions and sizes were determined analytically by parameterizing each degree of freedom using the data from the populated spots.

The first step in this process was to parameterize the Y-positions of the different species. To do this, each of the 5 most populated spots - A=7, Q=3; A=9, Q=4; A=11, Q=5; A=13, Q=6; A=12, Q=5 - were projected onto the x-axis and Gaussians were fit to each distribution. Figure 5.14 shows the 1D distributions with their Gaussian fits for 3 of the 5 spots in Figure 5.13 - A=7, Q=3; A=9, Q=4; A=11, Q=5. The distributions for the other two spots were omitted to keep the figure readable. The vertical axis is the yield in counts and the horizontal axis is the Y-Position in units of 0.1 mm. Each of the distributions is labeled on the figure with its corresponding spot. The red curves are the Gaussian fits.

The Y-Positions can then be parameterized as a function of the mass-to-charge ratio $(A/Q)$ of the incident particles using the centers of the Gaussian fits. The results of the parameterization are shown in Figure 5.15. The vertical axis in Figure 5.15 is the Y-Position in units of 0.1 mm and the horizontal axis is the $A/Q$. Now, the center of the Y-Position distribution for any spot corresponding to a combination of A and Q is known. A similar parameterization of the $E_{tot}$ was done in which each spot from Figure 5.13 was projected onto the y-axis and the distributions were fit with Gaussians to parameterize the calibrated energy as a function of the known species energy given the MARS tune. The combination of these two parameterizations allows for the determination of the center of any particle’s spot in the $E_{tot}$ vs. Y-Position space.

With the information from above, a center of the software PID gate can be determined for every set of particles with a given A and Q. Next, the width of the gate in both dimensions has
to be determined. Preliminary gates were hand-drawn around each of the 5 most populated spots. Then a rectangular gate is extended in the Y-Position dimension and the integral inside the gate is calculated. This extension is continued until the integral inside the gate produced in the $n^{th}$ extension step includes fewer than $x$ more events than the $(n-1)$ step where $x$ depended on the spot population. Next the same iterative extension is made in the $E_{tot}$ dimension. After the gate has been extended in both dimensions, the integral inside is compared to the integral inside the hand-drawn gate. If the parameterized gate encompasses $>99\%$ of the events inside the hand-drawn gate.
gate, the process for that spot is complete. If the parameterized gate does not meet that threshold, both dimensions are extended by one step and the process of extension in the Y-Position and then the $E_{tot}$ is continued until the threshold is met. Figure 5.16 shows the independently generated gates for the 5 most populated spots using the parameterized Y-Position and $E_{tot}$ centers and the widths from the iterative expansion process.

Once completed for each of the 5 spots, the width of the gate in the Y-Position dimension was parameterized as a function of $E_{tot}$. The width of the gates in the $E_{tot}$ dimension were found to be consistent for all spots for a given $B\rho$ setting. At this point, it is possible to generate gates entirely based on the parameterizations for all particle species. Figure 5.17 shows all of the final gates for

Figure 5.15: The parameterization of the Y-Position as a function of the mass-to-charge ratio ($\frac{A}{Q}$) of the incident residue at the MARS focal plane.
Figure 5.16: Software gates for the 5 most populated spots which were generated using the parameterized Y-Position and $E_{tot}$ centers and the widths after the iterative expansion process.

Each of the 6 MARS $B_ρ$ settings. In each figure, gates are made for the $N = Q + 1$ PID line, the $N = Q + 2$ PID line, and the $^{19}$O spot from the $N = Q + 3$ PID line. The $N = Q + 1$ line begins at the bottom with the $A=7, Q=3$ gate and includes gates for $\frac{A}{Q} = \frac{9}{4}, \frac{11}{5}, \frac{13}{6}, \frac{15}{7}$, and $\frac{17}{8}$. The $N = Q + 2$ line begins with the $A=12, Q=5$ gate and includes gates for $\frac{A}{Q} = \frac{14}{6}, \frac{16}{7}$, and $\frac{18}{8}$. These software gates represent the first step in the PID process.

At the level of PID shown in Figure 5.17, isobars with the same charge state cannot be distinguished from each other. For instance, $^{7}$Li$^{3+}$ is inside the same spot at $^{7}$Be$^{3+}$ and the $^{16}$N$^{7+}$ events of interest cannot be separated from $^{16}$O$^{7+}$ events. The next step in the PID process, then, is to determine the $Z$ of each particle. This is done by utilizing the $Z^2$ dependence of the energy lost.
Figure 5.17: The $E_{tot}$ vs. Y-Position PID gates for all particle species for each of the 6 MARS $B\rho$ settings. Each gate was generated using the parameterization process described in the text for the 5 most populated spots in each figure.
in the $\Delta E$ silicon. Particles with the same mass and total energy but different $Z$ will deposit very different energies in a transmission detector. The non-uniformity of the thickness of the detector complicates the situation (otherwise the $\Delta E$ vs. $Y$-Position and $\Delta E$ vs. $E$ figures would have been used for PID from the start), but by using the thickness map from Figure 5.12 this can become an advantage. Within each $E_{tot}$ vs. $Y$-Position software gate from Figure 5.17, the particles’ $Z$’s can be identified by their energy deposited in the $\Delta E$ vs. the thickness of the detector at the incident position. Figure 5.18 shows this $\Delta E$ vs. thickness plot for the events inside the $A=12$, $Q=5$ gate for the MARS $B\rho = 0.5829$ T m data.

The vertical axis in Figure 5.18 is the energy deposited in the $\Delta E$ silicon in MeV and the horizontal axis is the thickness of the $\Delta E$ detector at the position that the particle hit. In this space, it is clear to see the data separating into bands corresponding to the different particle $Z$s. SRIM calculations can then be used to confirm the species in each band. Figure 5.19 shows the $\Delta E$ vs. Si thickness PID plots for each of the populated $E_{tot}$ vs. $Y$-Position gates for the MARS $B\rho = 0.5829$ setting with the relevant SRIM line calculations overlaid. Each of the bands is labeled with the corresponding PID.

Using the SRIM lines it is possible to make PID gates for each particle species in the $\Delta E$ vs Si thickness space. In the cases of the top and bottom SRIM lines, at each value of Si thickness the distance between the line and the central line is calculated. The gate boundary is then defined as halfway between the two SRIM lines. Therefore, the two gate boundaries for the central SRIM line are asymmetric and always halfway between the central line and an outer line. For the outside lines, the distance from the line to the second gate boundary is the same as the halfway distance so that the gates for the outside SRIM lines are symmetric. Figure 5.20 is the same plot as Figure 5.18 but with the gates overlaid on the data. This process represents the second and last step in the PID procedure for the MARS silicon stack. For each residue at the MARS focal plane, the $E_{tot}$ and $Y$-Position are tested to see if the event lies inside of any $E_{tot}$ vs. $Y$-Position gates. If the event is inside one (and only one) of the gates, then the particle’s $\Delta E$ and the thickness of the silicon at the incident location are tested to see if the event is inside any of the $\Delta E$ vs. Si thickness gates. If
Figure 5.18: The $\Delta E$ vs. Si thickness PID plot for events inside the $A=12$, $Q=5$ $E_{\text{tot}}$ vs Y-Position gate. The vertical axis is the energy deposited in the $\Delta E$ silicon in MeV and the horizontal axis is the thickness of the $\Delta E$ detector at the position the particle hits. The data is separated into bands corresponding to the different particle Zs.

so, the particle is identified as the species corresponding to the SRIM line that defines the gate.

The uncertainty in the PID method was explored in both PID spaces - the $E_{\text{tot}}$ vs. Y-Position and the $\Delta E$ vs. Si thickness plots. In the case of the $E_{\text{tot}}$ vs. Y-position, first the $E_{\text{tot}}$ limits of the analytically produced gates corresponding to the 4 most populated spots in the $N = Z + 1$ line were used to determine the uncertainty of the PID with respect to the Y-Position. Figure 5.21 shows this process on the 4 spots for the data collected with MARS set for 0.5829 T m.

The Y-Positions of all events falling inside each of the 4 $E_{\text{tot}}$ limit ranges from Figure 5.21 can
Figure 5.19: The $\Delta E$ vs. Si thickness PID plots for each of the populated $E_{\text{tot}}$ vs. Y-Position gates for the MARS $B\rho = 0.5829$ setting. The SRIM calculation lines for each of the relevant particle species are overlaid and labeled with the corresponding particle identification.
Figure 5.20: The same plot as in Figure 5.18 with the PID gates overlaid. These software gates represent the second step in the PID process and the identification of the particle Z.

be plotted independently. Figure 5.22 shows the Y-Positions of all events inside the $A = 11, Q = 5$ gate (red) from Figure 5.21 with the Y-Position limits of the gate overlaid on the figure shown by the vertical black lines. The integral of the histogram inside the black lines, $Int_{inside}$, can then be compared to the integral of the histogram outside the lines, $Int_{outside}$. The ratio of the two integrations produces a conservative measure of the uncertainty in the PID.

In the cases of 3 of the 4 spots under consideration (including the one for $A = 11, Q = 4$) many of the events outside the Y-Position gate limits can clearly be attributed to one of the spots in the $N = Z + 2$ line. In the cases where this is an issue, $Int_{outside}$ is integrated over regions that are also the Y-Position limits of the intruding spot. This integration under the reduced area is then scaled
Figure 5.21: The $E_{tot}$ vs. Y-Position data for the MARS setting corresponding to $B_\rho = 0.5829$ Tm. For each of the 4 most populated spots in the $N = Z + 1$ line the $E_{tot}$ limits of the PID gates have been overlaid. The shapes of the Y-Position distributions inside these limits can be analyzed to determine the PID uncertainty in the Y-Position dimension.

to adjust for the decreased area so that it can be compared across cases. After this process, the largest value of $\frac{I_{int\text{, outside}}}{I_{int\text{, inside}}}$ for a combination of spot and $B_\rho$ setting is 0.017. A similar process was performed for the uncertainty contribution of the $E_{tot}$ dimension where histograms were populated inside the Y-Position gate limits and were integrated inside and outside of the $E_{tot}$ gate limits. In all cases, the resulting ratios were approximately an order or magnitude smaller than the contribution in the Y-Position dimension.

The second step of the PID process - the $\Delta E$ vs. Si thickness - also contributes to the uncer-
Figure 5.22: The distribution of Y-positions for events inside the A = 11, Q = 5 $E_{tot}$ gate limits. The vertical axis is the yield in counts and the horizontal axis is the Y-Position. The vertical black lines are the Y-Position edges of the A = 11, Q = 5 gate.

To address this contribution, a histogram was populated for each $\Delta E$ vs. Si thickness gate (the 3 from Figure 5.20, for instance) which shows the distribution of events inside the respective gates. Figure 5.23 is an example of one of these histograms for the case of $^{11}$B. On the vertical axis is the yield in counts and on the horizontal axis is the event’s position inside the gate defined by Equation 5.2.

$$
Position\ in\ Gate = \frac{\Delta E - \Delta E_{SRIM} (Si\ thickness)}{\Delta E_{Gate\ Boundary} (Si\ thickness) - \Delta E_{SRIM} (Si\ thickness)} \tag{5.2}
$$
Figure 5.23: The distribution of $^{11}$B events inside the $\Delta E$ vs. Si thickness gate corresponding to $^{11}$B. The vertical axis is the yield in counts and the horizontal axis is the particle’s position inside the gate defined by Equation 5.2. The limits of 1 and -1 correspond to the locations of the edges of the gate.

In Equation 5.2, $\Delta E$ is the energy deposited in the first silicon, $\Delta E_{SRIM}(Si\, thickness)$ is the value of the SRIM line at the Si thickness value of the event, and $\Delta E_{Gate\, Boundary}(Si\, thickness)$ is the value of the edge of the gate at the Si thickness value of the event. With the horizontal axis defined this way, the bins at the limits of 1 and -1 in Figure 5.23 represent events just inside the edge of the respective gate.

Using Figure 5.23 it is possible to estimate the uncertainty of this step of the PID process. First, Gaussian fits were made for each histogram (corresponding to individual gates at each MARS
setting) which has at least 50 identified particles. Then, the fits can be integrated inside the gates (between -1 and 1 in each case) and outside the gates. The ratio of these two integrations provides a measure of the uncertainty in the number of particles identified. These Gaussians, though, were not able to reproduce the shape of the distributions near the edges and, consequently, under-predicted the uncertainty. Figure 5.24 shows the histogram from Figure 5.23 with the Gaussian fit overlaid. The vertical axis has been changed to log scale in order to see the deviation of the fit from the histogram at the edges.
In order to better understand the behavior of the distributions near the edges of the PID gates, the wings of the distributions were fit with first order polynomials, also shown in Figure 5.24. These fits were integrated from the edges of the gate (either -1 or 1 depending on which line is being considered, the low edge or the high edge) out to the Position in Gate value where the fit crosses the horizontal axis. The sum of the integrations outside the gate on either side can be compared to the integration of the histogram between -1 and 1. When all of the gate distributions with total integrations greater than 50 particles are considered, the case with the largest ratio of integration outside the gate to inside the gate is 0.03. The majority of cases return a ratio much smaller than 0.01.

In the cases of the measurements of the uncertainties associated with both PID steps, only the worst cases have been reported above. This is because in neither case could the magnitude of the uncertainty measurement be meaningfully correlated with the characteristics of the species corresponding to the gates (i.e. Z, A, $E_{tot}$). Thus, there is no possibility to parameterize the uncertainty in order to allow for its determination for particle types with too few counts to do the analyses described above. As a result, a conservative PID uncertainty of 0.04 was used in all cases for the calculation of cross sections.

5.2.4 Determination of Detection Efficiencies

There are multiple detection and identification efficiencies which must be accounted for in order to make a high precision measurement. This section will detail the process for obtaining each one and report the results.

The first consideration is the livetime of the data acquisition system. While the data acquisition computer is processing information, there is a short time during which no new events can be recorded. This length of time is approximately 5 orders of magnitude longer than the time between beam bursts, however, so there is some chance that a portion of the events of interest will not be recorded. In order to measure the livetime of the system, two pulsers were sending signals into the acquisition system during the experiment - one with a frequency of 3 Hz and the other with a frequency of 50 Hz. Section 2.5.4 discusses these pulsers in more detail. The signals out of these
two pulsers were entirely uncorrelated with beam events or the frequency of beam bursts.

Each of the two pulser signals was discriminated and the discriminator logic signals were counted by two scalers and read into the data stream. One of the scalers was always live and counting while the other scaler was inhibited using the computer’s busy output. The ratio of the number counted in the inhibited scaler to the number counted in the raw scaler provides a measurement of the experimental live time, one measurement for each of the two pulsers. Theses two ratios were evaluated for 6 different sets within the data, producing 2 livetime measurements for each of the 6 MARS $B_\rho$ settings. The value of the livetime produced using the 50 Hz pulser was used in the calculation of the cross sections. The uncertainty in the livetime measurement was set to be the absolute value of the difference between the ratios from the two pulsers. Table 5.3 reports the livetimes for each $B_\rho$ setting.

<table>
<thead>
<tr>
<th>MARS $B_\rho$ Setting</th>
<th>Livetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5363 T m</td>
<td>0.942 ± 0.003</td>
</tr>
<tr>
<td>0.554 T m</td>
<td>0.944 ± 0.003</td>
</tr>
<tr>
<td>0.5829 T m</td>
<td>0.917 ± 0.003</td>
</tr>
<tr>
<td>0.6073 T m</td>
<td>0.938 ± 0.003</td>
</tr>
<tr>
<td>0.6304 T m</td>
<td>0.898 ± 0.003</td>
</tr>
<tr>
<td>0.6657 T m</td>
<td>0.912 ± 0.003</td>
</tr>
</tbody>
</table>

Table 5.3: The values of the livetime of the data acquisition system for each of the sets of data corresponding to 1 of the 6 measured $B_\rho$ settings of MARS. In each case, the reported livetime is the ratio of the inhibited scaler counts to the live scaler counts for the 50 Hz pulser. The uncertainty on each measurement is the absolute value of the difference between the ratio determined using the 50 Hz pulser and the ratio determined using the 3 Hz pulser.

The next efficiency to be discussed is the efficiency of the transmission of residues through MARS. This analysis is a measurement of the likelihood that a particle that enters the spectrometer will be transported to the focal plane. In order to determine this efficiency, a separate experiment was performed using a beam of 3.4 MeV/nucleon $^{16}$O$^7+$. The beam energy corresponds to the center of mass energy of the pionic fusion reaction and the beam species is an analog for the
$^{16}\text{N}^7+$ pionic fusion residues of interest. Section 4.1 discussed this experiment in detail. The analysis found that the transmission efficiency for the residues of interest through MARS using the experimental $B_\rho$ magnet settings is $0.262 \pm 0.008$. This transmission efficiency will be used in the calculation of the pionic fusion experimental cross sections. Importantly, this is the efficiency when the residues are monoenergetic, the rigidity is the same as the central rigidity of the MARS setting, and all particles are entering MARS directly through the center.

In the case of the pionic fusion experiment, residues were entering MARS with a range of magnetic rigidities. Those residues whose rigidities matched the central rigidity of the MARS settings are transported with the efficiency reported above and in Section 4.1. The spectrometer accepts a range of rigidities, however, and the transmission efficiency of the spectrometer will vary as the particle rigidity moves away from the central spectrometer setting. The size of the momentum window that MARS accepts is determined by the gap size of the MARS Coffin slits. During the pionic fusion experiment the Coffin slits were opened to $\pm 3$ cm.

The nature of the issue is best demonstrated by Figure 5.25 - the velocity distribution of identified $^{11}\text{B}$ residues at the MARS focal plane for the $B_\rho = 0.5829$ T m spectrometer settings. The distribution is peaked around the velocity corresponding to 0.5829 T m. The actual velocity distribution of $^{11}\text{B}$ residues produced in the $^4\text{He} + ^{12}\text{C}$ reaction, however, is not expected to have any such peaking. Indeed, this same peaked distribution can be found for all residue types (with significant statistics) and at all rigidity settings. As the particle velocities move away from the velocity corresponding to the $B_\rho$ tune, the MARS transport efficiency drops from the 26.16% reported above. This effect needs to be accounted for in order to use the data for non-central particle velocities.

It is the case that there is a "real" distribution of particle velocities which is being distorted by the variable efficiency as a function of particle velocity to produce Figure 5.25. The first step in the process of accounting for this efficiency is to find what this "real" distribution looks like. This information cannot be obtained directly through analysis of the particle velocity distributions, but it can come from considering the particle yields as a function of MARS $B_\rho$ setting. Figure 5.26
Figure 5.25: The velocity distribution for $^{11}\text{B}$ residues at the MARS focal plane for the MARS $B\rho$ settings for 0.5829 T m. The vertical axis the yield in counts and the horizontal axis is the particle velocity in units of $c$. The distribution is peaked around the velocity corresponding to the $B\rho$ setting of MARS and falls off on either side due to the falling transmission efficiency.

shows scaled particle yields for $^{11}\text{B}$ as a function of velocities corresponding to the 6 $B\rho$ MARS settings. Each of these points is an integration of a velocity distribution like the one in Figure 5.25. The scaled yields are essentially intermediate cross sections which do not have all of the various efficiencies and uncertainties accounted for. The reason for performing this scaling is simply so that the particle yields from the different $B\rho$ settings (which were run for various lengths of time and saw various beam rates) can be compared. The red line in Figure 5.26 is an exponential fit which approximately tracks the $^{11}\text{B}$ trend over the range of velocities.
Figure 5.26: Figure showing the scaled yield of $^{11}\text{B}$ residues at the MARS focal plane for 6 velocities corresponding to the 6 MARS $B\rho$ settings. The scaled yield allows the 6 sets of data to be compared to one another despite the data being collected for different lengths of time and with different average beam intensity. The red line is an exponential fit which reproduces the trend of $^{11}\text{B}$ yields over the range of velocities.

An assumption is made that the distribution varies smoothly and monotonically in this region. The exponential fit from Figure 5.26 is an approximation of the "real" velocity distribution for the $^{11}\text{B}$ residues. It is possible, then, to rescale the fit and compare it to the experimental velocity distributions. The number of counts in the bin containing the mean velocity of the distribution and the number of counts in the maximum bin are averaged. This average value is then divided by the exponential fit value at the mean velocity to find the scale factor which is then used to rescale the entire fit. Figure 5.27 shows the velocity distribution from Figure 5.25 with the rescaled exponential fit which represents the approximation of the "real" velocity distribution inside this velocity window.
Figure 5.27: The velocity distribution for $^{11}\text{B}$ shown in Figure 5.25 but with the scaled exponential fit overlaid representing the approximation of the "real" velocity distribution of the B residues in this velocity window. The vertical black lines are the limits of the MARS momentum acceptance window as defined in the text.

The difference between the rescaled exponential and the histogram represents the effect of the MARS transmission efficiency changing within the momentum acceptance window. Now, the histogram and the scaled exponential can be integrated over the range of velocities corresponding to the momentum acceptance window and the ratio of these two integrals is the MARS $B_{\rho}$ efficiency. The momentum acceptance window is defined as the symmetric distance around the mean velocity bin which contains $>95\%$ of the histogram entries. Each particle species with appreciable statistics for each MARS $B_{\rho}$ setting can contribute one measurement of the $B_{\rho}$ efficiency. Un-
Fortunately, the trend across MARS $B_\rho$ settings cannot be as confidently approximated for most particles’ scaled yields as was possible for $^{11}\text{B}$ (Figure 5.26). Using only those cases where a simple exponential fit line was consistent with the trend, there are not enough measurements of the $B_\rho$ efficiency to produce a high precision result.

For those particle types whose scaled yields could be confidently reproduced by an exponential (like $^{11}\text{B}$), the integral under the scaled exponential fit inside the momentum acceptance window was compared to the integral of a horizontal line inside the window. The value of the horizontal line was set to the same average value that was used to scale the original exponential fit described above. Figure 5.28 demonstrates this for the same $^{11}\text{B}$ distribution in previous figures. Doing this in all cases like $^{11}\text{B}$ where the original exponential fit (Figure 5.27) was consistent with the overall trend, the flat distribution is $97\% \pm 1\%$ of the exponential ("real") distribution.

Lastly, an assumption is made that the "real" distributions for all particle species, even the ones for which the exponential fits in the first step could not confidently reproduce the trend, are approximately exponentially decaying for higher velocity residues. Understanding that it comes with a systematic error of $3\% \pm 1\%$, the flat distribution approximation can be integrated for every particle species inside the momentum acceptance window. Each of these can be compared to the integration of the histogram over the same window to produce a measurement of the MARS $B_\rho$ efficiency. Equation 5.3 is the calculation of the MARS $B_\rho$ efficiency for a given flat distribution integration, $I_{\text{Flat}}$, and histogram integration, $I_{\text{Hist}}$.

$$B_\rho \text{Eff} = \frac{I_{\text{Hist}}}{I_{\text{Flat}}} \quad (5.3)$$

Figure 5.29 shows the results of this ratio for every particle species at every $B_\rho$ setting with the only condition that the number of identified particles in each distribution be at least 75. The vertical axis is the $B_\rho$ efficiency obtained from each of the particle distributions and the horizontal axis is an arbitrary counting of the distributions that contribute. The red line is the average of the data. The vertical error bars are given by Equation 5.4 where $\Delta I_{\text{Hist}}$ is the square root of the number of counts in the histogram and $\Delta_{\text{Flat}}$ is the absolute value of the difference between the
maximum bin and the center velocity bin. The average value, 0.514 ± 0.002, will be used along with the systematic error to calculate the cross sections.

$$\Delta (B\rho_{Eff}) = \sqrt{\left(\frac{\delta B\rho_{Eff}}{\delta I_{Hist}} \Delta I_{Hist}\right)^2 + \left(\frac{\delta B\rho_{Eff}}{\delta I_{Fit}} \Delta I_{Fit}\right)^2}$$  (5.4)

The fourth efficiency to be discussed is the angular efficiency of MARS. The entrance to the spectrometer is a slit system which was opened to create a 5 cm x 5 cm square entrance during the entirety of the pionic fusion experiment and the center of the opening is 31.1 cm ± 0.3 cm from the target position. Given this information, the pionic fusion final state model discussed in Section
Figure 5.29: The set of MARS $B_\rho$ efficiencies obtained by comparing the integral of the flat distributions to the integral of the velocity distributions inside each momentum acceptance window. The vertical axis is the measured efficiency and the horizontal axis is an arbitrary counting of the distributions providing an independent measurement. The red line is the average of the data.

3.3 was used to determine the fraction of $^{16}$N residues that make it into MARS. The $\cos^2(\theta)$ center of mass angular distribution for the pionic fusion process results in very little deflection off of the beam axis due to the low energy pion emission. The larger limiting factors are the finite size of the beam spot and the range of incident angles of the beam with respect to the target. Even given the limitations of the beam focus, the efficiency of residues of interest entering the spectrometer is predicted to be $> 99\%$. The uncertainty on the efficiency entering MARS was determined by calculating the effect of the distance measurement uncertainty on the acceptance of the residues.
This efficiency will be used only to calculate the cross sections for the $^{16}$N pionic fusion residues as these are the only species for which an analytic form of the angular distribution is assumed. Cross sections for all other particle species are not modified using an assumed angular distribution and so only correspond to the species’ production in the 9 msr solid angle acceptance of MARS.

Even considering only residues with trajectories which enter MARS through the 5 cm x 5 cm slits, the transmission probability of reaching the focal plane is not independent of the angle. For a particle with magnetic rigidity very close to the tuned rigidity of MARS, a trajectory down the center of the entrance will have a higher transmission probability than the same particle with a trajectory off axis. On the other hand, a particle with rigidity that is slightly off of the tuned rigidity may have a higher transmission probability for trajectories that are deflected from the beam axis. This creates a very complicated 2-dimensional efficiency space in angle and $B\rho$ which is, unfortunately, not well understood for MARS. The $B\rho$ efficiency found in Figure 5.29, though, was produced using experimental particle distributions which each sampled the entire angular space of the MARS acceptance and cumulatively sampled a very broad region of the rigidity space. Therefore, this complicated 2-dimensional efficiency space of angle and rigidity has already been accounted for.

The final MARS efficiency which will be discussed is the effect of the charge state distributions of the residues leaving the $^{12}$C target. For each isotope incident on the MARS focal plane silicons, the experiment is only sensitive to a single charge state. The only $^7$Li particles identified, for instance, have a charge state of +3. It is the case, however, that there will be some distribution of $^7$Li charge states downstream of the target. The fraction of $^7$Li particles with charge state +3 is the charge state efficiency. This charge state fraction is calculated for every particle type at each rigidity setting of MARS and the fractional population is used to calculate the cross sections.

A semi-empirical formula [79] was used to predict the equilibrium charge state distribution given the species of the reside and the energy (the central energy for each species at the MARS $B\rho$ settings). In order to use this method, 2 assumptions must be made. First, the assumption is made that the charge state distribution of the species is equilibrated in the target. Second, an
assumption is made that the change in the charge state distribution is negligible after the beam leaves the target and enters the vacuum. Given these assumptions, the first step in the calculation is to find the reduced parameter, $x$, which minimizes the scatter of $q_{\text{mean}}/Z_p$ around a smooth curve and is given by Equation 5.5.

$$x = \left( \frac{v_p}{v_0} Z_p^{-0.52} Z_t^{-0.019} Z_p^{-0.52} v_p / v_0 \right)^{1+1.8/Z_p}$$

(5.5)

In Equation 5.5, $v_p$ is the velocity of the species, $v_0$ is the Bohr velocity of $2.19 \times 10^6$ m/s, $Z_p$ is the Z of the species, and $Z_t$ is the Z of the target ($Z_t = 6$ for the carbon target used in the pionic fusion experiment). Using the reduced parameter, the mean projectile charge state is calculated from Equation 5.6.

$$q_{\text{mean}} = Z_p^{-0.07} \left\{ 12x + x^4 \right\} / x + 6 + 0.3x^{0.5} + 10.37x + x^4$$

(5.6)

Now with the mean charge state calculated, the width parameter, $d$, for the equilibrium charge distribution is calculated using $d = d_0 \sqrt{q_{\text{mean}} \left( 1 - \frac{q_{\text{mean}}}{Z_p} \right)}$ where $d_0$ is determined by experiment to be 0.5 and $k = 0.6$ according to the statistical model of atomic particles [80]. This width parameter is used to find the reduced width, $w$, using Equation 5.7 [79].

$$w = d Z_p^{-0.27} Z_t^{0.035} Z_p^{0.009} f \left( q_{\text{mean}} \right) f \left( Z_p - q_{\text{mean}} \right)$$

(5.7)

where

$$f(x) = \sqrt{\left( x + 0.37 Z_p^{0.6} \right) / x}$$

(5.8)

An assumption is made that the charge state distribution is Gaussian with a width equal to the reduced width, $w$. Now it is possible to calculate the fractional population of each charge state for the given particle using Equation 5.9 [81].
\[ p(q_i) = \frac{N}{w} e^{-\frac{(q_i - q_{\text{mean}})^2}{2w^2}} \]  

(5.9)

In Equation 5.9 \( q_i \) is the charge state, \( p(q_i) \) is the fractional population of the \( q_i \) charge state and \( N \) is a normalization factor which is chosen such that \( \sum_i p(q_i) = 1 \). For each identified residue species, then, the fractional population of the relevant charge state is used in the calculation of the cross section in order to produce total cross sections. There is a 2.3% relative uncertainty of the calculation quoted in [79] for the mean charge state and the uncertainty in the charge state fraction was found to be no higher than 0.03 in the pionic fusion data. Therefore, 0.03 will be the uncertainty on the determination that is used in the cross section determination.

5.2.5 Cross Section Calculation and Results

This section will report in detail the calculations and considerations that produce the final cross sections measured at the MARS focal plane. Equation 5.1 is used to calculate the cross section of each particle type identified at the MARS focal plane.

Each incident particle on the silicon stack is identified using the 2-step PID procedure outlined in Section 5.2.3. In general, the cross sections that will be reported are not angle- or energy-integrated. Only particles inside of 9 msr around the beam axis and only particles inside of a momentum window \( \left( \frac{\delta p}{p} \approx 3\% \right) \) are being considered. For every identified particle, an array element corresponding to that species is incremented. When all of the data for a particular MARS \( B\rho \) setting has been parsed in this way, the measured particle yields must be corrected for the various efficiencies described in Section 5.2.4. Equation 5.10 shows the calculation for this correction for all particle species except the pionic fusion residue of interest, \(^{16}\)N.

\[
\text{Yield}_{\text{Corrected}} = \frac{\text{Yield}_i}{T_L (B\rho) \times \epsilon_{B\rho} \times \epsilon_{B\rho,\text{Flat}} \times \epsilon_{\text{trans}} \times \epsilon_{\text{charge state}}} 
\]  

(5.10)

In Equation 5.10, \( \text{Yield}_i \) is the measured yield of one of the residue species, \( T_L (B\rho) \) is the measured livetime corresponding to the MARS \( B\rho \) setting being analyzed (values in Table 5.3), \( \epsilon_{B\rho} \) is the efficiency due to the momentum acceptance window (0.514), \( \epsilon_{B\rho,\text{Flat}} \) is the modification
introduced in order to use the flat velocity distributions instead of exponentials (0.03), $\epsilon_{\text{trans}}$ is the MARS transmission efficiency for a mono-energetic beam at the center of the $B\rho$ window (0.2616), and $\epsilon_{\text{charge state}}$ is fraction of the species yield in the measured charge state calculated for each residue species.

The case of the $^{16}\text{N}$ residues can be treated a little differently. The goal for these residues is to produce an angle- and energy-integrated cross section. Pionic fusion is the only mechanism which can produce $^{16}\text{N}$ in the reaction of $^4\text{He} + ^{12}\text{C}$. The shape of the energy and angular distributions given this single mechanism can be determined numerically using the Monte Carlo code discussed in Section 3.3. Thus, for the $^{16}\text{N}$ cross section, one more correction is added in the denominator of Equation 5.10 corresponding to the MARS angular efficiency, $\epsilon_{\text{angle}}$, which was also described in Section 5.2.4 and was found to be 0.999. There will be a second correction specific to $^{16}\text{N}$ as a result of only measuring a fraction of the total allowable energy distribution. This second correction factor will be discussed later in this section.

The next step in the calculation of the cross sections is the determination of the uncertainty in the $\text{Yield}_{\text{Corrected}}$. Equation 5.11 shows this calculation. Each of the terms in Equation 5.11 is calculated according to Equations 5.12 through Equation 5.17.

$$
\Delta \text{Yield}_{\text{Corrected}} = \left[ \left( \frac{\delta \text{Yield}_{\text{Corrected}}}{\delta \text{Yield}_i} \Delta \text{Yield}_i \right)^2 + \left( \frac{\delta \text{Yield}_{\text{Corrected}}}{\delta T_L (B\rho)} \Delta T_L (B\rho) \right)^2 + \left( \frac{\delta \text{Yield}_{\text{Corrected}}}{\delta \epsilon_{\text{trans}}} \Delta \epsilon_{\text{trans}} \right)^2 + \left( \frac{\delta \text{Yield}_{\text{Corrected}}}{\delta \epsilon_{\text{B}\rho;\text{Systematic}}} \Delta \epsilon_{\text{B}\rho;\text{Systematic}} \right)^2 + \left( \frac{\delta \text{Yield}_{\text{Corrected}}}{\delta \epsilon_{\text{Charge State}}} \Delta \epsilon_{\text{Charge State}} \right)^2 \right]^{1/2}
$$

$$
\frac{\delta \text{Yield}_{\text{Corrected}}}{\delta \text{Yield}_i} = \frac{1}{T_L (B\rho) * \epsilon_{\text{B}\rho} * \epsilon_{\text{B}\rho;\text{Systematic}} * \epsilon_{\text{trans}} * \epsilon_{\text{charge state}}}
$$

$$
\frac{\delta \text{Yield}_{\text{Corrected}}}{\delta T_L (B\rho)} = -\frac{\text{Yield}_i}{T_L (B\rho)^2 * \epsilon_{\text{B}\rho} * \epsilon_{\text{B}\rho;\text{Systematic}} * \epsilon_{\text{trans}} * \epsilon_{\text{charge state}}}
$$
\[
\frac{\delta Y_i \text{ield}_{\text{Corrected}}}{\delta \epsilon_{Bp}} = -\frac{Y_i \text{ield}_{T} \left( Bp \right) \epsilon_{Bp}^2 \epsilon_{\text{Systematic}} \epsilon_{\text{trans}} \epsilon_{\text{charge state}}}{TL \left( Bp \right) \epsilon_{Bp} \epsilon_{\text{Systematic}} \epsilon_{\text{trans}} \epsilon_{\text{charge state}}} \quad (5.14)
\]

\[
\frac{\delta Y_i \text{ield}_{\text{Corrected}}}{\delta \epsilon_{Bp, \text{Systematic}}} = -\frac{Y_i \text{ield}_{T} \left( Bp \right) \epsilon_{Bp}^2 \epsilon_{Bp, \text{Systematic}} \epsilon_{\text{trans}} \epsilon_{\text{charge state}}}{TL \left( Bp \right) \epsilon_{Bp} \epsilon_{Bp, \text{Systematic}} \epsilon_{\text{trans}} \epsilon_{\text{charge state}}} \quad (5.15)
\]

\[
\frac{\delta Y_i \text{ield}_{\text{Corrected}}}{\delta \epsilon_{\text{trans}}} = -\frac{Y_i \text{ield}_{T} \left( Bp \right) \epsilon_{Bp} \epsilon_{Bp, \text{Systematic}} \epsilon_{\text{trans}} \epsilon_{\text{charge state}}}{TL \left( Bp \right) \epsilon_{Bp} \epsilon_{Bp, \text{Systematic}} \epsilon_{\text{trans}} \epsilon_{\text{charge state}}} \quad (5.16)
\]

\[
\frac{\delta Y_i \text{ield}_{\text{Corrected}}}{\delta \epsilon_{\text{Charge State}}} = -\frac{Y_i \text{ield}_{T} \left( Bp \right) \epsilon_{Bp} \epsilon_{Bp, \text{Systematic}} \epsilon_{\text{trans}} \epsilon_{\text{charge state}} \epsilon_{\text{angle}}^2}{TL \left( Bp \right) \epsilon_{Bp} \epsilon_{Bp, \text{Systematic}} \epsilon_{\text{trans}} \epsilon_{\text{charge state}} \epsilon_{\text{angle}}^2} \quad (5.17)
\]

From Equation 5.11, \( \Delta Y_i \text{ield} \) is the quadrature sum of the statistical uncertainty (\( \sqrt{Y_i \text{ield}} \)) and the PID uncertainty (\( Y_i \text{ield} \ast \Delta \text{PID} \), where \( \Delta \text{PID} \) was estimated in Section 5.2.3 to be 0.04). For the case of \(^{16}\text{N}\) residues, the extra term in Equation 5.11 is \( \left( \frac{\delta Y_i \text{ield}_{\text{Corrected}}}{\delta \epsilon_{\text{angle}}} \Delta \epsilon_{\text{angle}} \right)^2 \) where

\[
\frac{\delta Y_i \text{ield}_{\text{Corrected}}}{\delta \epsilon_{\text{angle}}} = -\frac{Y_i \text{ield}_{T} \left( Bp \right) \epsilon_{Bp} \epsilon_{Bp, \text{Systematic}} \epsilon_{\text{trans}} \epsilon_{\text{charge state}} \epsilon_{\text{angle}}^2}{TL \left( Bp \right) \epsilon_{Bp} \epsilon_{Bp, \text{Systematic}} \epsilon_{\text{trans}} \epsilon_{\text{charge state}} \epsilon_{\text{angle}}^2} \quad (5.18)
\]

Equations 5.10 and 5.11 provide the value and the related uncertainty in the \( N \) term from the cross section equation. The next term is the integrated beam on target. The sum of the MARS CFD scaler for each scaler event at a given \( Bp \) setting is calculated. This total number of MARS CFD scaler counts is used to calculate the integrated beam charge incident on the target during the experimental time using the calibration from Section 5.1.2. That total beam charge deposited, \( I_{\text{charge}} \) in units of C, is converted to total beam particles, \( I \), using Equation 5.19.

\[
I = \frac{I_{\text{charge}}}{Q_{\text{beam}} q_e} \quad (5.19)
\]

In Equation 5.19, \( Q_{\text{beam}} \) is the charge state of the beam (2 for the \(^4\text{He}\) beam) and \( q_e \) is the elemen-
tary charge. The uncertainty in the integrated beam, $\Delta I$, is calculated using the two black lines denoting the fit error in Figure 5.4 to find $\Delta I_{\text{charge}}$ which is then converted to integrated particles using Equation 5.19.

The final term in the calculation of the cross section is the target areal density. The determination of the thickness of the carbon target in the pionic fusion experiment is detailed in Section 5.1.1 and the thickness value is reported in Table 5.1. For the reader’s convenience, each of the uncertainties that go into the cross section calculations is listed in Table 5.4.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Uncertainty Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta P_{ID}$</td>
<td>0.04</td>
</tr>
<tr>
<td>$\Delta T_L$</td>
<td>0.003</td>
</tr>
<tr>
<td>$\Delta \epsilon_{B\rho}$</td>
<td>0.002</td>
</tr>
<tr>
<td>$\Delta \epsilon_{B\rho,\text{Systematic}}$</td>
<td>0.01</td>
</tr>
<tr>
<td>$\Delta \epsilon_{\text{trans}}$</td>
<td>0.008</td>
</tr>
<tr>
<td>$\Delta \epsilon_{\text{Charge State}}$</td>
<td>0.03</td>
</tr>
<tr>
<td>$\Delta \epsilon_{\text{angle}}$</td>
<td>0.004</td>
</tr>
<tr>
<td>$\Delta \rho_{\text{areal}}$</td>
<td>18 $\mu$g/cm$^2$</td>
</tr>
<tr>
<td>$\Delta I$</td>
<td>See Black lines in Figure 5.4</td>
</tr>
</tbody>
</table>

Table 5.4: All of the uncertainties that go into Equations 5.11 through 5.18 with their symbols and their values.

Figure 5.30 shows the measured cross sections for every particle species with at least 1 identified particle and a lifetime long enough to be measured in MARS. Each of the 6 panels corresponds to, and is labeled with, one of the MARS $B\rho$ settings. In each case, the vertical axis is the calculated cross section in barns and the horizontal axis is the particle mass number, $A$. Each elemental species is denoted by a different color and the lines between points are drawn to guide the eye.

The Gemini statistical decay code was used to produce a comparison to the experimental residue cross sections. In total, Gemini was used to produce 58 million deexcitations of the completely fused system ($^{16}$O) with 162 MeV of excitation energy, corresponding to complete fusion of the reacting system. A more detailed discussion of the Gemini results were presented in Section 167.
Figure 5.30: The calculated cross sections at each MARS $B_\rho$ setting for all species with at least 1 identified particle whose lifetime is long enough to survive transport through MARS. In all cases, the vertical axis is the cross section in barns and the horizontal axis is the mass number of the particle, $A$. Each elemental species is drawn in a different color given by the legend and the lines are drawn between points to guide the eye. Note that a non-zero cross section for $^{16}$N was only measured in the 0.5829 T m and the 0.6657 T m windows.
3.2. The particle fragments from Gemini were passed through software filters which approximate the effects of the limited angular range of the MARS entrance and the $B\rho$ acceptance. The number of particles of each species that make it into MARS and are within each $B\rho$ window are then counted. Figure 5.31 shows the Gemini-predicted results overlaid on the experimentally measured results. In each case, the yield of $^{11}$B from Gemini was scaled to the cross section of $^{11}$B for each MARS setting.

The error bars on the Gemini predictions are the quadrature sums of the statistical error given the number of counts of each residue type and the difference in the yield produced in simulations with $0h$ and $7h$ spin. By comparing the calculated cross sections to the scaled yield of each particle from the Gemini simulation it is possible to explore the cross section trend across all particles. In general, each residue species can be produced in more than 1 type of reaction in reality. Gemini, though, is only simulating 1 of those reaction mechanisms - complete fusion and statistical deexcitation of the compound nucleus. Therefore, in the mass regions where the trend predicted by Gemini is consistent with the measured trend, the residues may be being produced in reactions with mechanisms similar to $^{11}$B with at least a large fraction of those coming from complete fusion events. In those regions where the Gemini prediction fails to reproduce the measured trend, it is likely that those residues are primarily being produced in reactions that are not complete fusion events. These other mechanisms likely include incomplete fusion, pickup, and potentially some multifragmentation reactions.

Since $^{11}$B was used for the scaling, the two are identical, by definition, in each panel. Gemini’s predicted trend for the residues with mass at least as large as $^{11}$B tracks fairly well with the measured trend for those residues where Gemini produced a yield greater than 0. This implies that particles in the mass range $A = 11$ to $A = 13$ are being produced in similar types of reactions. However Gemini is not successfully reproducing the trend of particles with mass $A = 7$ to $A = 9$. Gemini does not predict a yield greater than 0 for any residue larger than $A = 13$ for any of the energy ranges.
Figure 5.31: The same 6 panels from Figure 5.30 corresponding to the calculated cross sections (full circles connected by full lines) for all particles identified at the 6 $Bp$ settings for MARS. Overlaid on the calculated cross sections are the results from the Gemini simulation of $^{16}\text{O}$ deexcitations (open circles connected by dashed lines). The Gemini yields were scaled such that the yield for $^{11}\text{B}$ is identical to the calculated cross section. The error bars for the Gemini results are discussed in the text.
5.2.6 $^{16}$N Residues and Pionic Fusion Cross Section

A non-zero cross section for the $^{16}$N residues of interest was only measured at 2 of the 6 $B\rho$ settings - 0.5829 T m and 0.6657 T m. In both cases, only a single event was identified. The cross section corresponding to the single count in the 0.5829 T m window can be integrated over the entire kinematically allowed rigidity range in order to produce an energy-integrated cross section. Figure 5.32 shows the $B\rho$ distribution of the 7+ charge state pionic fusion residues determined by the final state model from Section 3.3. The shaded area of the histogram is the region corresponding to the 0.5829 T m $B\rho$ window. This region contains 42.9% of the total distribution. The $^{16}$N cross section reported in Figure 5.30 (c), 30 ± 30 pb, can be modified by this percentage of the overall allowable distribution to produce the energy-integrated gross cross section - 70 ± 70 pb. Because this measured cross section is consistent with 0 even before background subtraction, this work will be reporting an upper limit for the pionic fusion cross section.

The second count of $^{16}$N was collected in the $B\rho$ window centered at 0.6657 T m. Data was taken at this $B\rho$ setting in order to get a background measurement for the experiment as the allowable energy range for the pionic fusion residues does not extend this high. The data in the $B\rho$ window centered at 0.5363 T m was also a measurement of the experiment background as this is beyond the low edge of the allowable pionic fusion energy distribution. The intention of book-ending the pionic fusion region in this way was to use the two measurements to interpolate a background cross section inside the region of interest which can be subtracted from the gross cross section. Because no $^{16}$N residues were identified inside the window centered at 0.5363 T m, the background can’t be calculated using this interpolation. Instead, the cross section measured in the high $B\rho$ background region will be used to estimate the $^{16}$N background cross section in the region of interest using predictions from simulation.

Addressing this question of the background measurement using predictions from simulation is a tricky proposition. What follows is a discussion regarding determining the most likely sources of $^{16}$N, the steps taken to estimate the background present in the experiment, the assumptions that were made, and their justifications. Fundamentally, however, the source of the high-$B\rho$ $^{16}$N count
cannot be determined with certainty meaning that the estimation from simulation of the level of background in the region of interest can only aspire to be a most plausible estimate. There are some things that are known for certain, however: the background in the region of interest is very low (as only 1 total count was observed) and it is approximately equivalent to what was observed in the high-$B\rho$ region. Given these considerations, the goal of this process will be to produce the most plausible, consistent, and conservative estimation of the background level. The two simulations that were used to attempt to answer this question were Gemini [58] and antisymmetrized molecular dynamics (AMD) [82].

Figure 5.32: The allowable distribution of magnetic rigidities for the $^{16}\text{N}^{7+}$ pionic fusion residues determined using the final state model described in Section 3.3. The shaded region corresponds to the $B\rho$ window centered at 0.5829 T m.
The count of $^{16}$N in the high $B_\rho$ region could only have come from a reaction of the incident beam with a contaminant nucleus with larger mass than the $^{12}$C target. Possible reaction sites include the ParTI array materials (CsI(Tl), plastic, aluminum), aluminum from the target ladder or frame, and the various slits throughout MARS. Reactions on ParTI materials can only be initiated by beam particles whose trajectories are significantly off axis as the beam enters the array with $> 2.54$ cm of clearance on all sides. Products from these reactions with the proper rigidity would then have to arrive at the entrance of MARS with a trajectory close enough to the beam axis to enable the particle to be transported while also missing the target ladder structure. Given the thicknesses of the ParTI materials, the location of the target ladder relative to the MARS entrance, and the exclusivity of the MARS acceptance, the situation described is extremely implausible.

It is also very improbable that interactions with MARS slits or beam components could be creating $^{16}$N which is detected at the focal plane. In what could be called a "typical" MARS experiment, the products of interest are close enough in rigidity to the primary beam that the primary beam is steered into the coffin by the first dipole. That primary beam then passes through the MARS coffin slits and is dumped on a Faraday cup along the length of the coffin chamber. In the case of the pionic fusion experiment, the particles of interest were so separated in rigidity from the primary alpha beam that it was not steered into the coffin. Instead, the beam was dumped approximately on a gate valve after the first dipole. From the position of this effective beam dump, it is exceedingly unlikely that a reaction will result in an A=16 particle with a trajectory which will allow it to be accepted by the coffin slits and exit the the coffin’s downstream end with an appropriate energy to pass the velocity filter.

The most probable source of background $^{16}$N, then, are reactions on non-$^{12}$C nuclei at the target location as the kinematics provide the possibility to create a fragment that can be transported through MARS. While trace materials are certainly present, the most likely contaminant species at the target position are $^{13}$C in the target foil, aluminum in the target frame, and oxygen from adsorbed water on the surface of the target foil. The target foils were made with enriched $^{12}$C with a quoted purity of $> 99.9\%$. It is also extremely unlikely that a compound nucleus with
around 150 MeV excitation energy will deexcite by emitting only a single nucleon. Indeed, in over 100,000,000 simulated AMD and Gemini events for potential background reactions, there was not a single event which resulted in a fragment with mass $A = A_{\text{system}} - 1$ which would be the case in the $^4\text{He} + ^{13}\text{C} \rightarrow ^{16}\text{N} + \text{p}$ reaction.

While the alpha beam spot in the experiment was focused in the center of the carbon target, the tails of the beam profile do extend onto the aluminum target frame. Because aluminum is significantly more massive than carbon, however, the center of mass velocity of the system is greatly reduced. The $^{16}\text{N}$ fusion residues of interest from reactions on aluminum are centered at just over 15 MeV of total energy (compared to over 56 MeV total energy fusion residues from reactions with $^{12}\text{C}$). This is combined with the fact that the energy lost by the residue through the target frame is much larger than the same residue through the carbon foil as the stopping power of aluminum is much higher than carbon and the frame is more than 450 times thicker than the carbon target. Indeed, Gemini was used to simulate 2,500,000 deexcitations of $^{31}\text{P}$ and results for $^{16}\text{N}$ were considered after the energy lost in the target frame is accounted for. In each case, the reaction location along the thickness dimension is selected randomly and SRIM [75] is used to calculate the energy lost through the remaining thickness of the frame. The simulations resulted in more than 22,000 $^{16}\text{N}$ residues and each one stopped in the target frame. Because the target frame is the thinnest aluminum reaction location, it is extremely unlikely that the nitrogen background is being produced in reactions on beam line structures.

The last potential contamination to be discussed is oxygen adsorbed on the target. The carbon targets were baked under vacuum preceding the experiment in order to reduce the amount of oxygen in the target. However, it was shown in a previous pionic fusion experiment by Horn et al. [7] that it is still reasonable to assume a fairly significant oxygen contamination on the target. That experiment utilized a similar thickness carbon foil and a comparable baking technique and measured their experimental oxygen contamination to be on the order of 1%. This means that there is likely significantly more oxygen to react on than $^{13}\text{C}$ and the $^{16}\text{N}$ fusion residues will be centered around 36 MeV total energy, much closer to the region being measured. For these reasons, the rest of this
section will be dedicated to estimating the pionic fusion background assuming that the source of the high $B\rho$ background count originates from a reaction of a beam alpha on $^{16}$O contamination in the target as this is the most plausible scenario.

The process for estimating the background level of $^{16}$N given the measured cross section in the high $B\rho$ background region will be the same for both simulations. AMD and Gemini will be used to predict the distribution of $^{16}$N rigidities for the background reaction $^4$He + $^{16}$O $\rightarrow$ $^{16}$N + X. The number of predicted residues summed in the high $B\rho$ background region will then be compared to the sum predicted to be in the region of interest. That ratio can then be used to find the predicted background in the region of interest given the experimentally measured cross section in the 0.6657 T m background window.

Gemini was used to simulate 34,000,000 deexcitations of $^{20}$Ne with 176 MeV of excitation energy and between 0$h$ and 5$h$ spin. The cooled fragments were boosted into the lab frame using the center of mass velocity of the system. The $B\rho$ distribution of $^{16}$N fragments predicted by the simulation is shown in Figure 5.33 after the energy lost in the carbon target has been accounted for. The green shaded region corresponds to the region of interest for pionic fusion residues and the red shaded region corresponds to the high $B\rho$ window. Gemini predicts that the number of $^{16}$N residues created in reactions on $^{16}$O in the region of interest is 5.6 times higher than the $^{16}$N production in the measured background region. Applying this result to the measured high $B\rho$ cross section of 30 ± 30 pb, the Gemini-predicted $^{16}$N background in the pionic fusion region of interest is 200 ± 200 pb.

AMD was used to simulate 192,000 reactions of $^4$He + $^{16}$O to 300 fm/c. Each of those events was deexcited 100 times using the Gemini deexcitation code [58] to create 19,200,00 cooled events. The $B\rho$ distribution of $^{16}$N products from those simulations are shown in Figure 5.34 after the velocity boost from the center of mass has been applied. The energy lost by the $^{16}$N in the carbon target has also been accounted for. Again, the green shaded region corresponds to the region of interest for pionic fusion residues and the red shaded region corresponds to the high $B\rho$ window. There are more than 1100 counts inside the region of interest and 0 counts inside the high $B\rho$
Figure 5.33: The $^{16}$N $B\rho$ distribution predicted by Gemini deexcitations of $^{20}$Ne compound nuclei from reactions of the experimental alpha beam on $^{16}$O contamination in the target. The horizontal axis is the $^{16}$N magnetic rigidity in Tm. The green shaded area indicates the region of interest for pionic fusion residues and the red shaded area indicates the high $B\rho$ background region. The energy lost by the $^{16}$N residues in the carbon target has been accounted for.

These results suggest that the background level of $^{16}$N from beam reactions on $^{16}$O in the region of interest should be more than 1100 times higher than the background in the high $B\rho$ region. This is nonsensical according to the measured data which indicate a ratio of around 3 if one simply considers the widths of the region of interest and the high $B\rho$ background.

While it is disappointing that a more comprehensive model (compared with Gemini) does not yield meaningful results, it is not entirely surprising. The combination of system size, projectile energy, and desired observable (fragments with most of the mass of the system) conspire to create a
Figure 5.34: The $^{16}\text{N}$ $B\rho$ distribution predicted by AMD-simulated collisions of $^4\text{He} + ^{16}\text{O}$ followed by Gemini deexcitations to predict the contributions from reactions of the experimental alpha beam on oxygen contamination in the target. The horizontal axis is the $^{16}\text{N}$ magnetic rigidity in T m. The green shaded area indicated the region of interest for pionic fusion residues and the red shaded area indicates the high $B\rho$ background region. The $^{16}\text{N}$ rigidities have been adjusted for the energy lost by the residue in the carbon target.

very difficult-to-model situation. It has been hypothesized that the predicted $^{16}\text{N}$ production shown in Figure 5.34 could be coming from a semi-transparent process in which the reacting partners in AMD nearly pass through each other with only 1 nucleon-nucleon interaction. Such processes have been observed before in AMD calculations [83]; however, to confidently characterize the process being observed in this case would require a more concerted effort than was in the scope of this project. Regardless of the true process that AMD is predicting, the results are not consistent
with the experiment and not useful for addressing the level of background.

Given the results of the two simulation efforts, the background estimate will be made using the prediction from Gemini deexcitations of $^{20}$Ne. The ratio of events inside the region of interest to inside the high $B\rho$ background region are plausible when compared to the experimentally measured cross sections in the two regions and offer a more conservative estimation of background compared to a flat background estimation. Considering the uncertainty of the source of the background count and the large error bars associated with each of these results due to low statistics, this process has met the standards of probability, consistency with experiment, and conservativeness that were established at the outset.

With an acceptable background estimate established in the region of interest, the upper limit on the measured cross section can be reported. In this case, the upper limit is defined as the limit of sensitivity of the experiment, the high edge of the $1\sigma$ error bar on the background estimation in the region of interest. As reported above, the estimated background predicted using the results of the Gemini deexcitations is $200 \pm 200$ pb. The upper limit on the cross section, therefore, is 400 pb. In Figure 5.35, the upper limit of the cross section for the pionic fusion reaction $^4$He + $^{12}$C → $^{16}$N + $\pi^+$ (blue arrow) is compared with existing pionic fusion results (black circles) and the statistical model prediction from Section 3.4 (blue cross).

When compared with the other pionic fusion results, the measurement from this experiment implies a lower cross section than one might expect given the general trend as a function of colliding system mass. The statistical model prediction for the cross section is consistent with the upper limit, but is far enough below the experimental sensitivity that it is not reasonable to conclude whether or not there exists a collective mechanism for pion production in this reaction. It is reasonable to expect that the physics driving the pionic fusion mechanism are sufficiently complex that a simple accounting for the size of the reacting system is not enough to predict cross sections with certainty. Such a situation could plausibly explain why this result is seemingly not consistent with the larger trend produced by previous measurements, none of which used alpha projectiles or the same energy above the pion production threshold (140 MeV center of mass energy). The state
Figure 5.35: The cross section upper limit for the pionic fusion reaction \(^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{N} + \pi^+\) reported in this thesis (blue arrow) compared to existing pionic fusion results (black) and the result of the statistical model from Section 3.4. The previous measurements are from refs. [7, 8, 9, 10]. The blue cross is the statistical model prediction from Section 3.4.

of the field of pionic fusion, however, is not such that the question can be answered confidently - highlighting the necessity for further data and theoretical work.

5.3 Partial Truncated Icosahedron Pionic Fusion Analysis

The Partial Truncated Icosahedron (ParTI) phoswich detector array was designed for the detection of low energy charged pions emitted from pionic fusion reactions. The details of the array including its construction, dimensions, etc. are discussed in Section 2.3. It was used in this experiment with the intention of detecting \(\pi^+\) particles produced in the pionic fusion reaction \(^4\text{He} + ^{12}\text{C}\)
In this section, the process for calibrating and analyzing the ParTI array data will be discussed.

### 5.3.1 The ParTI Array Configuration in the Pionic Fusion Experiment

During the pionic fusion experiment the ParTI array was positioned in the backwards hemisphere, upstream of the target position. The signal paths and hardware configurations reported in Chapter 2 represent the conditions from the pionic fusion experiment. There were complications, however, that compromised various aspects of the ParTI array during the experiment.

Initially, the alignment of the ParTI array was not compatible with the transport of the beam to the target location. As a result, the decision was made to remove the innermost face of the ParTI array which contains the 3 partial hexagonal phoswiches. This reduced the total number of detectors in the array from 15 to 12. The upstream shielding for the ParTI array was also mounted to that inner structure and, thus, it was not present during the experiment. When the beam transport was readjusted to its final state, a possible secondary beam or beam halo was hitting the back (upstream) side of 4 of the phoswiches. In the cases of two of these phoswiches, the rates were orders of magnitude higher than what was deemed safe for the detector and, consequently, they were turned off and remained unpowered throughout the experiment. The other two phoswiches remained on during the experiment, but did not produce usable data. Three more phoswiches near these 4 were experiencing enough incident beam that their triggering capability was turned off such that they were only recorded following a particle being detected at the MARS focal plane.

Figure 5.36 shows a schematic view of the ParTI array color coded for the condition of each detector during the pionic fusion experiment. The sections filled in with white are faces of the array that were not populated either to accommodate the target ladder or as a result of bad alignment (the center 3 phoswiches). The sections filled in with green were collecting data following a MARS trigger and also providing triggers. The 3 sections in orange were powered, but taken out of the trigger such that they were only being recorded with MARS. The sections filled in red were not yielding useful data. The experimental configuration of the ParTI array, then, had 8 of the possible 15 phoswiches collecting data and 5 of a possible 15 triggering the acquisition. This brings the
solid angle coverage of working detectors to 11.7% when the array is being recorded following a particle being detected at the MARS focal plane. The geometrical efficiency for detecting pions from pionic fusion is 3.91% when considering detectors which can trigger the data acquisition and the \( \cos^2\theta \) emission distribution.

### 5.3.2 ParTI Phoswich PID and Energy Calibration

Because the ParTI array was positioned upstream of the target position it was not possible to get calibration points using scattered calibration beams. The fast plastic component of the detectors was also too thick to be able to calibrate the CsI(Tl) component using radioactive sources. Thus, a calibration method was developed based on the procedure described in [74] which relies on a calibration template determined in a separate experiment. Section 4.2 described the phoswich calibration experiment and the process of producing the fast vs. slow templates for the hexagonal and pentagonal phoswiches.

During the pionic fusion experiment, there were three classifications of events which could result in the recording of phoswich data. In the first case, an event in one of the 5 trigger-producing ParTI phoswiches satisfied the muon decay trigger conditions and the response for that phoswich was recorded. In the second case, a residue was detected at the MARS focal plane and all of the ParTI phoswich waveforms were recorded. Finally, in the third case, an event in a ParTI phoswich satisfied the muon decay trigger and a residue was detected in MARS in the same data event. These different types of data events will be used in different analyses discussed throughout the rest of this chapter. Figure 5.37 shows the number of events recorded during the pionic fusion experiment for each of the three trigger classifications and scaler-triggered events. There are approximately 1.5 orders of magnitude more ParTI-triggered events than MARS-triggered and approximately 2 orders of magnitude fewer coincident events than MARS-triggered.

The first step in the ParTI phoswich analysis is the location of the particle implantation response inside the digitization window that was recorded by the SIS 3316 digitizer. This process is nontrivial due to the different event classifications and is further complicated by the nature of the muon decay trigger. In the cases where the phoswich responses were recorded following a residue
Figure 5.36: A schematic representation of the ParTI array that is color coded for the condition of each of the phoswiches during the pionic fusion experiment as noted in the legend.
being detected in MARS, charged particle implantations in the ParTI phoswiches (which typically do not satisfy the muon decay trigger) can be located at any time in the digitization window with respect to the time location of the trigger. In the cases where the phoswich response satisfies the muon decay trigger, the location of the initial charged particle implantation still varies with respect to the location of the trigger. In order to get meaningful fast and slow integrations for PID, then, it is important to systematically locate the implantation responses within each event’s digitization window regardless of the event classification.

In every event, each of the ParTI phoswich responses is parsed in the same way. Beginning in the first digitized time bin, the ADC value at every digitization time is compared to a software
noise threshold until the first bin is reached which is above that threshold. This time bin is tagged as the beginning of the signal. The fast and slow integrations are then performed on the digitized waveform with respect to this time bin. The fast integration is the sum of the ADC values of the time bin that has the location of the beginning of the signal and the following 6 bins (a total of 28 ns). The slow integration is the sum of the ADC values of the 12th time bin after the beginning of the signal and the following 99 bins (a total of 400 ns). This is the same process that is used in the phoswich calibration experiment (Section 4.2) and in the PSI experiment (Section 4.3). In the cases where the phoswich response satisfied the muon decay trigger, there is expected to be a second pulse inside the digitization window. One of the likely sources of this second pulse is a pileup event where a second charged particle from a reaction induced by a subsequent beam burst implants in the detector. For the purposes of determining the PID and energy calibration for the phoswiches in this section, all of the second pulses are ignored and only waveforms in which the second pulse comes after the integration windows are considered.

The 3 panels in Figure 5.38 show the fast vs. slow PID plots for phoswich detector 1 for all data recorded during the pionic fusion experiment for the three different event classifications. In each case, the vertical axis is the fast integration of the phoswich response in ADC channels and the horizontal axis is the slow integration of the phoswich response in ADC channels. Panel (a) includes all events which were triggered by the muon decay trigger in phoswich 1, panel (b) includes all events where phoswich 1 was read in response to a MARS trigger, and panel (c) includes all events where there was a coincidence of both triggers.

The first thing to notice in Figure 5.38 is the quality of the PID space in panel (a). Some of the expected PID structures can be identified including a neutron/γ/cosmic (NGC) line and some true phoswich fast vs. slow PID lines for Z = 1 particle events. However, this detector was chosen for this demonstration because it is one of the more extreme examples of the effect of not having upstream shielding installed. The various hot spots in the PID space are due to charged particles entering the phoswich which do not originate from reactions on the target. There also appears to be a second neutron/γ/cosmic-like line associated with this phenomenon which is likely caused by
Figure 5.38: The fast vs. slow PID plots for the three event classifications for phoswich 1 in the pionic fusion experiment. In each case, the vertical axis is the fast integration of the implantation waveform and the horizontal axis is the slow integration of the waveform. (a) All events in phoswich 1 which were triggered by the muon decay trigger. (b) All events which contained a phoswich response when phoswich 1 was read following a MARS trigger. (c) All events in phoswich 1 which satisfied the muon decay trigger and a residue was detected at the MARS focal plane in the same data event.
these charged particle punching through the phoswiches from the wrong direction.

Panel (b) shows that when a residue is detected at the MARS focal plane, the data in the ParTI array is considerably clearer. In this case, the NGC line and a PID line for Z = 1 events are the only structures in the space and nearly all noticeable effects from the beam-like events are eliminated. Panel (c) which is the coincident classification lies somewhere in the middle of the two other panels with respect to the PID quality. These coincident triggers are also fairly rare making this event classification less useful for the purposes of making PID gates and calibrating.

As mentioned previously, the goal of the energy calibration process is to manipulate the phoswich’s fast vs. slow PID space for the pionic fusion data such that it matches the calibration template corresponding to its detector geometry. The first step in this process is to correct for the fact that the NGC line corresponds to 0 energy deposited in the fast plastic, but does not lie along the horizontal axis due to the fact that some of the CsI slow signal falls inside the fast gate. For each phoswich, points were manually picked along the NGC line and those points were fit with a line. The fast integrations are then corrected on an event-by-event basis in the analysis by subtracting the fast integration value of the NGC line corresponding to the particle’s slow integration. The process is demonstrated in Figure 5.39 where panel (a) shows the fast vs. slow PID plot from Figure 5.38 (b) with the fit of the NGC line overlaid and panel (b) shows the result of the correction such that now the NGC fit line is identically the horizontal axis. A similar process can be necessary to perform regarding the punch-in line’s deviation from the vertical axis due to large signals from the fast plastic leaking into the slow integration gate. However, since this analysis is only interested in pions and Z = 1 fragments, there are very few events depositing large energies in the fast plastic. As a result, only two of the phoswiches needed a correction for the punch-in line and, even in those cases, the deviation from the vertical axis did not manifest until well above the Z = 1 PID region.

After the NGC line and punch-in (where necessary) corrections have been made, the data from each of the ParTI phoswiches needs to be scaled to match the templates (the hexagonal geometry template is shown in Figure 4.5(b)). For each ParTI phoswich, the NGC line-corrected fast integration and the punch-in line-corrected slow integration are independently scaled such that the proton
Figure 5.39: Panel (a) shows the fast vs. slow PID plot for phoswich 1 (the same as Figure 5.38 (b)) with the fit of the NGC line overlaid. Panel (b) shows the transformed fast vs. slow PID plot where the NGC fit line is now on the horizontal axis.

PID line in the pionic fusion data matches the proton line in the template corresponding to the correct geometry. The proper scaling factors for each detector were those that best reproduced the template proton PID line. Figure 5.40 shows the MARS- triggered pionic fusion data for phoswich 1 (the same data shown in the previous 2 figures) after this scaling process overlaid on the hexagonal geometry’s fast vs. slow template. The horizontal axis is the slow integration (the scaled slow integration in the case of the pionic fusion data) and the vertical axis is the fast integration (scaled fast for pionic fusion data). The template data is shown with a colored z axis scale while the pionic fusion data is shown in black points. The determination of the correct scaling is uncertain at the level of 15% in the slow integration dimension which will carry over into the uncertainty of the measured energy. The proton PID line in the pionic fusion data (black) lies on top of the proton line in the template data.

Now, PID gates can be drawn in the fast integration vs. slow integration space. Because each phoswich is scaled so that it matches the template corresponding to its geometry, the PID gates will be drawn on the templates and then applied to each separate set of phoswich data. For both geometry templates, two gates are drawn: a proton PID gate and a pion region gate. The pion
Figure 5.40: Pionic fusion experiment data for MARS-triggered phoswich 1 data after the scaling process is shown in black points. The hexagonal PID template is shown in color underneath the pionic fusion data. The horizontal axis is the phoswich slow integration (scaled in the case of the pionic fusion data) and the vertical axis is the fast integration (also scaled in the case of the pionic fusion data). The proper scaling of the pionic fusion data was determined by a comparison of the proton line in the calibration template and the proton line in the pionic fusion data.

gate in both cases is drawn between the proton line and the NGC line. Figure 5.41 shows the two template fast vs. slow PID spaces expanded around the Z = 1 PID regions with the software proton (red) and pion (black) gates overlaid. Figures 5.42 and 5.43 show these same gates overlaid on each phoswich PID space. The proton PID line is drawn larger than the templates warrant due to the uncertainty in the scaling process and in anticipation of the lower resolution of the phoswiches in the pionic fusion experiment. Therefore, it is reasonable to expect some significant contamination
in the proton pionic fusion data from deuteron events.

![Graph](image)

**Figure 5.41:** The two template fast vs. slow PID spaces (Panel (a) is the hexagonal geometry and panel (b) is for the pentagonal geometry) with the proton (red) and pion (black) software PID gates overlaid. The vertical axis is the fast integration of the implantation pulse in ADC channels and the horizontal axis is the slow integration in ADC channels.

The next step in the calibration method is to apply the energy calibration found for the templates to the pionic fusion data. Due to the poor intrinsic energy resolution of the plastic scintillator, it was decided that the energy determination for particles in the phoswiches would be done using the slow integration and then determining the fast component using SRIM [75]. For each phoswich event inside the proton PID gate, the energy deposited in the CsI(Tl) scintillator is determined using the scaled slow integration and the energy calibration for the correct phoswich geometry from Figure 4.6 (d) for the hexagonal constructions and Figure 4.7 (d) for the pentagonal constructions. With the deposited energy in the CsI(Tl) calculated, the initial energy of the particle is found using SRIM, the identification of the particle as a proton, and the known thickness of the plastic scintillator (3 mm).

Some of these particle energies will be discussed in the following section regarding event coincidence. It is important, though, to comment on the uncertainty in the energy information.
Figure 5.42: Fast vs. slow PID figures for the first 4 of the 8 working ParTI phoswiches in the pionic fusion experiment and their overlaid proton PID and pion region gates.
Figure 5.43: Fast vs. slow PID figures for the remaining 4 of 8 working ParTI phoswiches with their overlaid proton PID and pion region gates.
from the phoswiches and how potentially useful these detectors can be moving forward. First, the scaling process, as described above, includes an estimated 15\% uncertainty in the proper scaling factor in the slow integration dimension. The translation of this scaling uncertainty into an energy uncertainty varies because of the non-zero offset in the calibration, getting larger as the energy deposited in the scintillator increases to a maximum of a 15\% difference in the CsI(Tl) energy. The uncertainty in the calibration is a second source of uncertainty and can be calculated using errors on the fit parameters. For a 55 MeV proton, the uncertainty from the calibration results in a 3\% uncertainty in the calculated energy. Finally, depending upon where the particle hits the phoswich detector, it will have passed through a variable thickness of the plastic scintillator. The largest possible angle that a particle can have entering one of the phoswiches is approximately 7.1° which corresponds to an effective plastic thickness of 3.02 mm, a 0.7\% difference in the thickness. This results in a negligible uncertainty in the deposited energy of protons and charged pions.

Ultimately, the phoswich energy uncertainty in this analysis is estimated to be between 15\% and 20\%. The largest source of uncertainty is the process of scaling the fast and slow integrations in order to match the template. This is only necessary when there is no possibility to have calibration beams during the experiment. For future applications, if precise determination of energies is important, the ParTI array should be used the the forward hemisphere in order to utilize scattered calibration beams.

5.4 Event Matching in MARS and the ParTI Array

In events where a residue was detected at the MARS focal plane each phoswich detector’s response was recorded for the 16 μs surrounding the MARS trigger time. This digitization window spans many beam bursts (which come approximately every 40 ns) and, possibly, many reaction events on the target. It is necessary to determine whether a charged particle detected in the ParTI array is from the same reaction event as the particle detected in MARS. There are two possible trigger classifications which can result in data in both detectors - the MARS-triggered event where the ParTI array is recorded in response to a particle being detected at the MARS focal plane or the coincidence trigger where one of the phoswich responses passed the muon decay trigger require-
ments and a particle was detected in MARS. The majority of events with data in MARS and the ParTI phoswiches fall into the first situation and the process for event matching in those cases is described in Section 5.4.1.

5.4.1 Event Matching for MARS-Triggered Events

In a MARS-triggered event, the recorded response from each phoswich is parsed in order to find a particle implantation. The first time bin with an ADC value above a software threshold is saved as the beginning of an implantation response. Figure 5.44 shows the digitizer time bin number of that signal beginning when the phoswich was recorded as a result of a $^7$Li fragment detected in MARS while the spectrometer was tuned for 0.5829 T m. The horizontal axis is the digitizer time bin of the beginning of the implantation response from the phoswich. For a single species of fragment in MARS at a particular $B\rho$, the time of flight through MARS is sharply peaked and the time required to transport the electronic signal from the MARS focal plane to the electronics near the ParTI array is constant. Therefore, phoswich signals which are produced by particles from the same event as the residue are expected to be located at approximately the same location in time relative to the arrival of the external trigger from MARS. Figure 5.44 shows this to be the case. There is a flat distribution of signal times from events which are uncorrelated with the residue in MARS and a single, sharp peak corresponding to particles produced in reactions from the same beam burst.

Comparable distributions can be made which are tagged on each particle type identified in MARS and for each of the 6 $B\rho$ settings studied during the experiment. Each of these combinations of residue species and central $B\rho$ provides a data point with a particular central velocity. The peak location can be extracted for all residues with enough statistics and their locations in the digitizer time window can be correlated with the velocity of the residue. Figure 5.45 shows the result of this process. The vertical axis is the time bin in the digitizer window and the horizontal axis is the velocity of the residue detected in MARS determined by the central $B\rho$. The red curve is a second order polynomial fit to the data. Ideally this trend should be linear in the case of non-relativistic particle velocities, however the amplitude dependence of the trigger time from the
Figure 5.44: The distribution of implantation times in the ParTI phoswiches when a $^7$Li fragment was detected in MARS during the 0.5829 T m MARS settings. The horizontal axis is the digitizer time bin of the start of the signal. The sharp peak in the distribution corresponds to phoswich events which are from the same event as the MARS residue. Each digitizer time bin is 4 ns wide.

MARS electronics causes the trend at high energies to level off. For this analysis, though, it is only important that the trend is monotonic.

Using the fit calibration from Figure 5.45 it is possible to determine on an event-by-event basis whether a phoswich signal is produced by a particle from the same beam burst as a particle detected in MARS. In each case, the expected velocity of the MARS-detected particle is used to calculate the expected time bin of the phoswich signal using the equation describing the fit. If the actual time bin of the phoswich signal is within 5 bins on either side of the expected time bin, the phoswich
Figure 5.45: The calibration of the implant signal beginning in the ParTI phoswiches as a function of the velocity of MARS residues. The vertical axis is the digitizer time bin where the phoswich signal arrived and the horizontal axis is the velocity of the residue given the MARS tune in units of c. The red curve is a second order polynomial fit to the data.

Now that event coincidences can be determined by the locations of the signals within the digitization window, the number of proton coincidences are shown in Figure 5.46. Panel (a) shows the number of protons measured in coincidence with particular residue species for the 0.5829 T m MARS window. The vertical axis is the count of protons detected and the horizontal axis is the species of the detected residue. Panel (b) shows the ratio of the number of protons detected for a given residue species divided by the number of residues of that species in the 0.5829 T m data.
The vertical axis is the ratio and the horizontal axis is the residue species identification. In both panels, only residue species which had at least 1 coincident proton are shown.

Figure 5.46: (a) The number of protons detected in the ParTI array as a function of the residue species they were detected in coincidence with. The vertical axis is the count of protons and the horizontal axis is the residue species identification. (b) The proton counts from panel (a) divided by the number of residues of each species identified in MARS.

The results of Figure 5.46 track roughly with the available statistics of the residue measurement as one would expect. Figure 5.46 is representative of the data collected at each of the $B\rho$ windows. In Section 5.4.2, the results of the Gemini-simulated deexcitations of $^{20}$Ne compound nuclei will be compared with the results from Figure 5.46.

Figure 5.47 shows the distribution of proton energies when a phoswich response comes in coincidence with a MARS residue for data in the 0.5829 T m $B\rho$ window. The minimum energy for a proton to punch through the fast plastic is 17 MeV and the PID gate for protons does not extend all the way into the punch-in line. This explains the low energy cut off in Figure 5.47 around 19 MeV. Unfortunately, there are not sufficient statistics to create meaningful distributions of proton energies for specific residue species. These results will also be compared with the Gemini deexcitations in Section 5.4.2.
Figure 5.47: The distribution of proton energies detected in the ParTI array in coincidence with any residue detected at the MARS focal plane. The vertical axis is a count of protons and the horizontal axis is the measured proton energy in MeV. Data is from the MARS $B_\rho$ setting at 0.5829 T m.

Moving on to the next possible event classification, a coincidence-triggered event describes the cases where a particle is detected at the MARS focal plane and a phoswich response passes the muon decay trigger conditions in the same event. For the cases described previously in this section where the ParTI array was externally triggered by MARS, the phoswich digitization windows were anchored to the real time arrival of the external MARS trigger. This allowed for the creation of the timing calibration in Figure 5.45. In the cases of the coincident trigger, however, the situation is complicated.

For these coincident events, the general situation can be described in the following way. At
some point in lab time a reaction creates a particle that implants in one of the ParTI phoswiches. At another point in time (or maybe the same time; this is the question that is ultimately being asked) a reaction creates a particle that begins its trajectory through MARS. At some later point in real time, that same phoswich registers another response which satisfies the muon decay trigger. At this point, the relative digitization window is set in the phoswich and the channel is being recorded. All of this must have happened before the signal arrives from the focal plane of MARS that the residue has arrived (technically this all could happen before the would-be MARS residue has even been created). Now that one of the phoswiches is in the middle of being recorded, the signal from MARS arrives at the ParTI digitizer and the external trigger begins the recording of all other phoswiches. From this situation, then, event coincidences must be determined between phoswiches that triggered themselves and the MARS residue and between phoswiches that were externally triggered and the MARS residue. Also complicating this process is the fact that the data stream does not include which phoswich triggered itself, only that at least one did. Furthermore, the total number of coincidence-triggered events is more than 2 orders of magnitude fewer than MARS-triggered events which limits the ability to do an analysis like the one in Figure 5.44 for multiple residue species.

There are two major consequences to what has been described. First, due to the fundamental timing difference between the MARS-triggered and coincidence-triggered events, it is not possible to use the same calibration to determine whether responses are from the same event. Second, there is not enough data in the coincidence-triggered category to produce a reliable comparable analysis. As a result, there will be no event-matching of protons to residues for events in this class. Importantly, this does not have any affect on the coincident pion measurement result in Section 5.4.3 and the number of events being affected is less than 1% of the number of events used in the analysis of the MARS-triggered data.

5.4.2 Comparison of Event Matching to Gemini

The Gemini-simulated deexcitations described in Section 3.2 of the $^{16}$O compound nuclei corresponding to complete fusions of the $^{4}$He + $^{12}$C can be compared to the measured event coinci-
dences in the pionic fusion experiment. In order to accomplish this, the ParTI array software filter developed for the final state model (Section 3.3) was implemented in the Gemini analysis. For each event which produces a fragment which is detected at the MARS focal plane, the number of protons that pass the ParTI array geometry and minimum energy filter are recorded. Figure 5.48 (a) shows the number of protons that are counted as a function of the residue they were coincident with for residues inside the 0.5829 T m $B_{\rho}$ window. Panel (b) shows the number of protons from panel (a) divided by the number of residues of the species produced again as a function of the residue identity. As before, only residues that are inside the 0.5829 T m $B_{\rho}$ gate and the protons that come with them are considered.

Double hits in a ParTI array phoswich were ignored such that in the cases where more than 1 simulated proton hits a single ParTI phoswich, neither is considered when filling the histograms in Figure 5.48. This is done to better match the experiment where double hits in a phoswich will produce fast vs. slow signatures that will not fall in the proton PID gate. Figure 5.48 can be
compared with the experimental results from Figure 5.46. In the experiment, far fewer protons are detected in coincidence with the lighter residues than are detected with the heavier residues. In the case of the simulated fusion events, however, the probability of detecting a proton in coincidence with a residue is mostly flat over the range of detected residue masses. This difference between the measurement and the simulation is consistent with the idea that many of the lighter residues in the experimental data are created in non-fusion reactions. In those other, more peripheral cases the available excitation energies limit the production of protons with enough energy to penetrate the plastic phoswich layer in the backward lab direction.

The other major difference between the Gemini simulation results in Figure 5.48 and the experimental results in Figure 5.46 is the presence of mass 14 residues. While some \( A = 14 \) residues were predicted in the Gemini simulation, none were inside the experimental momentum windows. It seems plausible that the lack of these heavier residue/proton coincidences in the simulation is a statistical limitation. The Gemini-simulated distribution of proton energies which are predicted to come in coincidence with detected residues can also be compared with Figure 5.47. Figure 5.49 shows the two distributions where the Gemini-predicted distribution (red) has been scaled to the experimental result (blue) at 38 MeV proton energy. In the case of both distributions, only protons in coincidence with residues inside the 0.5829 T m window are shown.

The results of Figure 5.49 are representative of the comparison of Gemini and experiment proton energies in each of the measured \( B_\rho \) windows. There is a significant overproduction of protons at the lowest and highest measured energies in the experimental data compared to the simulation. On the lower end, this is likely due to the fact that the transition from the punch-in line to the proton PID line in the fast vs. slow space is somewhat ambiguous. Therefore, it is likely that the experimental proton gate is misidentifying some charged particle events which stop in the fast plastic as low energy protons. There is of course no comparable ambiguity in the simulated results. Regarding the overproduction at high proton energies, this is likely due to what has previously been classified as beam-related events in the phoswiches. Figure 5.38 demonstrates this nicely. In the events where the phoswich is the trigger (panel 5.38(a)) there are prominent beamlike responses
Figure 5.49: The distribution of proton energies detected in the ParTI array in coincidence with any residue detected at the MARS focal plane (blue) and the Gemini prediction of the same distribution (red) scaled to match the experimental yield at 38 MeV. The vertical axis is a count of protons and the horizontal axis is the proton energy in MeV. The experimental data was collected with the MARS $B_\rho$ setting at 0.5829 T m and the simulated data requires a residue to have been produced within the MARS acceptance and with momentum inside the 0.5829 T m window.

which intersect with the higher regions of the proton PID line. When MARS is the event trigger (panel (b)), those beamlike structures are largely gone. They reappear, though, when both MARS and a phoswich trigger the event (panel (c)) which shows that these types of false proton responses can come in coincidence with MARS residues.

Excepting these differences at the extremes of the proton energy range, the Gemini-simulated proton energy distribution reproduces the measured distribution fairly well. The available statistics
in the backward direction and the energy resolution of the ParTI phoswiches limits the conclusions of the analysis. Still, in the proton energy ranges between 25 MeV and 65 MeV, the measured proton energy distribution is consistent with statistical emission from a compound nucleus.

5.4.3 Pionic Fusion Coincidences

Now that the methodology for event matching between the MARS silicon stack and the ParTI array has been established and the experimental results are consistent with the Gemini predictions, it is possible to look for pionic fusion coincidences. Two $^{16}$N residues were detected in the experiment - one inside the region of interest and one inside the high $B_{\rho}$ background region. Figure 5.50 shows the 3 phoswich waveforms that were recorded with the pionic fusion candidate event inside the 0.5829 T m $B_{\rho}$ window. In each case, the vertical axis is the phoswich response amplitude in digitizer ADC channels and the horizontal axis is the digitizer time bins within the digitized window. The red arrows in each panel note the location of the time bin that corresponds to coincident events with $^{16}$N. None of these three responses has the appropriate time to have been produced in the same beam burst as the recorded $^{16}$N residue (the second panel’s signal comes in at time bin 1527 when the expected bin for $^{16}$N is bin 1555). Furthermore, none of the three responses has the characteristic shape of the phoswich response to pion implantations. There were no phoswich waveforms recorded in the background $^{16}$N event.

There are three conclusions that can be drawn from the fact that no phoswich responses came from the same event as the two $^{16}$N residues. First, there are no coincidence pionic fusion events in the data. Second, the $^{16}$N candidate event in the 0.5829 T m window could still potentially have been the result of a pionic fusion reaction. Had any charged particle come in coincidence with the $^{16}$N residue, the event would have necessarily come from a reaction on contamination as the detected mass in the final state would have been higher than the reacting system. Lastly, the fact that no pion-like signals came in coincidence with the background count is a necessary condition given the energy range for pionic fusion.

The search for pion coincidences were extended beyond just $^{16}$N residues. The phoswich responses that were digitized in the same event as any $A = 16$ residues were also analyzed to find
Figure 5.50: The 3 phoswich responses that were recorded in the $^{16}$N event inside the 0.5829 T m $Bp$ window. In each case, the vertical axis is the ADC value in channels and the horizontal axis is the time since the beginning of the digitization window in digitizer time bines. The red arrow in each panel notes the position of phoswich coincident implants with a $^{16}$N residue in MARS. In each case, the beginning of the signal is not in the proper time location for the particle to have come from the same event as the $^{16}$N residue. None of the three waveforms has the characteristic shape of a pion implantation.

pion-like waveforms. All events where a particle was detected at the MARS focal plane that was inside of the A = 16 PID gate in the $E_{tot}$ vs. Y-position space (even if the particle could not be further identified in the $\Delta E$ vs silicon thickness PID step) were considered. There were no pion-like waveforms with the proper timing to indicate that the implantation occurred from the same beam burst as the detected residue. As was the case when considering coincident pions with the background $^{16}$N event, the expectation is that there would not be pions from the same events as
these other A = 16 residues. Had this search resulted in the positive identification of a coincident pion, it would have implied a potential issue with the calibration or PID.

5.5 $\pi^+$ Singles in the ParTI Array

The last type of pionic fusion sensitivity in the experiment is the detection of emitted pions that do not come in coincidence with a $^{16}$N pionic fusion residue in MARS. There were 6 ParTI phoswiches that were triggering the acquisition enabling them to be sensitive to these events (Figure 5.36). For the following analysis, only those detectors will be analyzed and, because the tune of MARS does not matter for ParTI-triggered events, the data which has previously been sorted into MARS $B\rho$ tunes will all be summed together. The general approach to the calculation of the cross section will mirror what has been discussed in Section 5.2. Pions will be identified using the PID gates from Figures 5.42 and 5.43 and various discriminatory analyses based on the known form of the pion waveform responses. That number of detected pions will be modified based on the efficiencies associated with their detection. Finally, this number of pion candidates will be compared to a background measurement to establish a background-subtracted measure of the pionic fusion cross section.

5.5.1 Pion PID Process

Every phoswich waveform response that was recorded in an event which was triggered by the ParTI array is analyzed in the way described throughout this section. The response to the charged particle implantation is located inside the digitization window by finding the first bin above a software threshold. The waveform is then integrated inside the fast and slow integration windows relative to that implantation response. The first step toward being identified as a pion implantation is the fast vs. slow integrations must lie inside the pion PID region (for the appropriate phoswich) shown in Figures 5.42 and 5.43. In order to ensure that the fast and slow integrations are not contaminated by the decay-like pulse in each response (because each of these events satisfied the muon decay trigger), only events in which the two pulses are separated by 412 time bins (1648 ns) are considered. The effect of this will be accounted for in Section 5.5.2.
It should be noted that the pion PID gates in Figures 5.42 and 5.43 do not follow the correct shape for a ΔE-E PID line. These gates were effectively drawn as the space bounded by the proton PID gate, the punch-in line, and the neutron/γ/cosmic line. The PID gate unquestionably encompasses the pion PID line as shown in the results of the PSI experiment in Section 4.3. Ideally, however, the pion PID gate would be much more selective than simply the entirety of the space between the two closest identified fast vs. slow structures. The original intention was to use the fast vs. slow responses from pions detected in coincidence with fusion residues to narrow the area to search for pions without the accompanying MARS residue tag. As previously reported, though, no pions were detected in coincidence with MARS residues such that this PID process cannot be constrained in this way. Thus, the analysis will continue with the very imprecise PID gate and the selectivity will have to be achieved through other discriminatory analyses.

For events which satisfy the time separation of the two pulses and whose fast and slow integrations fall inside the pion PID gate, the next selection criteria is based on the rise of the implantation pulse. Along with any potential pions, the PID region will also be populated with phoswich responses to a variety of other incident radiation events including neutrons and, to a lesser extent, γs. As charged particles, though, the pion phoswich responses will have a fast component corresponding to the energy lost in the fast plastic layer of the phoswich. The uncharged neutrons and γs, however, will only have a slow response. Figure 5.51 shows the distribution of rise times for the phoswich responses inside the pion PID gate. The rise time is calculated by the time bin of the start of the signal subtracted from the time bin of the peak of the signal. In the case of charged particles, this value should be quite small due to the quick rise of the fast component. A software limit was enforced at a 6 bin rise time such that responses with a faster rise than 6 bins move on to the next level of pion PID criteria.

The next pion PID condition relies on the timing between the implantation pulse and the second, decay-like pulse. The primary source of non-pion events inside the pion PID gates and passing the rise time selection are charged particle events which are followed by a true pile up event from a reaction in a subsequent beam burst. In the cases of these true pile up events, the time between
Figure 5.51: The distribution of phoswich implant response rise times for events which fall inside the pion PID gates. Charged pion events will have a fast component corresponding to the energy deposited inside the fast plastic and, thus, responses without this fast response cannot be pion implantations. The shaded region denotes the range of rise times less than 6 bins which pass the pion PID cut.

The implantation and the second pulse will be correlated to the cyclotron RF frequency. Any pion decays, however, will have no correlation to the beam RF. Figure 5.52 (a) shows the full distribution of this timing for phoswich 0. The vertical axis is the number of phoswich responses and the horizontal axis is the location of the implantation pulse in digitizer bin number. Because the second pulse is always at the trigger location around 2000 time bins, this is effectively a measure of the time difference. The first 15 bins of each phoswich response are used to establish a baseline and the distribution is truncated at 1860 bins on the high end due to the previous criteria that the
two pulses be separated enough that the PSD integrations are not contaminated.

Figure 5.52: (a) The full spectrum of ParTI array singles timing for phoswich 0 in the pionic fusion experiment. The vertical axis is the number of phoswich responses with the corresponding timing and the horizontal axis is the digitizer time bin location of the implantation pulse. (b) An expanded section of panel (a) which shows the periodic phenomenon corresponding to the cyclotron RF frequency. The arrow locations note the calculated locations of the beam bursts given the known cyclotron RF frequency.

Figure 5.52 (a) shows an approximately flat distribution of events over the range of implant-to-second pulse separations. Figure 5.52 (b) shows an expanded section of the timing distribution in order to emphasize its periodic structure which is a product of the events from true pile up from a subsequent beam burst. Starting from the bin location of the first peak in the distribution, the known cyclotron frequency, 23.46 MHz, can be used to predict the subsequent peaks in the distribution. The arrow locations note the results of this prediction. The arrow locations are consistent with the peak locations throughout the distribution.

Since the uninteresting pile up events are correlated with these peak locations, one can selectively eliminate them by ignoring phoswich responses that have a peak separation inside one of these RF peaks. For each of the 6 pion singles-sensitive phoswiches in the experiment, a figure like Figure 5.53 is created. The horizontal axis in Figure 5.53 is the phoswich time bin and the
vertical axis is the separation from that time bin to the closest RF peak bin location. The RF peak locations are determined by the calculation using the known RF frequency (the arrow locations in Figure 5.52 (b)). On an event-by-event basis, then, the time between the two peaks in the waveform is tested against the separation from the closest RF peak. If the score is 0 or 1 (meaning the event falls on the peak location or 1 bin to either side) then the event does not pass this level of the pion PID process.

![Graph](image_url)

Figure 5.53: Each phoswich digitization window bin is given a score which notes the bin’s distance to the closest RF peak. Each of the 6 pion singles sensitive phoswiches has a figure comparable to this one for phoswich 0.

The last set of pion PID conditions involve performing a fast vs. slow PSD analysis of the
second, decay-like pulses. True muon decay pulses following pion implantations may or may not have a fast component as this is determined by the direction of the positron decay daughter relative to the phoswich detector. Those with trajectories back towards the target and enough energy to leave the CsI(Tl) in which they implanted will deposit energy in the fast plastic and, thus, have a fast component to the response. Otherwise, there will only be a slow component. In all cases, however, there must be a slow component. So, as a first condition on the PSD of the second pulse, there must be a slow component to move on in the pion PID process.

Next, a more detailed analysis of the fast vs. slow PSD characteristics of the decay pulse can be used to identify potential pion events. The first part of this analysis involves accounting for the implantation pulse which may or may not be contributing to the integrations of the decay pulse. Figure 5.54 shows a phoswich response waveform for an event which has passed all of the pion PID conditions up to this point. One can clearly see the response to the implantation of the charged particle and a well-separated second pulse which may be a result of a daughter muon decay. This second pulse, however, is riding along the tail of the implantation response meaning that any integration of the response will be contaminated. A subtraction of the implantation response is necessary.

In order to properly make the subtraction, it is necessary to describe the shape of the implantation response as it returns to baseline even in the regions where it may be distorted due to the second pulse. The scintillation response from one of the phoswich components can be described analytically in the form of Equation 5.20. Here, \( I(t) \) is the number of photons emitted by the scintillator as a function of time, \( I_0 \) is the amplitude of the signal which depends on the energy deposited and the material characteristics, \( t \) is the time since the implantation, \( \tau_F \) is the characteristic decay time of the scintillator, and \( \tau_R \) is the characteristic rise time of the scintillator. Since the phoswiches have two scintillating components, the total number of photons emitted as a function of time is the sum of two equations of the form of Equation 5.20, one with the characteristic times of the EJ-212 plastic and the other with the characteristic times of the CsI(Tl) crystal.
The characteristic times for the rise and fall of each of the two scintillations are the same for all events and are close to the literature values (given in Table 3.2). There is some expected deviation that can arise from the travel time of the photons through the detector and response times associated with the PMTs. Still, the only terms that need to be determined on an event-by-event basis are the $I_0$ terms for each component which describe the amplitude of the signals. In the case of the fast

$$I(t) = I_0 \left( e^{\frac{-t}{\tau_F}} - e^{\frac{-t}{\tau_R}} \right)$$

(5.20)
component, this is achieved by solving Equation 5.20 for $I_0$ at $t =$ fast peak location, $I(t) =$ fast peak height and using the characteristic times for the plastic scintillation.

Determining $I_0$ for the slow component is more difficult primarily because the sharp response of the fast plastic creates a ringing effect that rides along with the slow component (which can be seen following the fast peak in Figure 5.54). In order to account for the presence of this periodic ringing and statistical fluctuations the waveforms undergo a smoothing process event-by-event. In the smoothed waveform, the value in each time bin is replaced by the average of the values in the bin and the 8 bins surrounding it. Figure 5.55 (a) shows the waveform from Figure 5.54 after the smoothing process. The fast peak is degraded substantially by the process, but the fast scintillation has already been determined. Now, the slow peak is determined by searching the smoothed pulse in the 30 time bins following the time bin of the fast peak + 6 bins. The value at the slow peak and the time location of the slow peak are used to solve Equation 5.20 for $I_0$ using the CsI(Tl) timing characteristics. Now that both $I_0$ terms have been determined, the predicted form of the total scintillation response is determined. Figure 5.55 (b) shows the original phoswich response waveform with the calculated implant response overlaid as the red curve.

With the analytical form of the implantation response determined in each phoswich waveform, fast and slow integrations can be performed on the second pulses and the calculated implantation response can be integrated over the same regions. Then, the integration of the calculation is subtracted from the integration of the raw histogram. Figure 5.56 shows the effect of the subtraction on the fast (panel (a)) and slow (panel (b)) integrations as a function of the starting bin of the implantation signal. In both cases, the vertical axis is the difference in the fast/slow integration before and after the subtraction of the implantation response. When the implantation is most separated from the second pulse (early implantation time bins) the correction from the subtraction is approximately 0. As the separation between the pulses decreases, the effect of the subtraction increases.

Now, with the implantation pulse properly subtracted from the second pulse, the fast and slow integrations can be compared to the standard fast vs. slow PID space. Figure 5.57 shows the fast
Figure 5.55: (a) The same phoswich response as Figure 5.54 after the smoothing process discussed in the text. The vertical axis is the response amplitude in ADC channels and the horizontal axis is the time in ns since the beginning of the digitization window. (b) The same raw phoswich response shown in Figure 5.54 with the calculated analytical form of the implantation pulse overlaid in red.

Figure 5.56: The effect of the implant subtraction on the fast integration of the second pulse (a) and on the slow integration of the second pulse (b). In both cases, the vertical axis is the difference in the integration before and after the subtraction and the horizontal axis is the digitizer time bin of the beginning of the implantation pulse.

vs. slow PID space for implant pulses in phoswich 1 in color and the fast vs. slows of the second pulses after implant subtraction in black. At this point many of the second pulses can be identified.
as pile up proton events as their fast vs. slow signatures fall inside the proton PID region.

Figure 5.57: The fast vs. slow PID space for the implantation responses is shown in color with the fast vs. slow for the second pulses after implant subtraction overlaid in black points.

The same analysis was performed on the PSI data and the results are shown in Figure 5.58. Here, the vertical axis is the integration of the waveform inside the fast gate and the horizontal axis is the integration of the waveform inside the slow gate. The data shown in the colored z-axis is the fast vs. slow PID space for the implantation responses. The data in black shows the fast vs. slow space for integrations of the muon decay pulses. These data confirm that the expected location of the muon decay fast vs. slow signature is, in general, near the neutron/γ line and is never above
the proton line which is just visible at the top of the frame.

Figure 5.58: The fast vs. slow PID space for the data from the PSI experiment for the implantation responses is shown in color with the fast vs. slow for the muon decay pulses overlaid as black points. The majority of the muon decay pulses are very close to the n/γ implantation responses and are never inside or above the proton implantation responses.

Based on the information in Figure 5.58, the last pion PID condition for the pionic fusion data is that the implant subtracted fast and slow integrations of the second pulse must be inside the neutron/γ line or inside the pionic fusion pion gate.
5.5.2 Pion Detection Efficiencies, Uncertainty Calculation, and Cross Section Determination

In the same way that was described for the $^{16}$N data collected at the MARS focal plane, a cross section for pionic fusion can be calculated from the data in the ParTI array using Equation 5.1. The integrated beam flux, $\Phi$, and the areal density of the target, $\rho_{\text{areal}}$, have been discussed already. The number of detected pions, $N$, has to be corrected for the various detection and identification efficiencies inherent in the utilization of the ParTI array. Equation 5.21 shows the process of making this correction where $\epsilon_{\text{Livetime}}$ is the live time of the data acquisition, $\epsilon_{\text{Geo}}$ is the geometrical efficiency for pion detection, $\epsilon_{RF}$ is the efficiency that comes as a consequence of ignoring the events that are correlated with the cyclotron RF peaks, and $\epsilon_{\tau}$ is the percentage of the total muon decay curve that the analysis is sensitive to.

$$N = \frac{N_{\text{measured}}}{\epsilon_{\text{Livetime}}\epsilon_{\text{Geo}}\epsilon_{RF}\epsilon_{\tau}}$$  \hspace{1cm} (5.21)

The live time of the data acquisition was discussed in Section 5.2.4. The geometrical efficiency for the ParTI array was discussed in Section 5.3.1 and reported to be 3.91% after all considerations are made regarding the condition of the ParTI array during the experiment. Given the known cyclotron RF frequency, a beam burst arrives at the target location every 10.66 digitizer time bins. Events which fall inside the time bin where a beam burst arrives or in the two adjacent time bins are ignored in the pion PID process. In practice, then, only approximately 72% of the time window is being accounted for. Therefore, $\epsilon_{RF}$ is 0.72. Finally, the digitizer is only sensitive to up to 8 $\mu$s following each implantation while the muon decay curve, of course, extends to $t = \infty$. The integration of the muon decay curve after the 8 $\mu$s digitization window is 2.6% of the area. Furthermore, the region of consideration is being truncated on the side of quick decays by the necessity that the two peaks be separated by at least as long as the end of the slow integration. Approximately 18% of the muon decay curve is lost in this truncation. Ultimately, considering the two truncations, the lifetime efficiency is approximately 0.79.
There is another important efficiency which has heretofore not been mentioned and cannot be accounted for - the efficiency of the muon decay trigger. Effectively, what is the likelihood given a pion event in a ParTI phoswich that the response will satisfy the muon decay trigger? One could estimate this efficiency with coincident events in MARS and the ParTI array. For those events, what is the ratio of MARS and ParTI triggers versus just MARS triggers? Because there were no coincident events of any kind, however, this kind of estimation is not possible. The effectiveness of the muon decay trigger will depend on various experimental conditions including trigger threshold, PMT voltages, noise levels, and the timing and energy characteristics of the muon decay. Many of these conditions are difficult to reproduce with any accuracy offline and without a charged pion beam. If properly accounted for, the muon decay trigger efficiency would increase the corrected number of measured pion-like events (thus increasing the measured cross section) and would almost certainly be one of the largest sources of error in the measurement. The analysis will proceed without this correction and, at the end of this section, the omission’s effect on the conclusion will be addressed.

Each of the known efficiencies used in Equation 5.21 has an associated uncertainty which will contribute (along with the statistical uncertainty) to the total uncertainty in the determination of the corrected count of pion-like events. The uncertainty in the lifetime measurement, again, was covered in Section 5.2.4 and will not be covered again. The uncertainty in the geometrical efficiency was determined by changing the orientation of the entire ParTI array with respect to the beam by 4.75° in the final state Monte Carlo simulation described in Section 3.3. This is the maximum misalignment of the array for which the beam can still pass through the hole in the center. This results in an uncertainty in the geometrical efficiency of 0.007%.

When considering the uncertainty in the measure of $\epsilon_{RF}$ the exact number of bins being ignored and the total number of digitized bins is known. Therefore, no uncertainties will be associated with this correction. The last uncertainty to examine is with respect to the fraction of the muon decay curve the experiment is sensitive to. The size of the digitization window is known exactly and the uncertainty in the lifetime of charged muons is negligible, both of which imply no contribution to
the uncertainty from this correction. However, for actual pion implants, \( t = 0 \) with respect to the muon decay is not precisely the location of the charged particle implantation response. Instead, the muon decay curve is shifted by the survival time of the implanted pion. Therefore, the uncertainty in \( \epsilon_T \) will be the change in the muon decay curve coverage of the digitization window when that decay curve is offset by 1 pion lifetime, 26 ns. The change in coverage is 1.12\% of the decay curve.

The total uncertainty of the pion cross section measurement was calculated in the same way as for the cross sections at the MARS focal plane (Equations 5.11 through 5.17) except considering the appropriate ParTI efficiencies. With all efficiencies and uncertainties accounted for, the gross cross section calculated for pion candidate events is 82 nb ± 17 nb.

In order to estimate a background measurement for the pion cross section, the entire PID process described in Section 5.5.1 was also performed on all the events with implant fast vs. slow integrations that fall in all other regions of the PID space that are outside the pion gate. No pion implantations are expected to populate this region of the fast vs. slow PID space so any of these phoswich responses which pass all subsequent levels of the pion PID process are false pion-like responses. It was found that 0.44\% of the events inside the non-pion region passed all other pion PID conditions. An assumption is made that the same rate of false positive phoswich responses is possible inside the pion gate. Therefore, using the rate of false positives in all non-pion PID regions and the total number of events inside the pion gate, an estimated number of expected background pion-like events is calculated. This number is then treated exactly like the measured pion candidate events and a background cross section is calculated to be 107 nb ± 22 nb.

With the gross cross section and the background cross section calculated, the background-subtracted cross section is the difference and the uncertainty of that quantity is the uncertainty of the two added in quadrature. This results in a background-subtracted cross section of -25.7 nb ± 27.6 nb. This cross section is consistent with zero. Using the same definition as before for the upper limit (the location of the high 1\( \sigma \) error bar on the background measurement), an upper limit on the pionic fusion cross section from the measurement of single pions can be set at 129 nb.

This result was expected given the measurement consistent with zero made at the MARS focal
plane. Even with the ParTI array performing in its ideal state, the detection of pion singles in the target chamber is a significantly less precise measurement. This is evident in the very different values of the calculated upper limits where the ParTI array’s sensitivity is on the order of $10^3$ worse.

Given the result thus far, the effect of not accounting for the efficiency of the muon decay trigger can be discussed. It is certainly the case that a proper understanding of this efficiency will raise the corrected number of pion-like events calculated inside both the pion and proton gates. Thus, the calculated gross and background cross sections will increase. It is also the case that this efficiency correction will come with some associated uncertainty. The most likely scenario, then, is that the addition of this efficiency will raise the upper limit of this already lower sensitivity measurement and inclusion of the extra uncertainty term would only exacerbate the background-subtracted cross section’s consistency with zero.

However, it is not unreasonable to imagine a scenario in which energy and time dependencies of the muon decay trigger efficiency increase the separation between the gross and background cross sections. Indeed, it is expected that the trigger should be more efficient as the amplitude of the PMT response increases. The efficiency may be higher, then, in the proton line than in the pion gate simply because more energy is being deposited by the particles in the proton line. This argument is complicated, though, by the fact that the muon decay trigger is just as dependent on the amplitude of the second pulse. If the majority of the pion-like events are actually from other background processes (as our data suggests) then the distribution of amplitudes of the second pulses should be identical for implants that fall inside the proton and pion gates.

The efficiency of the muon decay trigger, $\epsilon_{MDT}$ will also depend on the distribution of time separations between the two pulses. As the time between the pulses increases, the baseline of the second pulse is flatter as the scintillation from the implantation has had time to return to zero. The time separation of the two pulses from background events is approximately flat over the range of the digitization window (Figure 5.52) where the separation between the implantation and true muon decays will be shorter on average. Again, this may significantly increase the efficiency of the
trigger inside the proton line compared to true muon decays inside the pion gate. This would have the effect of increasing the corrected number of pion candidate events compared to background events.

It is clear that a more detailed understanding of the muon decay trigger is necessary for nanobarn-or-better pion sensitivity. Still, in the case of this experiment, there is no reason to believe that a proper accounting of this efficiency would have changed the result. In the most extreme case, the difference in the efficiency for events inside the proton and pion gates would overcome the uncertainties in the two measurements such that the background-subtracted cross section would be inconsistent with zero. This would necessarily mean that the measured cross section would be on the order of many nanobarns (since the error bars on the background-subtracted cross section are already on the order of nanobarns). Since this is inconsistent with the result of the detection of residues in MARS, it can be said with confidence that the understanding of the muon decay trigger efficiency is not limiting the ability to report a cross section. This is to say nothing of the significant uncertainty that would be associated with this hypothetical double differential efficiency, \( \delta \epsilon_{MDT} / \delta E \delta dt \).

The condition of the ParTI array in this pionic fusion experiment was compromised to a degree that it is difficult to use this result to motivate future nanobarn-level pion detection experiments using only the array. It is certainly the case that precision pion measurements made inside a target chamber without the ability to tag events based on a more precise instrument (like residues separated by a spectrometer) is a difficult proposition. Still, with an ideally functioning ParTI array (upstream shielded, fully populated, etc.) and the ability to determine the efficiency of the muon decay trigger one can see a path to approaching subnanobarn sensitivity.

5.6 Commentary Regarding other Pionic Fusion Channels

The entirety of this manuscript has been dedicated to the measurement of the cross section of the pionic fusion reaction \( ^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{N} + \pi^+ \) into particle bound states of the fusion residue. In this section I will discuss the possibility of identifying other pionic fusion processes in the discussed experimental data. These processes include pionic fusion through the emission of the
other pion flavors, $\pi^0$ and $\pi^-$, as well as through the $\pi^+$ channel into particle unbound states of $^{16}\text{N}$.

### 5.6.1 Other $\pi^+$ Fusions

First, we will consider the scenario in which pionic fusion occurs and a $\pi^+$ is emitted with energy that leaves the fusion reside in a particle unbound state. It is difficult to estimate the expected cross section of these processes relative to the cross section of pionic fusion into a low energy state. Simply considering statistical emission (as in the model from Section 3.4), the cross section of fusion into particle unbound states should be considerably higher than into near-ground states since the available phase space is much higher. However, if a collective process for pionic fusion exists, that process is likely most likely at the threshold energy as all other statistical processes would be at their lowest in the pionic fusion regime. It is the case, therefore, that the cross section for fusion into particle unbound states could be somewhat lower than fusion into bound states, considerably higher than fusion into bound states, or anywhere in between.

Regardless of the relative probabilities, one can determine what these kinds of $\pi^+$ fusions into particle unbound states would look like in this experimental design. First, the ParTI array would be sensitive to the charged pions and could identify those charged pions as long as they have enough energy to punch through the plastic layer. These lower energy pions, should they exist in the data, are already contributing to the pion singles cross section measurement discussed in Section 5.5.2. Considering these other potential pions changes nothing about the result of that measurement being consistent with zero so nothing further can be said about these other $\pi^+$ fusion reactions based on data from the ParTI array alone.

According to the associated levels of $^{16}\text{N}$ [84], all of the known levels between the ground state and the energy above the pion production threshold decay through the emission of a neutron. The efficiency for detecting the decay neutron in the ParTI array is exceptionally small and so will not contribute to our sensitivity. What remains, though, of the fusion residue is $^{15}\text{N}$ which can be detected at the MARS focal plane provided the momentum distribution of the residues after neutron emission is inside the measured rigidity gates. Figure 5.59 shows the prediction
for the rigidity distribution of $^{15}\text{N}$ after $\pi^+$ emission followed by neutron emission with kinetic energy equal to the difference between the available energy and the kinetic energy of the pion. The horizontal axis is the rigidity of the fusion residue, $B\rho$, and the vertical axis is the number of residues with that rigidity. The shaded region is the total window of rigidities measured during the pionic fusion experiment.

![Figure 5.59: The distribution of magnetic rigidities of $^{15}\text{N}$ $\pi^+$ fusion residues following the pion and neutron emissions. The horizontal axis is the magnetic rigidity, $B\rho$, in T m and the vertical axis is the count of residues. The shaded region is the measured $B\rho$ region in the pionic fusion experiment.](image)

It is clear that, if these events were present in the data, the measurement at the focal plane of
MARS was sensitive to them. The shaded region in Figure 5.59 includes the $B_\rho$ measurements that have been, to this point, called the region of interest and the background regions. Since the predicted distribution of $^{15}\text{N}$ pionic fusion residues is broad enough to cover this entire region, there can be no true background measurement for these processes. A different way of estimating the background is discussed in Section 5.6.4 and a final determination of the $^{15}\text{N}$ detection results is presented.

5.6.2 $\pi^0$ Fusions

The next pionic fusion channel that can be considered is fusion followed by the emission of a $\pi^0$. In this scenario, the experiment is not sensitive at all to the emitted pion as the ParTI array’s detection efficiency for two correlated $\gamma$s (from the decay of the $\pi^0$) is exceedingly small. The fusion residue associated with neutral pion emission in this case is $^{16}\text{O}$. The available final states of the fusion residue are limited, however, by the conservation of isospin number. The entrance channel consists of two reacting nuclei ($^4\text{He}$ and $^{12}\text{C}$) with $T = 0$ ground states. In order to create a pion ($T = 1$) in the final state, the fusion residue must also be in a $T = 1$ state. Therefore, the lowest possible final state of the $^{16}\text{O}$ residue is the lowest $T = 1$ state which, according to the associated levels of $^{16}\text{O}$, is 12.8 MeV above the ground state.

All available known levels of $^{16}\text{O}$ after $\pi^0$ fusion are particle unbound and decay through either proton or alpha emission. The detectable residues associated with $\pi^0$ fusion, therefore, are $^{15}\text{N}$ and $^{12}\text{C}$. The last bending magnet in MARS was set such that the N = Z PID line was not incident on the silicon detector stack so the experiment was not sensitive to $^{12}\text{C}$ pionic fusion residues. As just discussed in Section 5.6.1, though, it was sensitive to $^{15}\text{N}$ residues as long as part of the distribution falls inside the measured $B_\rho$ windows. For this consideration, one can refer back to Figure 5.59. The available energy in the fusion reaction is higher in the case of $\pi^0$ fusion both because the neutral pion mass is smaller than the charged pion mass and because the Q-value of the reaction is larger. Thus, the width of the distribution in Figure 5.59 is more narrow in the $\pi^0$ case, but the location of the center of the distribution is still determined by the center of mass velocity. The experiment, therefore, was sensitive to these $^{15}\text{N}$ fusion residues from the $\pi^0$ channel as well.
There is expected to be a decay proton in coincidence with the potential $^\text{15}\text{N}$ residues following $\pi^0$ fusion. The ParTI array is sensitive to protons, however, they must have at least 17 MeV of kinetic energy in the lab in order to make it through the plastic scintillation layer so that they can be identified. Because all ParTI phoswiches are located in the backward hemisphere and the protons can only have as much energy as is left over after the pion emission, it is very unlikely that an event will exist with a $^\text{15}\text{N}$ residue and an identifiable proton. Still, coincidence events with a $^\text{15}\text{N}$ and any charged particle (a phoswich response with a fast component) can potentially be a signature of a $\pi^0$ fusion. All of these possibilities will be explored in Section 5.6.4.

5.6.3 $\pi^-$ Fusions

The last of the three pionic fusion channels to discuss is $\pi^-$ fusion. The ParTI phoswiches’ sensitivity to incident $\pi^-$ particles was discussed in some detail in Section 4.3. In summary, the fast and slow integrations of the implantation response can be used to identify $\pi^-$ events in the same PID line as $\pi^+$ implantations. However, the capture lifetime of the $\mu^-$ daughters on the detector material nuclei is significantly shorter than the mean lifetime of the muons. The consequence of this is that there is no decay pulse which can be used to further identify the pion event. The sensitivity of the ParTI array is not sufficient to identify charged pions based on the fast vs. slow PID alone. Furthermore, the utilization of the muon decay trigger means that $\pi^-$ events are not likely to be recorded. For these reasons, the experimental sensitivity for $\pi^-$ is effectively zero.

In the case of $\pi^-$ fusion, the associated residue is $^{16}\text{F}$ which is unstable in its ground state. All known energy levels of $^{16}\text{F}$ decay through emission of a proton. There is a reduction in the available energy in this reaction compared to the case of the $\pi^0$ channel because of the Q-value and larger mass of the $\pi^-$. Therefore, the emitted proton will never have enough energy in the lab to be identified in the ParTI phoswiches, but, as in the case of the $\pi^0$ channel, it is possible to look for charged particle coincidences with potentially detectable fusion residues.

Following the proton decay of the $^{16}\text{F}$ residue, one is left with $^{15}\text{O}$ which survives long enough in its ground state to make it to the MARS focal plane. The $+7$ charge state is technically identifiable in the silicon stack inside the $A = 15, Q = 7$ PID spot in the $E_{\text{tot}}$ vs. Y-position space (see
Figure 5.17). There were, however, no identified $^{15}$O residues detected at the MARS focal plane. All excited states of $^{15}$O decay through proton emission into $^{14}$N which is not identifiable at the MARS silicon stack since it is inside the N = Z line which is not being focused onto the detector. Because none of the possible residues are detected and $\pi^-$ responses in the ParTI phoswiches are not discriminatory enough, this experiment was not sensitive to the $\pi^-$ fusion channel.

5.6.4 $^{15}$N Residues as a Signature of Pionic Fusion Reactions

The discussions in the previous sections have demonstrated that $^{15}$N residues inside the momentum region of interest can be an identifier of both $\pi^+$ and $\pi^0$ pionic fusion reactions. A significant number of $^{15}$N residues were detected over the course of the experiment and the calculated cross sections are shown in Figure 5.60 in each of the 6 rigidity windows (black circles). In this section, the experimental events which include a $^{15}$N residue will be considered based on the possible pionic fusion scenarios outlined above.

The strongest coincidence-type event involving a $^{15}$N pionic fusion residue is in the case of a $\pi^+$ fusion where the residue and the charged pion are detected. The consideration of all recorded waveforms in coincidence with $^{15}$N residues, though shows that there are no such events in the data. The next possible scenario requires that an identified proton be detected in one of the ParTI phoswiches in coincidence with a $^{15}$N reside and with an energy inside the allowable region given the available energy in the $\pi^0$ fusion reaction. Again considering all phoswich responses in coincidence with the $^{15}$N residues, there is 1 response with fast and slow integrations that put the event inside the proton PID gate. The center of mass energy measured for the proton is 42.2 MeV which is above the total available energy assuming a $\pi^0$ fusion reaction. If one reconstructs this event assuming a 3-body final state (the proton, $^{15}$N, and a $\pi^0$) the center of mass energy in that final state is over 117 MeV. Since the available energy in a $\pi^0$ fusion reaction is 37 MeV, it can be concluded that this is not a plausible pionic fusion event even considering the uncertainties in the energy and the lab angle given that the ParTI phoswiches are not position sensitive.

Moving one rung further down on the hierarchy of identified pionic fusion-like events, one can look at the number of charged particles that come in coincidence with a $^{15}$N residue. There
are 8 of these types of events detected which span all momentum windows of MARS that were investigated. Nothing more can be said about these charged particles in the ParTI phoswiches as they did not have sufficiency energy to punch into the CsI(Tl) layer which is a requirement for PID and for determination of the energy. The probability that a $\pi^0$ fusion would be followed by a proton emission without sufficient energy to be identified is high, thus it is plausible that some of these events are $\pi^0$ fusions. However, the lack of an identification or energy measurement leaves these events too ill-defined to be of use in this measurement. This is particularly true when one considers that it is quite common for the various background reactions being considered to produce protons with energies in this region.

Having exhausted all the possible cases of a coincident measurement of a $^{15}$N residue and a proton or pion in the ParTI array, one can look just at the number of detected $^{15}$N residue events and compare this to an estimated background. Because no measurement was made in a momentum region outside the distribution of possible pionic fusion residues, the $^{15}$N background cannot be determined in the same way as the $^{16}$N background. Instead, the result of that $^{16}$N background estimate (20 counts in the Gemini prediction corresponds to a cross section of approximately 29 pb) was used to scale the $^{15}$N Gemini predictions. The red crosses in Figure 5.60 represent the Gemini-predicted $^{15}$N cross sections as a function of rigidity. The measured cross sections are consistent (with or smaller than) the cross sections predicted by the Gemini simulation of the most prominent background reaction.

No upper limit will be reported based on the measured $^{15}$N cross sections for a two reasons. First, the method for estimating the background relies on scaling from a previous measurement and so the uncertainties are compounded as it is applied to another low-statistics measurement. Second, there are two pionic fusion channels that are potentially contributing to the production of $^{15}$N residues and one cannot discriminate the two based solely on measurement of the residues in the momentum regions that were measured. Given the uncertainties in this analysis of the various other pionic fusion channels, we cannot confidently place any upper limits.

It is unsurprising that these experimental results are unable to confidently place limits on the
cross sections of these other pionic fusion channels as the experiment was not optimized for these cases. The inability to measure a true background for $^{15}\text{N}$ in this data, even one that can be used to anchor a simulation like in the case of the $^{16}\text{N}$ residues, eliminates any real possibility of making a precision measurement. This is only exacerbated by the fact that considering residues with masses lower than the total mass of the system expands the space of possible background reactions. Barring the detection of a pion event in coincidence with a $^{15}\text{N}$ residue it was extremely unlikely that any conclusions regarding these other channels could have been drawn from this
experiment as it was performed.
6. CONCLUSIONS

An experiment to measure the cross section of the pionic fusion reaction $^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{N} + \pi^+$ was performed at the Cyclotron Institute at Texas A&M University. The Partial Truncated Icosahedron (ParTI) phoswich detector array was designed and characterized for use in the experiment in conjunction with the Momentum Achromat Recoil Spectrometer (MARS). This allowed for experimental sensitivity for the two pionic fusion characteristic identifiers - the charged pion and the fusion residue. A Monte Carlo simulation of pionic fusion final states was developed in order to determine experimental detection efficiencies as well as help determine the experimental regions of interest. A model was developed in order to predict pionic fusion cross sections assuming purely statistical emission from an excited compound nucleus and the results of the model were compared to the experimentally determined upper limit of the cross section.

Geant4 simulations of the ParTI phoswiches were used in the design of the detectors to predict their pion identification capabilities (Section 3.1). The ParTI phoswiches were then constructed and tested in various beam experiments which confirmed that the detectors were operating as they were designed to. The calibration experiment using secondary beams from MARS (Section 4.2) showed the phoswiches to have good fast vs. slow particle identification (PID) characteristics for light charged particles at least up to $Z = 3$. Charged pion beams delivered by the HIPA accelerator at the Paul Scherrer Institute (PSI) were used to confirm the phoswiches’ ability to identify charged pions both through the fast vs. slow PID method and using the characteristic response of the phoswiches to the decay of the implanted muon daughters (Section 4.3). The timing capabilities of the phoswich detectors when recorded using the SIS3316 digitizers were demonstrated through both the measurement of the muon decay curve and through the determination of event coincidences with the MARS spectrometer (Section 5.4.1).

Methodologies were developed and discussed for energy calibration and PID for data collected using a silicon stack with a non-uniformly thin silicon at the MARS focal plane (Section 5.2). Various detection efficiencies related to the transmission of particles of interest through the spec-
trometer were measured (Sections 4.1 and 5.2.4) and used to produce high precision cross section measurements of all species detected at the MARS focal plane (Section 5.2.5). Using the measured cross sections for the $^{16}\text{N}$ pionic fusion residue and Gemini simulations of the background reactions (Section 3.2), an upper limit for the reaction $^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{N} + \pi^+$ was placed at 400 pb (Section 5.2.6). A Weisskopf statistical emission model was developed to compare with the measured cross section (Section 3.4) and the result of the model was consistent with the measured upper limit though the sensitivity of the measurement was not of a level to say with confidence that no collective mechanism for pion production exists.

The path forward for the pionic fusion project at the Cyclotron Institute depends upon future upgrades to the facility. Cross sections for pionic fusion of lighter ions have been reported to be large enough that the facility’s beam intensities for light beams can accommodate a successful measurement. In order to effectively navigate this region, though, a new gas cell should be designed (or the existing one upgraded) to utilize helium targets. The range of possible accelerated energies for helium beams is also limiting the possible pionic fusion reactions in the low mass region. For beams heavier than $^4\text{He}$, the facility is capable of delivering the proper energies, in general, but the delivered beam intensities are too low to combat the declining pionic fusion cross sections as a function of system mass.

This work has shown that MARS can be an exceptionally effective tool for the measurement of these exotic fusion reactions and by coupling it with the ParTI array there remains the potential to perform measurements of a quality that does not exist in the field of pionic fusion. Ultimately, I think it would be unreasonable to attempt a higher mass pionic fusion measurement at the Cyclotron Institute without a significant increase (at least an order of magnitude) in the beam intensity capabilities of the facility.

The ParTI array has applications that extend beyond the measurement of pionic fusion cross sections. The array was designed to be geometrically flexible. It can be configured in any number of partial truncated icosahedron orientations. It can also be configured as a wall or in rings with simple modifications of the tabs that hold the frames together. Each detector can also be used.
as a singular telescope. In general, the ParTI array can be adapted for any experiment in which elemental identification of light charged particles with low angular granularity is acceptable. Because the scintillators are coupled using a thin layer of optical grease, the dynamic range of the detectors can be easily modified as well. The CsI(Tl) layer can be made thicker to facilitate the detection of higher energy light charged particles or the thickness of the plastic scintillator can be reduced in order to extend the elemental identification of the detectors to higher Z particles. For most applications, mounting the array in the forward direction would also be preferable.
REFERENCES


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APPENDIX A

MICRON DATA SHEETS FOR THIN STRIP SILICONS

Figure A.1
Figure A.4
Rear View

Front View

Design W with PSD Metal on Design X1 Ceramic. 3D Assembly.
Front and Rear View.
DETECTOR HANDLING INSTRUCTIONS

These detectors are fragile and are sensitive to contamination from sodium transferred from fingers and mucous.

1. Always wear a pair of close fitting nitrile gloves and a face mask when handling the detector.
2. Remove any tape carefully (glue from the tape can also contaminate the detector) change gloves if necessary.
3. Remove the nuts or screws from the shipping case carefully ensuring that they do not fall onto the surface of the detector. Be careful not to touch the wire bonds.
4. Hold the detector on the sides of the printed circuit board when taking out of the box.
5. Place in a clean dry area.
6. When plugging in the detector hold the edge of the detector making sure to keep the fingers away from the wire bonds, make sure that the ends of cables do not scratch the chip surface.

Supplies of nitrile gloves can be sourced from Kimtech (www.kimtech.com) and face masks from Berkshire (berkshire.com/products/11-face-masks)

Failure to follow these instructions may invalidate your warranty.
Figure A.6
Figure A.8
Figure A.9
Figure A.10
Figure A.13
Lucite/Plexiglass Light guide polish procedure.


2. 1200 grit (MicroMesh 3200) sanding pad. Lubricate with water.

3. 2000 grit (MicroMesh 6000) sanding pad. Lubricate with water.

4. 3000 grit (MicroMesh 12000) sanding pad. Lubricate with water.

5. Novus fine scratch remover.

6. Polishing wheel and rouge step 1. There are 3 blocks of rouge located in the machine shop with polishing wheels for each step. The piece should be polished with each of the 3 steps in succession. Wear gloves and facemask when using the rouge and polishing wheel. Keep the wheel speed at 450 or lower for all polishing wheel steps. Do not hold the guide against the wheel for too long as it will melt. Keep a good grip on the guide at all times, the wheel will tear it out of your hands.

7. Polishing wheel and rouge step 2. Same polishing tips apply for step 2.


Use diaper cloth for wiping during and after each step. Use different cloths for sanding, applying Novus and the 3 different polishing wheels.
APPENDIX C

SOLIDWORKS DRAWINGS FOR THE PIONIC FUSION EXPERIMENT

In this section, all of the technical CAD drawings for the ParTI array, the beam line upgrades, etc. are included. Each section will have a list of descriptions of the drawings that follow.

C.1 ParTI Array

- Figure C.1 is the hexagonal fast plastic component.
- Figure C.2 is the pentagonal fast plastic component.
- Figure C.3 is the fast plastic component for the central partial-hexagonal phoswiches.
- Figure C.4 is the hexagonal CsI(Tl) crystal.
- Figure C.5 is the pentagonal CsI(Tl) crystal.
- Figure C.6 is the CsI(Tl) crystal for the central partial-hexagonal phoswiches.
- Figure C.7 is the hexagonal light guide.
- Figure C.8 is the pentagonal light guide.
- Figure C.9 is the light guide for the central partial-hexagonal phoswiches. This part was machined using the SolidWorks file and a CNC, not using the drawing.
- Figure C.10 is the standard pentagonal phoswich frame.
- Figure C.11 is the pentagonal phoswich frame for the bottom pentagonal phoswiches that connect to the base.
- Figure C.12 is the ring that holds the pentagonal phoswiches into their frames.
- Figure C.13 is the standard hexagonal phoswich frame.
- Figure C.14 is the phoswich frame for the center 3 partial-hexagonal phoswiches.

- Figure C.15 is the ring that holds the hexagonal phoswiches in their frames.

- Figure C.16 is the plate that holds the center 3 phoswiches in the center hexagonal frame.

- Figure C.17 is the tab which makes the hexagonal-to-pentagonal frame connections.

- Figure C.18 is the tab which makes the hexagonal-to-hexagonal frame connections.

- Figure C.19 is the flag which is inserted into the beam pass through hole in the array during alignment in order to sight the vertical dimension from the view port in the MARS target chamber.

- Figure C.20 is the upstream shield for the ParTI array.

- Figure C.21 is the tungsten nozzle that attaches to the center phoswich holder.

- Figure C.22 is the bar which connects to the ParTI base that provides a flat face to make flush with the upstream entrance port for alignment purposes.

- Figure C.23 is the ParTI array base for the MARS target chamber.

- Figure C.24 is the holder for the two upstream leveling feet for the ParTI base.

- Figures C.25 and C.26 are the holders for the two downstream leveling feet for the ParTI base.

- Figure C.27 is the plastic foot that connects the ParTI array to the base from the back pentagonal frame.

- Figure C.28 is the plastic foot that connects the ParTI array to the base from one of the front pentagonal frame.

- Figure C.29 is the plastic foot that connects the ParTI array to the base from the other front pentagonal frame.
All measurements in inches
6x EJ-212
pent fast component

SolidWorks Student Edition.
For Academic Use Only.
All measurements in inches
4x EJ-212
All measurements in inches
8x CsI(T1)

SolidWorks Student Edition.
For Academic Use Only.
All measurements in inches

CsI(Tl)
CsI pent slow component

Figure C.5
All measurements in inches
4x CsI(Tl)
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**3x Aluminum**

**Figure C.10**
3x Aluminum
6x Aluminum

SECTION A-A

5 phoswich holder
12 x $\phi 0.150$ THRU ALL
10-24 UNC THRU ALL

2 x $\phi 0.150$ Hole Depth 0.400
10-24 UNC Hole Depth 0.300

6 x $\phi 0.125$ Hole Depth 0.400

4x Aluminum

Figure C.13
Figure C.14
4x Aluminum

SECTION A-A

DEBUR AND BREAK SHARP EDGES

DIMENSIONS ARE IN MILLIMETERS

UNLESS OTHERWISE SPECIFIED:

FINISH: SURFACE FINISH: TOLERANCES:

LINEAR: ANGULAR:

DO NOT SCALE DRAWING

REVISION

NAME SIGNATURE DATE

DRAWN

CHECKED

APPROVED

MFG

Q.A

SolidWorks Student Edition. For Academic Use Only.

Figure C.15

269
SECTION A-A
SCALE 1:1
1x Titanium
Material supplied by Andrew

3 x Ø 0.194 THRU ALL
On Ø 3.600 circle
60°
A
A
2.000
1.600
1.700

2.500
3 x
0.194 THRU ALL
On 3.600 circle
1.100 typ
on 3.000 circle
1.700 typ
60°
A
A

0.500
1.100
1.300

1x Titanium
Material supplied by Andrew

DEBUR AND BREAK SHARP EDGES
FINISH: UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

Q.A
MFG
APPV'D
CHK'D
DRAWN

SOLIDWORKS Educational Product. For Instructional Use Only.
4 x Ø 0.194 THRU ALL

20.905°

12x Aluminum

Figure C.18
If possible, please score this crosshair into the paddle on both sides.
Figure C.20
MT-18F Tungsten Alloy
All Dimensions in Inches

Figure C.21
Modify existing part

4 x \( \varnothing 0.20 \) THRU ALL
1/4-20 UNC THRU ALL
Figure C.24
Figure C.25

foot block and brace left side
4 x Ø 0.201 THRU ALL
1/4-20 UNC THRU ALL
0.313 THRU ALL
3/8-16 UNC THRU ALL
0.250
1.000
2.000
2.482 ref
3.000
3.300

Ø 0.313 THRU ALL
3/8-16 UNC THRU ALL

0.580

VIEW A
75.00°

foot block and brace right side

SOLIDWORKS Educational Product. For Instructional Use Only.
Figure C.27
1x Poly Carb
C.2 The Z-Cube

- Figure C.30 is the support plate for the Z-Cube.

- Figure C.31 is the aluminum stand construction for the Z-Cube.

- Figure C.32 is the 8 inch conflat flange that has the header PCB potted into it with the feedthroughs for 10 34-pin headers.

- Figure C.33 is an 8 inch conflat with 10 BNC feedthroughs.

- Figure C.34 is an 8 inch conflat with 20 LEMO feedthroughs.

- Figure C.35 is the Z-Cube.
Figure C.32
Figure C.34
C.3 Beam Line Modifications and Pionic Fusion Misc.

- Figure C.36 is the flange designed for the lid of the MARS target chamber in order to house the actuator arm holding the electron-suppressed Faraday cup.

- Figure C.37 is the half nipple which was welded onto the target chamber Faraday cup flange.

- Figure C.38 is the holder for the miniature cameras and the lamp.

- Figure C.39 is the adapter that mounts the camera holder to the partial target ladder beneath the Faraday cup.

- Figure C.40 is the bracket that holds the miniature camera.

- Figure C.41 is the MuMetal sleeve that surrounds each ParTI PMT.

- Figure C.42 is the holder for the two target heating lamps which attaches to the bottom slot cut into the target ladder.

- Figure C.43 is the cover for the heating lamp holder.

- Figure C.44 is the target frame made from Macor which held the beam tuning phosphor on the target ladder to be heated.

- Figure C.45 is the Macor adapter that connected the target ladder to the actuator arm so that the MARS target chamber would not act as a heat sink while the target ladder was being heated under vacuum.
Figure C.39
2x Aluminum

Figure C.40
Figure C.41
Figure C.42
Aluminum

2 x Ø 0.170 THRU ALL

Figure C.43
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**Material:** Macor

**Dimensions:**
- 0.8630
- 1.0650
- 0.4315
- 0.0625
- 0.6000
- 0.5325

**Figure C.44**

SOLIDWORKS Educational Product. For Instructional Use Only.
Macor provided by Andrew Zarrella

Figure C.45
C.4 Electron-Suppressed Faraday Cup

- All drawings for the electron-suppressed Faraday Cup used in the MARS target chamber during the pionic fusion experiment.
**LIST OF MATERIAL**

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⚠️ **MAT'L:**
ACCEPTABLE ALTERNATE - POLYPHENYLENE SULFIDE (PPS)

---

**DRILLED HOLE TOLERANCES**

| .013 TO .136 | +.002 | -.001 | .234 TO .750 | +.005 | -.001 |
| .136 TO .234 | +.003 | -.001 | .750 TO 2.000 | +.006 | -.002 |

**CYCLOTRON INSTITUTE**

ELECTRIC DISC INSULATOR FOR FARADAY CUP

**DRAWN BY S. MOLITOR**

DATE: 10/29/09

**ENG. APPOD.**

**TEAM LEAD.**

**PROG. MGR.**

**DIRECTOR REL.**

**NEXT ASSEMBLY**

**SCALE 4 = 1 SHEET 1 OF 1**

**DWG. NO. A-K5-31-MM-670**

Figure C.46
LIST OF MATERIAL

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⚠️ MAT'L: ACCEPTABLE ALTERNATE – POLYPHENYLENE SULFIDE (PPS)

Figure C.47
APPENDIX D

PARTI ARRAY INSERTION AND ALIGNMENT PROCEDURE

The following is a procedure for inserting and aligning the ParTI array inside the MARS target chamber.

- Before putting the ParTI array in the chamber, sight the target positions using the MARS view port.

- Remove the target and Faraday cup flanges from the MARS target chamber lid and then remove the wedge viewer from its upstream actuator arm as the ParTI array does not fit while it is in, even fully retracted.

- Take off the target chamber lid using the crane near the MARS line.

- Insert the ParTI array base in the MARS target chamber with the plastic stands attached to the base. The back stand should be secured and the two front stands should be loose in the oversized through holes.

- Open the Z-Cube and make all necessary connections on the Z-Cube flanges. Route the cables through the Z-Cube port and into the MARS target chamber.

- Close the Z-Cube.

- Thread at least 2 zip ties through empty screw holes in the top of the populated ParTI array and make loops.

- Lift the populated ParTI array using the looped zip ties and the crane near the MARS line.

- Lower the ParTI array into the MARS target chamber until you can screw the 3 bottom detector frames into the 2 plastic stands on the base.
• Secure the ParTI array to the base stands using the 6 screw holes.

• Disconnect the crane from the zip ties and remove the zip ties from the array so they are not in the way of the target ladder.

• Plug all of the ParTI cables coming from the Z-Cube onto the backs of the PMTs making sure to route the cables so that they do not block the beam upstream.

• Insert the ParTI alignment flag into the beam hole in the center frame in the ParTI array. The flag at the end of the pole should extend far enough beyond the ParTI array so that it is visible through the MARS view port.

• Sight the vertical alignment of the ParTI array using the lines on the alignment flag. Adjust the height of the array using the 4 leveling feet on the base and a flat head screwdriver. The ParTI array is aligned vertically when the flag is at beam height and the levels on the base are centered. Note: there is some wiggle in the flag’s seating in its hole.

• Tighten the braces on the front corners of the ParTI base against the inside wall of the MARS target chamber so that the array does not slide and is pushed flush against the flat surface of the entrance port in the upstream part of the chamber.

• Use the crane to put the lid back on the MARS target chamber and bolt it down.

• Insert the Faraday cup and target ladder flanges back into the target chamber lid. When inserting the target ladder, come in from the downstream side and slide forward into position to be sure that it does not come down on the top of the ParTI array.

• With all target chamber and Z-Cube flanges secured, it is possible to power PMTs and troubleshoot using cosmics.