OPEN ACCESS

Fusion of ²⁰O incident ions with ¹²C target nuclei

To cite this article: M J Rudolph et al 2013 J. Phys.: Conf. Ser. 420 012122

View the article online for updates and enhancements.

You may also like

- Extension of the ratio method to protonrich nuclei X Y Yun, F Colomer, D Y Pang et al.
- <u>Comparison of C doping technique</u> <u>between SiC and C targets for high-</u> <u>photoresponsivity BaSi₂ films by radio-</u> <u>frequency sputtering</u> Taira Nemoto, Ryota Koitabashi, Masami Mesuda et al.
- <u>Chronology of the three-body dissociation</u> of ⁸He B Laurent, F M Marqués, C Angulo et al.





DISCOVER how sustainability intersects with electrochemistry & solid state science research



This content was downloaded from IP address 3.139.82.23 on 26/04/2024 at 05:18

Fusion of 20 O incident ions with 12 C target nuclei.

M. J. Rudolph¹, Z. Q. Gosser¹, K. Brown¹, T. K. Steinbach¹, S. Hudan¹, R. T. de Souza¹, A. Chbihi², B. Jacquot², M. Famiano³, J. F. Liang⁴, D. Shapira⁴, D. Mercier^{1,5}

E-mail: desouza@indiana.edu

¹ Department of Chemistry and Center for Exploration of Energy and Matter

2401 Milo B. Sampson Lane, Bloomington IN 47405, USA

 2 GANIL, Caen, France

³ Western Michigan University, Kalamazoo, MI, USA

⁴ Oak Ridge National Laboratory, Physics Division, Oak Ridge, TN 37831 USA

⁵ Current address: RIKEN Brain Science Inst., 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

Abstract.

Evaporation residues resulting from fusion of ²⁰O incident ions with ¹²C target nuclei have been measured for the first time. The cross-section associated with compound nuclei that de-excite *via* emission of charged particle is extracted. The resulting excitation function is compared with the predictions of a standard fusion model followed by statistical decay code. A significant underprediction of the measured cross-section by the fusion-evaporation model raises the question of whether the fusion cross-section is larger for the neutron-rich projectile or the statistical de-excitation is incorrectly predicted. Improvements in the experimental technique which should allow future measurement of the total fusion cross-section are described.

1. Introduction

Neutron stars are fascinating objects providing a broad range of nuclear density from subsaturation to super-saturation at relatively low temperature [1]. The outer crust of an accreting neutron star is particularly interesting as it presents a unique environment for nuclear reactions to occur. At the density of the outer crust, the electron Fermi level becomes sufficiently large to lead to electron capture reactions, resulting in neutron-rich nuclei [2]. Isotopes of nuclei ranging from oxygen to iron have been calculated to be produced in this environment. It has been proposed that these nuclei, though present at the level of contaminants [3, 4], may play an important role in the behavior of the neutron star. For example, it has been proposed that enhanced fusion between such nuclei might provide an additional heat source necessary to ignite the carbon burning intimated to be responsible for the phenomenon of X-ray superbursts [5]. Radioactive beam facilities provide the opportunity to explore these possibilities experimentally. One reaction estimated to be a potential source of additional heat is ${}^{24}O{+}^{24}O{}$ [2]. As this reaction is presently unfeasible at existing facilities however, we elected to investigate the potential enhancement of fusion with neutron-rich beams by investigating the reaction ${}^{20}O{}$ + ${}^{12}C{}$.

Fusion of light neutron-rich nuclei also allows one to address interesting nuclear structure and fusion dynamics questions. Simple barrier penetration models work well for predicting the fusion of light stable nuclei. Increasing the neutron number decreases the distance through which the



Figure 1. Experimental setup used to measure the fusion of incident 20 O ions with 12 C target nuclei.

nuclei must tunnel to achieve fusion. This trend should result in a systematic increase in the astrophysical S factor with increasing neutron number, N. In addition, when multiple neutrons are added to the system, new modes of excitation of the neutron-rich skin could emerge. Recent TDHF calculations for the fusion of neutron-rich nuclei [6] indicate the importance of neutron transfer channels at near barrier energies. These considerations motivate a systematic program to measure how fusion rates increase with neutron number in light systems. Light systems present a good choice as the largest neutron excesses can be achieved and extreme N/Z will provide the most stringent tests of fusion models.

2. Experimental details

The experiment was conducted at the GANIL-SPIRAL facility in Caen, France by bombarding a natural ¹²C target with a radioactive beam of ²⁰O ions. A primary beam of ²²Ne accelerated to an energy of 79 MeV/A impinged on a carbon production target. From this primary target, a 20 O beam was extracted, re-accelerated by the CIME cyclotron to an energy of 3 MeV/A, and transported to the experimental area. This incident energy was the minimum energy that could be delivered by the beam transport system At the target, the beam intensity was typically $\approx 1-2$ $\times 10^4$ p/s. The experimental setup used in the measurement is depicted in Fig. 1. The detectors used in the experiment were situated in a rectangular stainless steel scattering chamber that was evacuated to a pressure of $\approx 2 \times 10^{-6}$ torr. This chamber measured approximately 105 cm x 35.6 cm x 29.7 cm with the long axis situated along the beam direction. At the entrance of the chamber was an annular fast-plastic detector readout by a photomultiplier tube. This detector which had a 13mm diameter hole was used to reject beam halo. Just upstream of the target was a retractable, multi-anode ionization chamber (CID). This standard, transverse-field Frisch-gridded ion chamber served two purposes. Its principal purpose was to degrade the initial beam energy from E/A = 3 MeV to the desired range of E/A = 1-2 MeV. This attenuation was accomplished by passing the 20 O ions through CID operated at a pressure of P=89.5 - 180.1 mbar of CF_4 resulting in a tolerable divergence. CID also provided a continuous measurement of the beam identity and purity, a critical issue in radioactive beam experiments. Throughout the experiment ²⁰O ions were selected on an event-by-event basis by utilizing their energy loss measured in CID [7]. Directly after CID on a retractable mount was a silicon surface barrier detector. Periodically during the experiment, the beam intensity was decreased and the surface barrier detector was inserted in order to measure both the average energy and energy dispersion of the beam after degrading.

Immediately downstream of CID was a microchannel plate detector that served as a compact time-zero detector [8]. The 100 μ g/cm² carbon foil in this detector served as both an electron emission foil as well as the target for the experiment. Electrons ejected from this foil, due

to the passage of ²⁰O ions through it, were accelerated by a wire harp and then reflected by an electrostatic mirror, produced by two additional wire planes, onto the surface of a chevron microchannel plate (MCP) stack. Amplification of the primary electrons by the MCP provided a fast time signal for the subsequent time-of-flight measurement.

In the near Coulomb barrier energy domain investigated, compound nuclei produced by fusion reactions de-excite by emission of neutrons, protons, and alpha particles, deflecting the resulting evaporation residue from zero degrees. Consequently, a large fraction of the residue cross-section is calculated to be observed in the angular range $3^{\circ} \leq \theta_{lab} \leq 20^{\circ}$ [9, 10]. Evaporation residues and light charged particles emitted in the reaction were detected by two annular silicon detectors situated 12 cm (T3) and 17.8 cm (T2) downstream of the target which subtended the angular range $11.3^{\circ} \leq \theta_{lab} \leq 21.8^{\circ}$ and $3.5^{\circ} \leq \theta_{lab} \leq 10.8^{\circ}$ respectively. These annular silicons are highly segmented ion-implanted passivated detectors [11] with pie-shaped sectors on their ohmic surface and rings on their junction side. Signals from the pie sectors were used to provide both fast timing signals, as well as energy signals while signals from the rings provided additional energy information. Signals from both rings and pies determined the angular emission direction of the charged particle. The sub-nanosecond timing achieved with such segmented detectors has been previously described [12].

Evaporation residues produced in the angular range $\theta_{lab} \leq 3.5^{\circ}$ were detected by a 40mm diameter MCP located along the beam axis followed by a zero degree ionization chamber (ZDIC). This ZDIC detector employed the same transverse field, Frisch-grid design as CID but had fifteen anodes arranged in a 5 x 3 geometry with five anodes oriented along the beam direction. It was operated with a fill gas of CF₄ at a pressure of P=20-40 mbar. Beam running continuously through ZDIC required the center anodes to separate evaporation residues from a constant beam background of 10^4 p/s, however the segmentation transverse to the beam resulted in a smaller beam background at larger angles $1.0^{\circ} \leq \theta_{lab} \leq 3.0^{\circ}$.

3. Experimental results and Discussion

Displayed in Fig. 2 is a two-dimensional spectrum of the energy versus time-of-flight for particles entering the T2 detector. The energy displayed is the energy deposited in the silicon detector while the time-of-flight corresponds to the time-of-flight between the target MCP and the T2 detector. Clearly evident is the prominent elastic peak with an energy of ≈ 40 MeV. Originating from the elastic peak and extending down to approximately 25 MeV is a near vertical band. Particles along this locus have a time-of-flight consistent with elastically scattered particles. For these particles, a lower energy is measured due to the incomplete collection of charge by the silicon detector. Walk of the leading edge discriminators used for the silicon timing signals is responsible for the slight positive slope of this band. This incomplete charge collection occurs despite the detector being biased to -80V, well above the manufacturer's nominal full depletion value. Biasing at a voltage of -90V did not noticeably reduce the incomplete charge collection problem. A quoted breakdown voltage of -100V prevented biasing the detector to a substantially higher value during the experiment. Also evident in the spectrum is a locus of points originating from the elastic peak and increasing in time as the deposited energy decreases. Points along this locus correspond to particles degraded in energy prior to entering the silicon detector. Consequently, their measured time-of-flight reflects their degraded energy. Slit scattering of particles from the acceleration and reflecting grids of the target MCP detector is the most likely source of the energy loss. Located below the slit scatter line is a haze corresponding to slit scattered particles for which incomplete charge collection occurs. Located at higher energies and longer times with respect to the slit scatter line is yet another locus of points. This locus exhibits a similar energy-time relationship as the slit scatter line. The large cross-section of \approx 50-70 barns associated with these points clearly indicates that they have an atomic and not nuclear origin. However, as they occupy the same region of the energy-TOF spectrum as that



Figure 2. Two dimensional energy-TOF spectrum for particles detected in the T2 detector. The polygonal gate indicates the region used to search for coincidences between evaporation residues in T2 and light charged particles in T3. See text for details.

expected by the evaporation residues they represent a daunting background for measuring the fusion cross-section. Subsequent to the experiment, bench tests with alpha sources conclusively demonstrated that scattering from the reflecting grids of the MCP provided a false early start signal resulting in this background.

The energy-TOF spectrum for particles entering the T3 detector is displayed in Fig. 3. While the principal spectral features of the elastic peak, incomplete charge collection, and slit scatter line observed for T2 also exist for T3, it is interesting to note that the incomplete charge collection in T3 appears to be significantly less severe than for T2. The background due to false early target MCP signals from the reflecting grid is also evident in this detector supporting the result that the problem arises from the MCP detector and not the T2 silicon detector.

The evaporation residues present in the experiment result from de-excitation following the fusion reaction. The nuclide composition of the evaporation residue distribution can be calculated by utilizing a multi-particle Monte Carlo evaporation code such as evapOR [13]. This model uses a simple fusion model (Bass) [14] to predict the fusion cross-section, followed by a Hauser-Feschbach approach to model its subsequent decay. Calculations were performed at incident energies varying from $E_{lab}=20$ MeV to $E_{lab}=45$ MeV assuming a triangular angular momentum distribution. In Table I, the percentage of the evaporation distribution attributable to various nuclides is shown for three incident energies. Even at the lowest energy, $E_{lab}=22$ MeV, while 84% of the residues are formed through purely neutron decay channels, a significant fraction of the evaporation residue yield $\approx 16\%$ is formed through some charged particle emission. With increasing incident energy, the percentage of yield involving some charged particle emission increases to 27% at E=42 MeV.

In order to extract fusion events from the large atomic background evident in Fig. 2 and Fig. 3, we therefore elected to require a coincidence between detection of an evaporation residue in T2 and a charged particle in T3. The potential region of interest for evaporation residues



Figure 3. Two dimensional energy-TOF spectrum for particles detected in the T3 detector.

 Table 1. Predictions of the evapOR model of the percentage of the evaporation residue distribution populated by various nuclides

Nuclide	22 MeV	$27 {\rm MeV}$	42 MeV
$^{30}\mathrm{Si}$	40.5	31.8	15.9
29 Si	43.6	51.2	56.9
^{30}Al	5.3	4.0	2.3
^{29}Al	1.4	2.5	5.4
^{27}Mg	7.5	8.4	8.3
^{26}Mg		1.5	9.0

is well-defined by the slit-scatter line in Fig. 2 and extends to longer times. It is indicated by the polygonal gate displayed in Fig. 2. Coincident with detection of a particle in this gate a particle in T3 was required. All coincident particles in T3 are clustered in time occuring with a time spread of ≈ 2 ns. This time spread of the charged particle in T3, short compared to the RF beam burst period of 100ns, indicates that random coincidences play no significant role. This result is hardly surprising due to the low beam intensity. At the highest incident energy, $E_{lab}=$ 41.0 MeV, all of the coincident particles are clustered in the range 8 MeV $\leq E \leq 22$ MeV. At the intermediate energy, $E_{lab}= 25.0$ MeV, although particles for the most part are clustered in the same energy range, a couple of particles are observed with $E \leq 5$ MeV. At the lowest incident energy, $E_{lab}= 19.8$ MeV, the detected energies are significantly lower, $E \leq 13$ MeV. The energy-TOF relationship observed for these evaporation residues coincident with a charged particle has been previously published [7].

We compared the experimental data with the predictions of the statistical model code evapOR [13]. Evaporation residues and light charged particles from the model were subsequently filtered by the geometrical acceptance of the experimental setup and detection thresholds were accounted for. The efficiency for detecting a LCP in coincidence with a residue in T2 is principally determined by the small solid angle of the T3 detector and the isotropic emission of the LCPs.

This efficiency is relatively constant with incident energy and approximately 3.0% to 3.5% [7]. Both the impact of a finite beam spot size as well as multiple scattering in CID are included in the efficiency calculations. The beam spot size was assumed to be a gaussian with a width of 7mm at 4 sigma, based upon beam optics calculations. The multiple scattering in CID as a function of pressure was determined by an experimental measurement at OakRidge National Laboratory. In this experiment, a low-intensity beam of 3 MeV/A ¹⁸O was passed through a gas cell containing CF₄ and the resulting beam spot was imaged on a multiwire proportional counter located downstream. Neither the multiple scattering in CID nor the finite beam spot has a significant influence on the calculated coincidence efficiency [7].

Having corrected for the geometric efficiency, it is possible to extract the cross-section associated with fusion followed by charged particle emission, σ_{CP} . The total number of incident beam particles was determined from the target MCP detector and cross-checked against the CID detector at the running intensity and the SBD detector at low intensity. In both cases, the integrated counts of the target MCP and the other two detectors were in reasonable agreement though the integrated counts in CID were typically 10% higher. This slightly larger number of counts in CID can be understood due to the divergence of the beam on degrading. The resulting cross-sections are presented in Fig. 4. These measured cross-sections decrease with decreasing incident energy from 492 ± 105 mb at $E_{lab}=40.6 \pm 0.286$ MeV to 82.3 ± 26 mb at $E_{lab}=19.6 \pm 0.449$ MeV. Vertical error bars reflect the statistical errors associated with the measurement while horizontal error bars indicate the dispersion (sigma) in incident energy due to degrading the incident beam.

The observed change in the cross-section with energy is influenced by both the overall decrease in the fusion cross-section with decreasing energy, as well as changes in the population of charged particle decay channels with decreasing energy. Shown for comparison in Fig. 4 are the predictions for both the total fusion cross-section (solid line) and the cross-section associated with charged particle channels (dashed line) predicted by the evapOR model. Comparison of the experimental data with the model predictions yields two significant results. The first noteworthy point is that the measured cross-sections exceed those predicted by the model for the charged particle channels by a factor of ≈ 2 . This is true at all incident energies including the highest incident energy which is well above the Coulomb barrier. The second interesting result is that the dependence of the experimental cross-section with decreasing incident energy is weaker than that predicted by the fusion-evaporation model. Each of these observations is independently interesting. For example, if one might question the uncertainty involved with degrading the incident beam to the lowest incident energy, the impact of this uncertainty in energy is significantly less, and less important for the highest energy point where the excitation function is relatively flat. Thus, the larger cross-section at the highest energy point is particularly noteworthy.

4. Fusion in ${}^{16}O+{}^{12}C$ system

To provide a reference for the fusion of neutron-rich oxygen and carbon nuclei as well as ascertain whether the simple fusion model correctly predicts the fusion cross-section for β -stable nuclei, we measured the reaction ${}^{16}\text{O} + {}^{12}\text{C}$ immediately following the ${}^{20}\text{O}$ beamtime with the identical setup. The subsequent analysis of the experimental data closely followed the analysis performed for the ${}^{20}\text{O}$ induced reaction.

Shown in Fig. 5 as the solid points is the extracted fusion cross-section that decays by charged particle emission. In contrast to the decay of ${}^{32}Si^*$, the fusion product of this reaction, ${}^{28}Si^*$, decays principally by charged particle emission as indicated in Table II. For comparison with the experimental data the total fusion cross-section as well as the fusion cross-section as the solid and dashed lines respectively. It is apparent that the measured cross-section agrees well with the model



Figure 4. Measured fusion cross-sections associated with charged particle emission channels (solid points) compared to the predictions of the evapOR model. The total predicted fusion cross-section is shown as a solid line while the cross-section predicted for the charged particle channels is represented by the dashed line.

prediction. This agreement indicates that the model does a good job of predicting the fusion cross-section of the reaction ${}^{16}\text{O} + {}^{12}\text{C}$ and the subsequent charged particle de-excitation of the ${}^{28}\text{Si}^*$.

Due to the fact that only two data points exist from our ¹⁶O measurement, we subsequently performed an experiment at WMU. A beam of ¹⁶O was accelerated by the 6MV tandem to energies between 20 and 35 MeV and impinged on a $100\mu g/cm^2$ carbon foil. This target foil also served as the electron emission foil of the target MCP. As the beam energy could be easily varied and a low energy beam could be transported, there was no need to degrade the beam energy as was done in the GANIL experiment. Consequently, the uncertainty in the energy is determined by the tandem accelerator and is typically of the order of ≤ 20 keV. Evaporation residues and light charged particles were detected with silicon detectors as in the GANIL experiment. Evaporation residues coincident with light charged particles in T3 were identified by their energy and timeof-flight. The resulting data are shown in Fig. 5 as the open symbols. The agreement of this data with the predicted excitation function bolsters our confidence in the ²⁰O results.

Table 2. Predictions of the evapOR model of the percentage of the evaporation residue distribution for different nuclides in the reaction ${}^{16}O + {}^{12}C$ Nuclide 24 MeV 35 MeV

vucnae	24 MeV	30 meV
$^{27}\mathrm{Si}$	10.8	4.7
^{27}Al	63.9	29.2
^{26}Al	2.0	17.6
^{26}Mg	6.0	24.7
^{24}Mg	16.4	15.3
^{23}Na	0.3	3.4
20 Ne	0.5	5.1



Figure 5. Measured fusion cross-sections from the reaction ${}^{16}\text{O} + {}^{12}\text{C}$ associated with charged particle emission channels (solid points) compared to the predictions of the evapOR model. The total predicted fusion cross-section is shown as a solid line while the cross-section predicted for the charged particle channels is represented by the dashed line. Also shown as open symbols is the fusion cross-section of ${}^{20}\text{O} + {}^{12}\text{C}$.

Subsequent to the experiment at GANIL we have expended considerable effort to determine the source of the problems with our experimental approach. We have determined that our failure to extract the total fusion cross-section in E575S was attributable to two problems: slit scattering in the setup combined with charge trapping in the silicon detectors. While we fully anticipated the presence of slit scattering prior to the experiment, it was the combination of the two problems that prevented us from measuring the total fusion cross-section. These problems are described in detail below. Characterizing these problems not only involved measurements with alpha sources in Bloomington but included beam measurements at Western Michigan University's (WMU) tandem accelerator.

The fundamental problems encountered at GANIL in E575S can be understood by reexamining the E-TOF plot shown in Fig. 2. In addition to the prominent elastic peak at ≈ 40 MeV, a slit scatter line due to scattering from the acceleration and reflecting grids of the MCP is evident. Two other features are noteworthy. The first is a near vertical locus originating from the elastic peak which we previously described as incomplete charge collection. Based upon our tests subsequent to the GANIL experiment we now describe this data as due to a process of "charge trapping". This "charge trapping" phenomenon is also responsible for the haze located below the slit scatter line and is described below in more detail. For all the data shown in this plot only one pie segment registered any significant signal. Hence, this locus is not due to charge splitting resistively between two adjacent pies. The second noteworthy feature of Fig. 2 is the locus that lies above the slit scatter line which we refer to as the "ghost" line. This "ghost" line populates the region of the spectrum in which the evaporation residues are expected. The large cross-section associated with the "ghost" line (≈ 70 barns), definitively indicates an atomic scattering process is responsible. To better understand scattering in the experimental setup we performed tests at WMU with a ¹⁶O beam incident on a ¹²C target. These tests at WMU demonstrated unequivocally that scattering within the MCP detectors used in E575S was



Figure 6. E-TOF measured at WMU for ${}^{16}\text{O} + {}^{12}\text{C}$ at $\text{E}_{lab} = 35$ MeV. The slit scattering line is double-valued in this orientation due to the difference in transit time for the scattered beam within the MCP detector.

responsible for the "ghost" line. When the beam passed through the reflector grid prior to the carbon foil, scattering of electrons from the reflector grids directly into the MCP resulted in an early start signal. This early start was indistinguishable from a late stop associated with fusion residues. By reversing the orientation of the MCP detector relative to the beam, the errant scattering from the reflector grids occurs late relative to the carbon foil and thus does not appear in the E-TOF map.

Having rotated the detector so that the beam passes through the carbon foil before passing through the reflector planes eliminates the "ghost" line, and a clear island of fusion residues is observed as evident in Fig. 6. Integrating these residues however, results in a measured fusion cross-section for ¹²C + ¹⁶O that is low by approximately 30%. The reason the measured cross-section is low is because of "charge trapping" in the silicon detector which results in an incomplete measurement of the energy for approximately 30% of the incident particles. This charge trapping is evident by comparing the energy signal measured on the two sides of the detector.

It should be realized that the fundamental obstacle in measuring the fusion cross-section is the coincident problems of slit scattering and charge trapping. In the absence of slit scattering the charge trapping problem would not present an obstacle in measuring the fusion cross-section. It would however hamper our ability to accurately measure the energy of all fusion residues. In



Figure 7. Photograph of the gridless MCP detector. The top steel plate and permanent magnets have been removed to show the internals of the detector. Visible on the right side of the detector is the microchannel plate stack and its voltage divider board. Mounted along the center line of the detector in the top of the photograph is an alpha source that directly precedes the secondary emission foil. Following the electrostatic rings is a surface barrier detector used for measurements of the detector efficiency. NdFeB permanent magnets provide the magnetic field.

preparing for future measurements we have therefore pursued two independent fronts. We have sought a) to minimize slit scattering in the setup and b) to eliminate the charge trapping in the silicon detector. To minimize slit scattering in the setup we have recently designed and constructed a new set of microchannel plate (MCP) detectors. These new MCP detectors, displayed in Fig. 7, utilize a crossed E-B field [15] design thus eliminating all accelerating and reflection grids used in the previous MCP design. Bench tests with alpha sources indicate that the efficiency of the detector with a 1.5 μ m aluminized mylar foil is 80%. This efficiency with an alpha source is the expected efficiency for a secondary emission foil for light-ions. In a test setup consisting of an alpha source mounted in front of a gridless detector followed by a surface barrier detector (SBD) with a 40cm flight path we observe a dramatic reduction in the slit scattering. In addition to particles with the approportate energy-time relationship, we observe particles slit scattered from the source prior to traversing the time-of-flight path and particles slit scattered upon entering the SBD detector. The contribution of both of these scattered sources is less than 0.5% as compared to the yield of particles for which both energy and time are consistent. In effect, scattering from background sources has been reduced two orders of magnitude by implementation of the gridless MCP detector. In the near future, before any radioactive beam measurements, we intend to demonstrate our readiness by measuring the total fusion excitation function for the well-known reaction ${}^{16}\text{O} + {}^{12}\text{C}$.

We have investigated the origin of the charge trapping phenomenon occuring in the detectors. By measuring the E-TOF of alpha particles from a radioactive source with different silicon designs with varying degrees of segmentation we have determined that the problem is associated with the degree of segmentation on the entry junction side of the detector. Moreover, we have observed that for the S2 design detector used in these experiments (T2), entering through the ohmic side of the detector seems to eliminate the charge trapping problem. Shown in Fig. 8 is the correlation between the energy measured in a ring and the energy measured in a pie when the alpha particles are incident on the pie (ohmic) surface of the detector. The vertical bands observed in this plot however, correspond to charge sharing, not charge trapping. It is demonstrated that charge sharing is the origin of the vertical bands by summing the energy



Figure 8. Correlation between energy measured in the pies and the rings of a Micron S2 design detector. The vertical bands in the left plot indicate charge sharing between adjacent rings. Shown in the inset are the total counts associated with three regions in the plot. The vertical bands correspond to 30% of the incident particles. After summing the energy in adjacent rings, for 96.6% of the incident particles both the ring and the pie side of the detector registers a consistent energy.

in adjacent rings and comparing the resulting summed energy to the energy measured in the pie. Following this summation, for 96.6% if the incident alpha particles a consistent energy is measured in the ring and pie segments.

Unfortunately, tests demonstrate that good timing is only achieved by utilizing the exit surface of the detector. The high segmentation of the rings in the present S2 design is incompatible with using this side of the detector to achieve sub-nanosecond timing. Consequently, we are working on designing a new less segmented silicon detector. A new design of the silicon detector has an additional benefit. In comparison to the S1 and S2 designs used in the present work newer fabrication technology would allow the new design to have a thin entrance window. Reduction of the dead layer from the present value of $\approx 1 \ \mu m$ to $\approx 0.1 \ \mu m$ will definitely improve the measurement of the low energy evaporation residues that penetrate only $\approx 10 \ \mu m$ into the detector. With these improvements in both the MCP and silicon detectors we anticipate being able to test the improved experimental setup in the near future.

5. Conclusions

This first attempt to measure the total fusion cross-section in the system 20 O and 12 C demonstrated that while the overall approach utilized appears feasible, there are still some technical obstacles to overcome. We have subsequently improved the experimental approach for future studies by developing a gridless MCP design that utilizes a crossed electric and magnetic field to provide a start for the time-of-flight of the evaporation residue. We have also determined that the charge trapping problem encountered is due to the high segmentation of the silicon detectors used. We are presently designing a less segmented silicon design with a low threshold entrance window better suited to these near and sub-barrier fusion studies. Despite the setback with the present dataset, we have successfully extracted the cross-section for fusion

of ²⁰O and ¹²C nuclei into a compound nucleus which subsequently undergoes charged particle decay. The measured cross-section exceeds that of a simple fusion model for the same channels. For the fusion of β -stable ¹⁶O with ¹²C this fusion-evaporation model correctly predicted the measured cross-section. This underprediction of the cross-section by the model for the neutron-rich projectile could point to either an overall enhancement of the fusion cross-section, or may indicate that the competition between charged particle emission and neutron decay in the deexcitation phase is incorrectly extrapolated by the statistical model from the ¹⁶O and ¹²C system. With the technical developments described above it should be possible to measure the total fusion cross-section for ²⁰O and ¹²C system and begin systematic near-barrier fusion studies for neutron-rich nuclei in this mass range.

6. Acknowledgments

We wish to acknowledge the support of the GANIL staff in providing the high quality radioactive beam that made this experiment possible. We also wish to thank Dr. A. Kayani for making beamtime at Western Michigan University available to us to test our experimental approach and refine the necessary detectors. This work was supported by the U.S. Department of Energy under Grant No. DEFG02-88ER-40404 (IU).

References

- $[1]\,$ Lattimer J M and Prakash M 2004 Science ${\bf 304}$ 536
- [2] Horowitz C J, Dussan H and Berry D K 2008 Phys. Rev. C 77 045807
- [3] Horowitz C J et al. 2009 Phys. Rev. E **79** 026103
- [4] Horowitz C J et al. 2009 Phys. Rev. C 79 065803
- [5] Strohmayer T and Bildsten L 2006 Compact X-ray Stellar Sources (Cambridge University)
- [6] Umar A S, Oberacker V E and Horowitz C J 2012 Phys. Rev. C ${\bf 85}$ 055801
- [7] Rudolph M J et al. 2012 Phys. Rev. C 85 024605
- [8] Starzecki W et al. 1982 Nucl. Instr. Meth. A **193** 499
- [9] Tarasov O B and Bazin D 2003 Phys. At. Nucl. 66 1578
- [10] Gavron A 1980 Phys. Rev. C **21** 230
- $[11] \ MicronSemiconductor \ URL \ \texttt{www.micronsemiconductor.com}$
- [12] deSouza R T et al. 2011 Nucl. Instr. and Meth. A632 133
- [13] Nicolis N G and RBeene J 1993 unpublished
- [14]~Bass R 1977 Phys. Rev. Lett. $\mathbf{39}~265$
- [15] Bowman J D et al. 1978 Nucl. Instr. and Meth. 148 503