PROCEEDINGS OF SCIENCE

p process overview: (p,γ) and (α,γ) reactions in regular and inverse kinematics

A. Spyrou[*1,2,3], **S. J. Quinn**[1,2,3], **A. Simon**[1,3,4], **A. Battaglia**[4], **A. Best**[4], **B. Bucher**[4], **M. Couder**[4], **P. A. DeYoung**[5], **A. C. Dombos**[1,2,3], **X. Fang**[4], **J. Gorres**[4], **J. Greene**[6], **A. Kontos**[1,3], **Q. Li**[4], **L. Y. Lin**[1,2], **A. Long**[4], **S. Lyons**[4], **B. S. Meyer**[7], **T. Rauscher**[8,9], **A. Roberts**[4], **D. Robertson**[4], **K. Smith**[4], **M. K. Smith**[4], **E. Stech**[4], **W. P. Tan**[4], **X. D. Tang**[4], **and M. Wiescher**[4]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Department of Physics and The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[5] *Department of Physics, Hope College, Holland, Michigan 49423, USA*
[6] *Physics Division, Argonne National Laboratory,Argonne, IL 60439, USA*
[7] *Department of Physics and Astronomy, Clemson University, 118 Kinard Laboratory, Clemson, South Carolina 29634-0978, USA*
[8] *Centre for Astrophysics Research, School of Physics, Astronomy, and Mathematics, University of Hertfordshire, Hatfield AL10 9AB, United Kingdom*
[9] *Department of Physics, University of Basel, 4056 Basel, Switzerland*
E-mail: spyrou@nscl.msu.edu

The astrophysical p process is responsible for the production of neutron-deficient nuclei that are not accessible by the s and r processes. Many scenarios have been proposed for the production of these so-called p nuclei but to date the nucleosynthesis mechanism is still not well understood. In order to understand the synthesis of these rare isotopes and to identify the environment in which they are produced it is critical to have accurate nuclear physics input in the astrophysical models. This includes masses, beta-decay properties and most importantly nuclear reaction rates. Here we present a brief overview of the p process with a focus on the experimental efforts to study the relevant reactions in regular and inverse kinematics. We report on the recent results on (p,γ) and (α,γ) reactions, using the NSCL SuN detector at the University of Notre Dame and present future plans for measurements at the ReA3 facility at Michigan State University.

XIII Nuclei in the Cosmos,
7-11 July, 2014
Debrecen, Hungary

[*]Speaker.

PoS(NIC XIII)025

1. p process

The majority of the elements heavier than iron are created primarily through two neutron-induced processes, the slow (s-) and rapid (r-) neutron capture processes [1]. There is, however, a small number of neutron-deficient isotopes, called “p nuclei”, which cannot be produced by these two processes and for this reason alternative production sources are proposed. In the original nucleosynthesis publication B^2FH [2], the production of the p nuclei was attributed to the “p process”, a process dominated by proton-capture reactions. Later it was found that the conditions for such proton capture reactions to occur were not fulfilled and an alternative scenario was proposed, one that involved photo disintegration reactions on pre-existing seed nuclei [3]. This “γ process” requires high-enough temperature environments for the γ-induced reactions to take place (T_9= 1.5-3.3 GK); at higher temperatures the photodisintegration reactions will destroy all produced p nuclei into lighter, iron-peak nuclei.

Several astrophysical scenarios have been proposed as possible sites for the p process to occur, and it is still not clear if the p nuclei are produced in only one scenario or whether they have contributions from several ones. Nucleosynthesis in supernovae Ia [4], the rp process in X-ray bursts [5], and the νp process in SNII neutrino-driven winds [6, 7] are some of the proposed scenarios. However, the only scenario that is, to some extend, able to produce p nuclei across the whole mass range is the γ process. The γ process takes place in the SNII explosions of massive stars, when the shock wave passes through the O/Ne layer which has the right temperature, density and seed-nuclei for producing the p-nuclei [3, 8]. More detailed reviews of the p process are provided in the Review Articles [9] and [10].

Major uncertainties are present in the modeling of all aforementioned scenarios that are related to both astrophysical and the nuclear physics inputs. On the nuclear physics side a main deficiency is the fact that from the large number of reactions ($>$ 20000) involved in these calculations, only a very small number is measured experimentally. The rest has to be provided by statistical model calculations. It is therefore of paramount importance to constrain these theoretical calculations by comparing them to the available experimental data and optimizing their input parameters, such as Optical Model potentials (OMP), Nuclear Level Denisity (NLD) and γ-ray Strength Function (γSF). In addition, new measurements that cover a broad range of energies and masses are needed to constrain the models further (Sec. 2).

On top of these systematic model comparisons, it is also important to identify and measure specific reactions that seem to have a direct influence on the final result of the calculations, namely the p-nuclei abundances. This was done for the p process through two sensitivity studies: one is a model-independent approach, which focused on the competition between different types of reactions [11]; the second one presents the reactions that seem to have a direct impact on the abundance calculations in a 25$M_\odot$ star, when the shock front passes through the O/Ne layer [12]. In both cases, the need for measurements of (p,γ) and (α,γ) reactions was emphasized. In particular the sensitivity study of Rapp *et al.* [12] showed that the majority of the important reactions involve radioactive nuclei highlighting the need for future radioactive beam measurements.

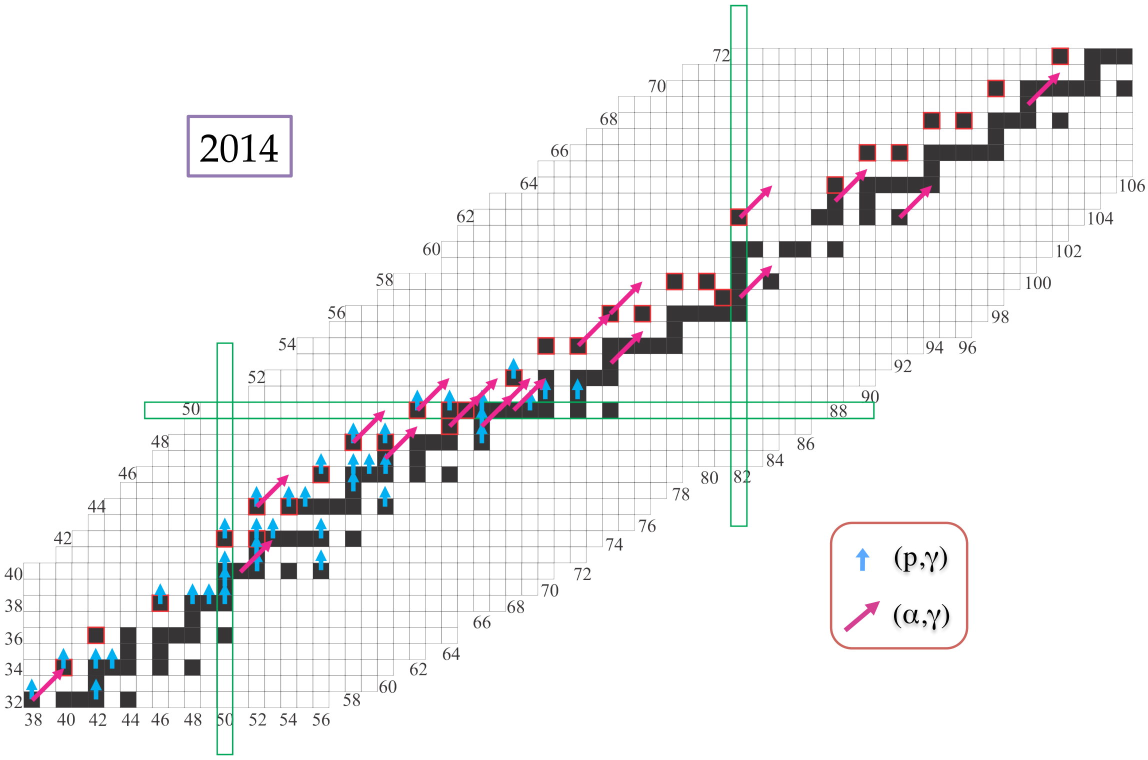

Figure 1: Chart of nuclei between atomic number 32 and 72 (Ge and Hf). The measured (p,γ) and (α,γ) reactions are marked with the blue-vertical and magenta-slanted arrows, respectively.

2. Overview of Experimental Results

Measurements dedicated to the study of the astrophysical p process started in the 1990s with (p,γ) and (α,γ) reactions on relatively low-mass nuclei (e.g ^{70}Ge(α,γ)^{74}Se [13] and (p,γ) reactions on Mo isotopes [14]). At first all measurements were done using the activation technique, which later was complemented by the angular distribution technique [15] and the summing method [16]. Today (2014) there are 37 (p,γ) and 17 (α,γ) reactions published in refereed journals, which are shown in Fig. 1. The (p,γ) measurements are all concentrated at low masses, below Z=52. This is in accordance with the sensitivity studies [12], which show that (p,γ) reactions only on light nuclei affect the final abundance distribution of p nuclei. Varying (p,γ) reactions on heavier nuclei did not have a significant influence on the final abundances. On the other hand, Fig. 1 shows that the (α,γ) reaction measurements are spread across a broader mass range, up to Z=69. The number of measurements, however, is much smaller than the (p,γ) measurements, and it is important to continue these measurements in order to reduce the larger uncertainties associated with (α,γ) reactions.

In Fig.1 it can also be observed that all existing measurements involve stable targets. To date there are no measurements on radioactive nuclei in this mass region despite the fact that sensitivity studies [12] have shown that most of the reactions that have an influence on the final abundance distributions are reactions involving unstable isotopes. It is therefore crucial to develop new techniques for measurements of (p,γ) and (α,γ) reactions in inverse kinematics using radioactive ion

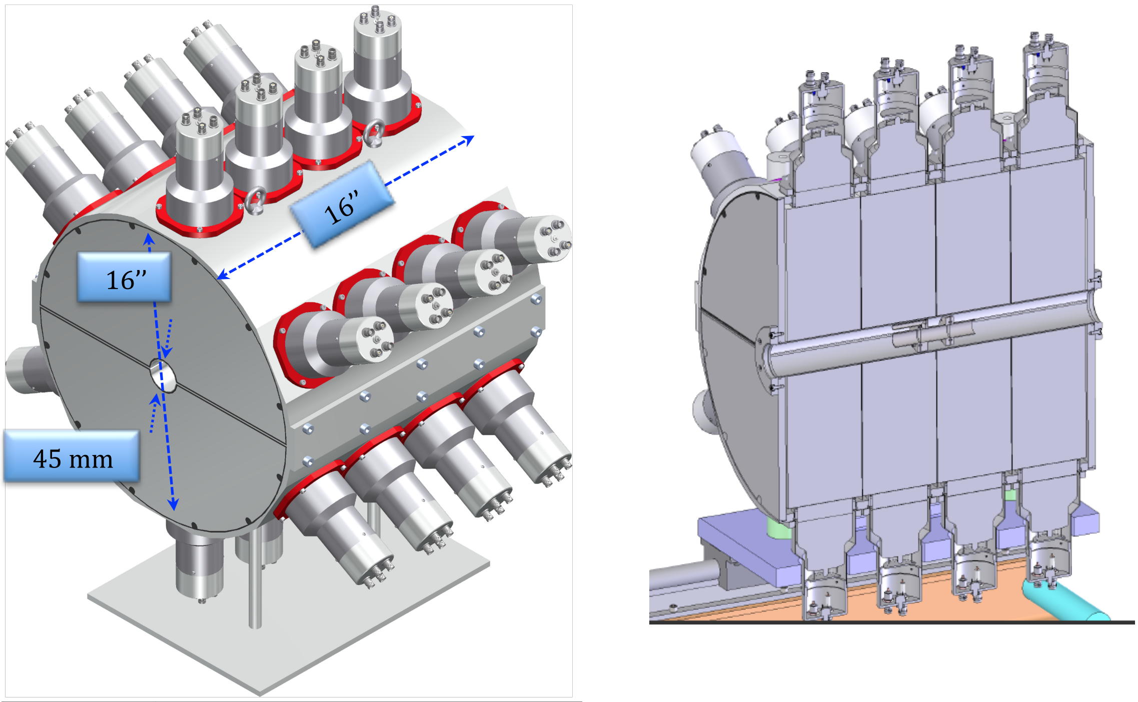

Figure 2: Mechanical design of the Summing NaI detector (SuN). SuN consists of eight optically-isolated segments, each being read by three PMTs. The figure on the right-hand side shows a cut-view of SuN where the target location and the detector segmentation are visible.

beams. Many of the radioactive beam facilities around the world have recently put effort into developing such techniques, using the storage ring at GSI [17], the DRAGON separator at TRIUMF [18], the LISE spectrometer at GANIL [19] and the SuN detector at the NSCL [20]. In the present work we focus on the latter. In the following sections we describe the development of the SuN detector, the first experiments that were done with stable beams in regular kinematics and the first application of the summing technique in inverse kinematics.

3. Experimental Setup - SuN

The Summing NaI (SuN) detector was developed at Michigan State University in 2011 [21]. SuN is a cylindrical NaI(Tl) detector, 16$''$ in height and 16$''$ in diameter, with a 45 mm borehole along its axis, as shown in Fig. 2. SuN was designed to provide the largest possible solid angle coverage and γ-detection efficiency. The full energy peak efficiency for a 661 keV γ from the ^{137}Cs decay is 85%. SuN is segmented in eight optically isolated pieces and each segment is read by three photomultiplier tubes. The segmentation allows for a more accurate determination of the summing efficiency, as described in detail in Ref. [21], and in addition it allows for a rough Doppler correction for inverse kinematics experiments as presented in Ref. [20].

SuN uses the summing technique for cross section measurements of (p,γ) and (α,γ) reactions [16, 21]. In the summing technique, the de-excitation of the produced nucleus is measured through the summation of all emitted γ rays in a γ cascade. The resulting signal is located at the energy of

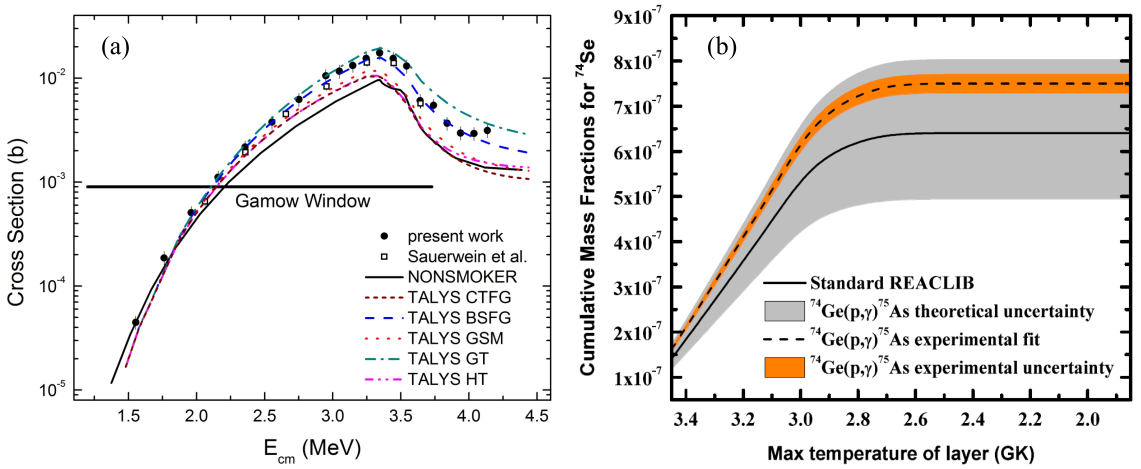

Figure 3: (a) Cross section of the ^{74}Ge(p,γ)^{75}As reaction. The SuN results are compared to a previous measurement by Sauerwein *et al.* [26] and to five theoretical calculations performed with the code TALYS [**?**]. (b) Cumulative mass fraction of the lightest p-nucleus ^{74}Se as a function of the maximum temperature of each layer in the star, showing the effect of varying the reaction rate of the ^{74}Ge(p,γ)^{75}As reaction. The grey band corresponds to a variation of a factor of 3 up and down which is the typical uncertainty in the theoretical calculations. The orange (narrow) band corresponds to the uncertainty of the experimental results.

the entry state of the produced nucleus. The energy of the entry state is calculated as $E_\Sigma = E_{c.m.} + Q$, where $E_{c.m.}$ is the center-of-mass energy of the interacting nuclei, and Q is the Q-value of the reaction. Taking into account the relatively large Q-values of the involved reactions and the relatively high energies (1 - 4 MeV), the sum peak typically appears at energies around 8 - 15 MeV, a region where the only source of background is coming from cosmic-ray muons. This allows for the reaction signal to be easily separated from room background.

The SuN detector has been used in several experiments since its commissioning to measure the ^{74}Ge(p,γ)^{75}As [22], ^{58,60,61,62,64}Ni(p,γ) [23], ^{90,92}Zr(p,γ)^{91,93}Nb [24], ^{58}Ni(α,γ)^{62}Zn [25] reactions and many others. In this paper we present the first reaction as an example.

4. ^{74}Ge(p,γ)^{75}As

The reaction ^{74}Ge(p,γ)^{75}As was identified in a p-process sensitivity study [12] as one of the most important reactions, which affect the final abundance of the lightest of the p nuclei, ^{74}Se. Unlike the rest of the light p nuclei, ^{74}Se is the only p nucleus which is highly overproduced by the p-process models. The majority of the reactions that participate in the production or destruction of ^{74}Se was already measured and the ^{74}Ge(p,γ)^{75}As reaction was one of the few reactions with no experimental data.

Our measurement took place at the FN Tandem accelerator of the University of Notre Dame. A proton beam of energy between 1.6 and 4.2 MeV was used together with a 320(16) $\mu g/cm^2$ target, 97.55% enriched in the isotope ^{74}Ge. The cross section results are shown in Fig. 3a (black points), together with another recent measurement [26] (open squares) and a series of theoretical calculations using the code TALYS. Excellent agreement is observed between the two measurements.

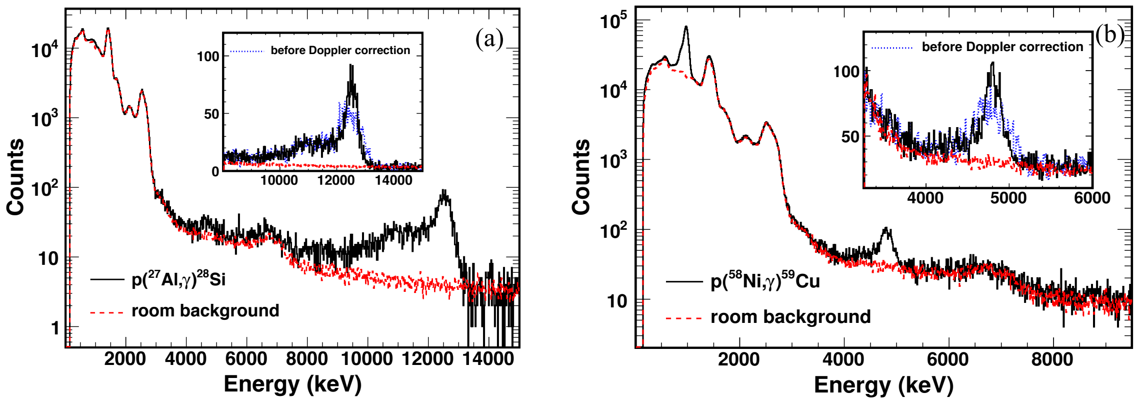

Figure 4: (a) Sum spectrum from the ^{27}Al(p,γ)^{28}Si reaction in inverse kinematics. (b) Sum spectrum from the ^{58}Ni(p,γ)^{59}Cu reaction in inverse kinematics. In both spectra the black-solid line corresponds to the experimental spectrum, the red-dashed line is the room background spectrum , and the blue-dotted line in the inset shows the raw experimental spectrum, without Doppler corrections.

Using these experimental results we performed astrophysical calculations with the post-processing code NucNet Tools [27]. The calculations corresponded to the SNII scenario for a 25M$_\odot$ star. The results of the calculations are shown in Fig. 3b, where the grey band shows the theoretical uncertainty of the ^{74}Ge(p,γ)^{75}As reaction varied by a factor of $\pm$3, while the orange band represents the uncertainty after our measurement. These results show that the overproduction of ^{74}Se was not caused by the ^{74}Ge(p,γ)^{75}As reaction, and in fact the new result causes an even larger overproduction of the lightest p nucleus.

5. SuN in inverse kinematics

As mentioned before, the majority of the reactions participating in a p-process network involve radioactive nuclei, and it is therefore extremely important to develop techniques for measuring these important reactions in inverse kinematics, using radioactive ion beams. For this reason we report here on the first application of the summing technique in inverse kinematics [20]. Two known reactions were chosen as proof-of-principle for the technique. These were the ^{27}Al(p,γ)^{28}Si and ^{58}Ni(p,γ)^{59}Cu. ^{27}Al and ^{58}Ni beams were delivered by the FN Tandem accelerator at the University of Notre Dame. A TiH$_2$ target was used for these measurements that was produced at Argonne National Laboratory. The spectra from the two reactions are shown in Fig. 4 in the black lines. The red-dashed lines correspond to the room background, while the blue-dotted lines (inset) show the same spectra before Doppler corrections are applied. The resonance strengths extracted for the two reactions are in excellent agreement with previous measurements [20].

With the successful application of the summing technique in inverse kinematics, our efforts are now focusing on using this technique with radioactive ion beams at the ReA3 facility at the NSCL, Michigan State University. The ReA3 facility can provide reaccelerated rare isotope beams with energies up to $\approx$ 5 MeV/u, which are ideal for p-process measurements. ReA3 has reaccelerated the first radioactive beam in the summer of 2013 and the first physics experiments will take place soon.

This opens exciting and unique opportunities for direct measurements of reactions of astrophysical interest using reaccelerated radioactive ion beams.

6. Conclusions

The astrophysical p process is still not fully understood. Experimental efforts are focusing on reducing the uncertainties coming from the nuclear physics input in astrophysical calculations. Several stable beam experiments have been performed during the last three decades and have improved our understanding of (p,γ) and (α, γ) reactions, especially for light nuclei. Recently, the community has been focusing more on developing new techniques for measurements in inverse kinematics using radioactive ion beams. For this purpose we have developed the SuN detector at Michigan State University. The detector was used in a series of stable beam experiments at the University of Notre Dame, providing new measurements of previously unexplored reactions. In addition, SuN was used for the first time for (p,γ) reaction measurements in inverse kinematics. Future measurements with radioactive ion beams at the ReA3 facility at Michigan State University are being planned.

The authors would like to acknowledge the support of the National Science Foundation under Grant Nos. PHY-1102511 (NSCL) and PHY 08- 22648 (Joint Institute for Nuclear Astrophysics). TR was partially supported by the Swiss NSF and the European Research Council (grant GA 321263-FISH).

References

[1] B. Meyer, *Annu. Rev. Astron. Astrophys.* **32** (1994) 154.

[2] K. M. Burbidge, G. R. Burbidge, W. A. Fowler, F. Hoyle, *Rev. Mod. Phys.* **29** (1957) 547.

[3] M. Rayet, N. Prantzos, M. Arnould, *Astron. Astrophys.* **227** (1990) 271.

[4] C. Travaglio and F. K. Röpke and R. Gallino and W. Hillebrandt, *Astroph. J.* **739** (2011) 93.

[5] H. Schatz, *et al.*, *Phys. Rep.* **294** (1998) 167.

[6] C. Frohlich, *et al.*, *Phys. Rev. Lett.* **96** (2006) 142502.

[7] S. Wanajo and H.-T. Janka and S. Kubono, *Astroph. J.* **729** (2011) 46.

[8] T. Rauscher, A. Heger, R. D. Hoffman, and S. E. Woosley, *Astrophys. J.* **576** (2002) 323.

[9] M. Arnould, S. Goriely, *Phys. Rep.* **384** (2003) 1.

[10] T. Rausher, N. Dauphas, I. Dillmann, C. Frohlich, Zs. Fulop and Gy. Gyurky, *Rep. Prog. Phys.* **76** (2013) 066201.

[11] T. Rausher, *Phys. Rev. C* **73** (2006) 015804.

[12] W. Rapp, J. Gorres, M. Wiescher, H. Schatz, F. Kappeler, *Astroph. J.***653** (2006) 474.

[13] Zs. Fulop, A. Z. Kiss, E. Somorjai, C. E. Rolfs, H. P. Trautvetter, T. Rauscher, H. Oberhummer, *Z. Phys. A* **355** (1996) 203.

[14] T. Sauter and F. Kappeler, *Phys. Rev. C* **55** (1997) 3127.

[15] S. Harissopulos, E. Skreti, P. Tsagari, G. Souliotis, P. Demetriou, T. Paradellis, J. W. Hammer, R. Kunz, C. Angulo, S. Goriely, T. Rauscher, *Phys. Rev. C* **64** (2001) 055804.

[16] A. Spyrou, H.-W. Becker, A. Lagoyannis, S. Harissopulos, C. Rolfs, *Phys. Rev. C* **76** (2007) 015802.

[17] Q. Zhong *et al.*, *Journal of Physics: Conference Series* **202** (2010) 01201.

[18] A. Simon, J. Fallis, A. Spyrou, A. M. Laird, C. Ruiz, L. Buchmann, B. R. Fulton, D. Hutcheon, L. Martin, D. Ottewell, and A. Rojas, *Eur. Phys. J. A* **49** (2013) 60

[19] P.Ujic, A. Lagoyannis, T. J. Mertzimekis, F. de Oliveira Santos, S. Harissopulos, *et al.*, *AIP, Conference Proceedings* **1377** (2011) 321.

[20] S. J. Quinn, A. Spyrou, A. Simon, *et al.*, *Nucl. Instr. Meth. A* **757** (2013) 62.

[21] A. Simon, S. J. Quinn, A. Spyrou, *et al.*, *Nucl. Instr. Meth. A* **703** (2013) 16.

[22] S. J. Quinn, A. Spyrou, A. Simon, *et al.*, *Phys. Rev. C* **88** (2013) 011603(R).

[23] A. Simon, A. Spyrou, T. Rauscher, C. Frohlich, S. J. Quinn, *et al.*, *Phys. Rev. C* **87** (2013) 055802.

[24] A. Spyrou, S. J. Quinn, A. Simon, T. Rauscher, *et al.*, *Phys. Rev. C* **88** (2014) 045802.

[25] S. J. Quinn, A. Spyrou, E. Bravo, T. Rauscher, A. Simon, *et al.*, *Phys. Rev. C* **89** (2014) 054611.

[26] A. Sauerwein, *et al.*, *Phys. Rev. C* **86** (2012) 035802.

[27] http://sourceforge.net/projects/nucnet-tools/ (2013).