Using HECTOR for Cross Section Measurements of $^{102}Pd(p,\gamma)^{103}Ag$

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Abstract. The High EffiCiency TOtal absorption spectrometeR (HECTOR) consists of 16 scintillating crystals that are made of thallium-doped sodium iodide (NaI(Tl)). Each of the crystals is coupled to two photomultiplier tubes (PMT) and the detector is oriented to create a cubic array surrounding a target. This cubic array orientation allows for simultaneous measurements of the individual gamma (γ) rays produced during the de-excitation of the reaction products, creating a coverage of nearly 4π steradian. HECTOR was constructed to measure capture reactions relevant for the nucleosynthesis process at low energies. The work presented here focuses on a (p,γ) reaction on ^{102}Pd, one of the p-nuclei produced during the p-process. The experiment was conducted at the University of Notre Dame using the FN tandem accelerator at the Nuclear Science Lab. A highly enriched ^{102}Pd target was bombarded with a proton (p) beam at energies between 3.5-8.0 MeV in 200 keV steps. The measured cross section is compared with experimental data found in literature and theoretical models.

INTRODUCTION

Nucleosynthesis of elements heavier than iron (Fe) in stars occurs via three different processes: the s-, r-, and p-process. The s- and r-processes are responsible for the production of a majority of nuclei past Fe by means of "slow" or "rapid" neutron capture, respectively, followed by β^- decay.[1] The p-process occurs less often on the proton-rich side of the line of stability and is responsible for the production of only 35 proton-rich nuclei such as ^{102}Pd and ^{108}Cd, which are known as p-nuclei.[1] This process occurs in specific stellar environments – burning phases of stellar interiors and supernova explosions – and uses cascades of gamma (γ) rays to initiate reactions.[2] During the explosion, γ-rays then penetrate the supernova and destroy s-nuclei, shifting the overall abundance towards p-nuclei by means of photodisintegration reactions: (γ,p), (γ,n), and (γ,α), that produce unstable nuclei that β^+ decay back towards the line of stability.[3] Although the reactions taking place in the stellar environments are (γ,p), (γ,n), and (γ,α), their cross sections can be determined from the capture reactions (p,γ), (n,γ), and (α,γ) which can be studied in the lab.

Measuring the cross sections, or probability, or p-process reactions can shed light on different p-process scenarios that occur during the supernova explosions. The experiment, conducted at the University of Notre Dame in June 2018, focused on measuring the cross sections for p-nuclei that could prove important to the p-process itself. These cross sections continue to be constrained in hopes of improving theoretical models of the p-process scenarios with different outcomes during a supernova explosion to improve the accuracy of the model network.

EXPERIMENT

The detector used for this experiment was the High EffiCiency TOtal absorption spectrometeR (HECTOR). This detector consists of 16 4x4x8 inch thallium-doped sodium iodide (NaI(Tl)) scintillating crystals.[4] Each of these crystals is coupled to two photomultiplier tubes (PMT), utilizing a total of 32 PMTs, partially shown in Figure 1 (a). The detector is then oriented to create a cubic array surrounding an inserted target, as shown in Figure 1 (b), creating a 4π steradian coverage. This orientation allows for the individual γ-rays produced during the de-excitation of the reaction products from the target to be measured simultaneously.

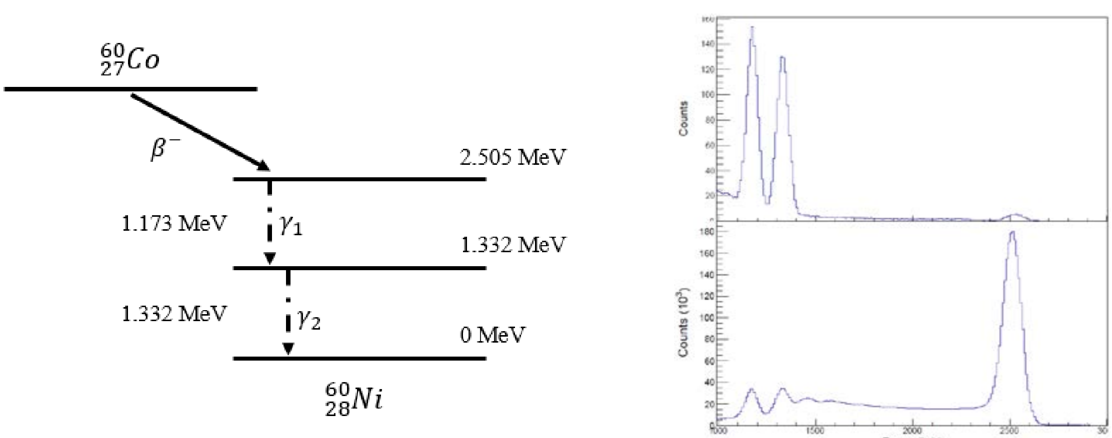
(a) (b)

FIGURE 1. (a) 16 PMTs on the top of HECTOR coupled to the top 8 scintillators. (b) HECTOR in a cubic array.

Using the FN tandem accelerator at the University of Notre Dame, a beam of protons was accelerated towards HECTOR and the targets of interest. The experiment took measurements for ^{90}Zr, ^{102}Pd, ^{108}Cd, and ^{110}Cd. However, the data inspected in this analysis focuses specifically on the p-nucleus, ^{102}Pd.

GAMMA-SUMMATION

A single decaying nucleus emits a cascade of photons that can be detected as single photons in individual peaks on a spectrum, which is typically produced by conventional detectors.[5] However, in gamma-summing detectors such as HECTOR, each individual γ-ray cascade is recorded as one single energy peak. To demonstrate this technique, the simple decay scheme of ^{60}Co is examined (Figure 2a).



(a) **(b)**

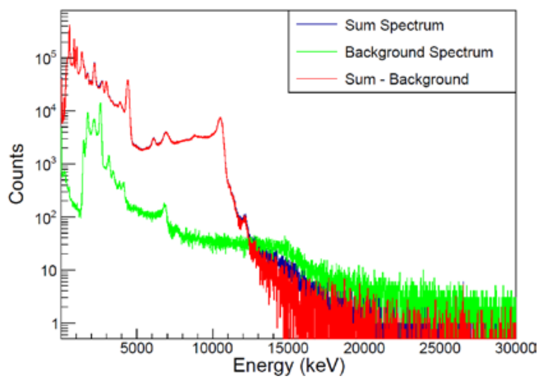
FIGURE 2. (a) Decay scheme for ^{60}Co. (b) TOP – single γ-ray spectrum. BOTTOM – γ-ray summation peak.

After ^{60}Co has β^- decayed to ^{60}Ni, the new ^{60}Ni nucleus is excited to an energy of 2.504 MeV and 2 γ-rays are emitted to return ^{60}Ni to its ground state. The gamma rays have energies of 1.173 MeV (1173 keV) and 1.332 MeV (1332 keV) respectively. In Figure 2b (top), a traditional γ-ray spectrum displays the 2 individual γ-rays and their energies, with a very small peak at the sum energy of the rays. In Figure 2b (bottom), the sum spectrum shows one large peak at the total excess energy the nucleus must release when it de-excites.

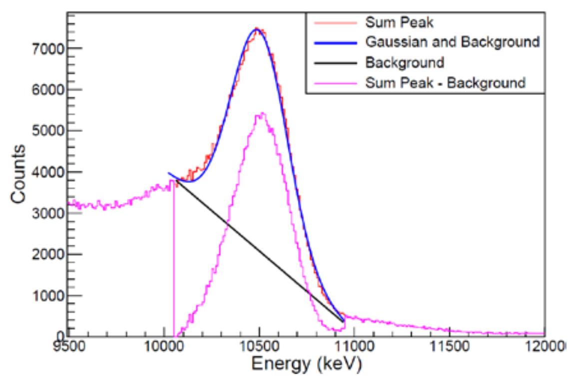
In the case of beam induced reactions, the energy of the sum peak, which is the excitation energy of the reaction product, is equal to the sum of the proton beam energy in the center-of-mass system and the Q-value of the reaction, where Q = 4.1885 MeV for ^{102}Pd(p,γ). For example, if the beam energy is 8 MeV, a γ-ray sum peak would be expected at approximately 12.2 MeV. By taking the integral of this peak, the number of total counts recorded by the detector can be found and used for further cross section calculations.

BACKGROUND SUBTRACTION AND INTEGRATION

In order to get the correct γ-ray spectrum, a spectrum from the recorded data and a background run, where there is no target or beam in HECTOR, needed to be plotted. The background runs taken for the experiment were at least 4 times longer than most of the data collection runs and therefore needed to be scaled by calculating a time ratio between the data and background runs. The now scaled background spectrum was subtracted from a recorded data spectrum, shown in Figure 3 (a). This subtraction removes excess γ-rays produced from cosmic rays around the detector that could affect the number of counts recorded by HECTOR during the runs where reactions are taking place.



(a)



(b)

FIGURE 3. (a) Full γ-ray sum spectrum for a 6352.2 keV beam energy. Each colored line represents the following: original sum spectrum (blue), background spectrum (green), sum spectrum after background subtraction (red). (b) Sum peak of the spectrum. Each colored line represents the following: original sum peak (red), gaussian and first-order polynomial background fit (blue), background fit (black), sum peak with background subtracted (purple).

To get the integral of the sum peak from the data spectrum, the peak needed to be fit with a gaussian and a first-order polynomial function (to account for the background fit). The parameters of this fit varied between energies in order to get the best possible shape of the curve so that it closely matched that of the sum peak. Because it is known that the peak should appear at approximately the sum energy, the gaussian and polynomial were fit over a range around that energy (Figure 3 (b)). After the fitted background was subtracted, the plot was integrated underneath the sum peak to obtain the number of counts collected by the detector.

MULTIPLICITY AND EFFICIENCY

One of the values recorded during the experiment keeps track of the multiplicity of an event. The multiplicity is the number of detectors that fired for one specific γ-ray cascade. The number of γ-rays in the cascade is correlated to the number of segments that fired.

The multiplicity then affects the efficiency of HECTOR. The efficiency (ε) gives the percentage of decays that can actually be detected by HECTOR. The values needed for the efficiency curves cannot be found experimentally but instead are found through simulations that provide efficiency as a function of multiplicity and sum peak energy. Details of the procedure are described in Ref. 4. This procedure generates constants (p_0, p_1, and p_2) that, when multiplied with the multiplicity using a second-order polynomial function, produce the efficiency of each reaction, shown in Equation (1).

$$\varepsilon(m) = p_0 + p_1 + p_2 m^2 \tag{1}$$

CROSS SECTION CALCULATIONS

The cross sections (σ) of ^{102}Pd(p, γ) reactions at given energies are calculated using the following formula:

$$\sigma = \frac{N_{det}}{N_{beam} * d * \varepsilon} \tag{2}$$

where, N_{det} is the number of counts from the detector found by the integral of the sum peak, N_{beam} is the total number of particles from the beam that were found using an analog scaler throughout the experiment, d is the thickness of the target in atoms/cm^2, and ε is the efficiency of the detector at a given beam energy. The uncertainty in the $N_{beam,}$ target thickness (d), and efficiency was taken at 5%. The center-of-mass energy (E_{CM}) was found by averaging the energy before the beam hits the target and the energy after. The uncertainty in the E_{CM} was found by subtracting either the initial or final energy value from the average beam energy. Finally, the uncertainty in N_{det} was found by taking the square root of N_{det} and the integral of the first-order polynomial fit to the background. Error propagation was then used to calculate the uncertainty of σ.

RESULTS

Cross section measurements were taken at 15 different beam energies. The calculated values of the cross section, labeled as HECTOR in Figure 5, were then plotted with theoretical values and measured values from Dillmann, et al. and Ozkan, et al.[6,7,8] The predictions are taken from published results obtained with the NON-SMOKER code, which is a standard model for cross section calculations in nuclear astrophysics.[6] Only 14 energies are shown in Figure 5 because the lowest energy resulted in γ-ray measurements that coincided with a background emission line.

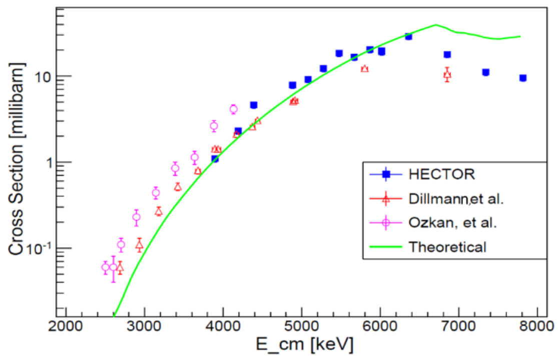


FIGURE 4: Measured cross section values from this work and other literature compared to theoretical values.

CONCLUSIONS

By using γ-summing techniques, cross sections can be easily obtained and more information regarding the production of p-nuclei in exploding supernova can be found. Using HECTOR and its sum-peak spectroscopy properties, γ-summation was completed in an experiment at the University of Notre Dame in attempts to simulate (γ,p) reactions in the supernova explosion by measuring the cross section of (p,γ) in the lab. The ^{102}Pd(p,γ) reaction was further analyzed and cross section measurements were obtained.

The cross-section measurements that were acquired from the HECTOR experiment were then compared to other measurements by Dillmann, et al. and Ozkan, et al., as well as theoretical values from NON-SMOKER models. The data collected kept the same overall trend as the other experimental values but more closely matched the theoretical values from 3.5-6.5 MeV and lay between the theoretical and Dillmann, et al. values at energies between 6.5-8.0 MeV. It is important to point out that this deviation lies above the neutron emission threshold. This threshold is the point in which (p,n) reactions can occur instead of the (p,γ) reactions that produce the cross section measurements. Therefore, the results are the new cross section measurements from this (p,γ) reaction.

These new cross section measurements are to be used in network calculations that take the measurements as parameters to simulate potential p-process scenarios and produce possible outcomes. By changing the cross sections, supernova explosions can be simulated, and the p-process scenario can be compared to the observed amounts of p-process nuclei.

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