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# First measurements of capture reactions for the $\gamma$ -process using HECTOR

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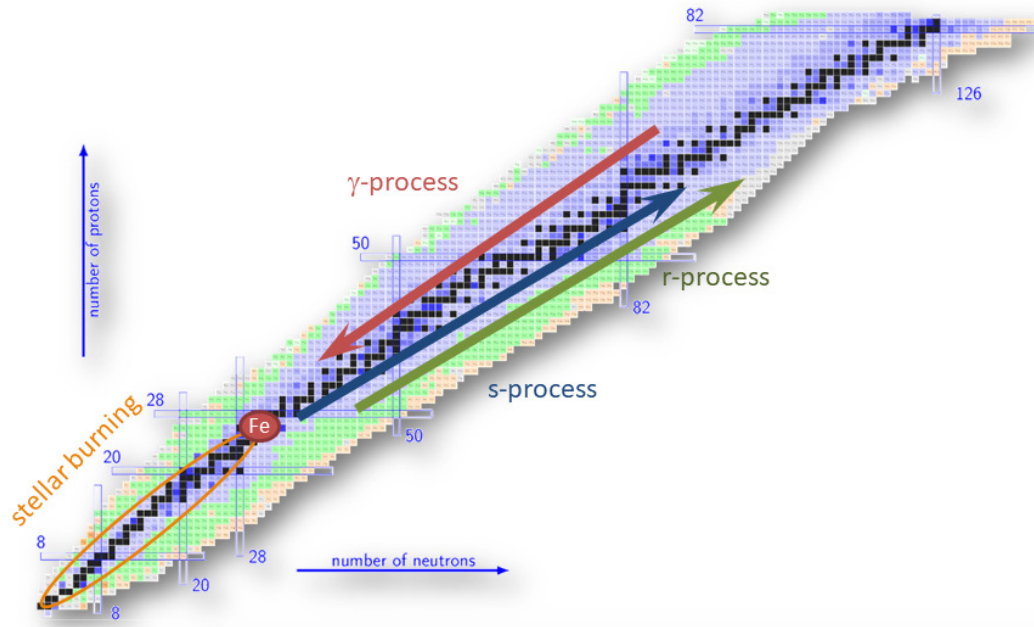
**Abstract.** The first measurements of the capture reactions for the astrophysical  $\gamma$ -process using HECTOR, a total absorption spectrometer are presented. Two reactions:  $^{102}\text{Pd}(p,\gamma)^{103}\text{Ag}$  and  $^{90}\text{Zr}(\alpha,\gamma)^{94}\text{Mo}$  were measured using the  $\gamma$ -summing technique. The results are compared with the previous measurements found in the literature and with the NON-SMOKER predictions. The results from the current work are in a good agreement with the data found in the literature and serve as a test of the newly developed detector.

## 1. The $\gamma$ -process nucleosynthesis

There are multiple nucleosynthesis processes responsible for production of elements heavier than iron, see Figure 1. Since these elements cannot be synthesized during stellar burning processes due to the high Coulomb barrier and thus a low reaction cross section, they have to be produced during reactions with uncharged particles [1]. There are two processes that explain the origin of most of the heavy isotopes: the s- and r-processes [2, 3, 4], which are a combination of neutron capture and  $\beta$ -decay. However, these processes do not explain the origin of several of the proton-rich isotopes of the elements between selenium and mercury that are shielded from the  $\beta$ -decay path by the valley of stability [5]. To be precise, there are 35 isotopes that cannot be produced via neutron capture processes. Several processes have been proposed to explain the origin of these nuclei [6]; however, the most favorable scenario to-date is the  $\gamma$ -process [7].

The  $\gamma$ -process is comprised of mainly  $\gamma$ -induced (photodisintegration) reactions:  $(\gamma,n)$ ,  $(\gamma,p)$  and  $(\gamma,\alpha)$ . The temperatures necessary for the  $\gamma$ -process to occur are of the order of 1.5-3.5 GK [5, 8]. As such, the  $\gamma$ -process has to take place in explosive environments, for example, type II [7, 8, 9, 10] or type Ia supernovae (SN) [11, 12, 13, 14, 15], where such temperatures can be achieved. In these environments, during the explosion, a high flux of  $\gamma$  rays is emitted. These  $\gamma$  rays pass through the volume of the star with the explosion shockwave and interact with the matter present in the environment (i.e., the elements produced during the stellar burning stages and by the s-process) triggering a sequence of  $(\gamma,p)$ ,  $(\gamma,\alpha)$  and  $(\gamma,n)$  reactions. These reactions produce unstable, proton-rich nuclei that, after the flux of  $\gamma$  rays ends,  $\beta$ -decay towards stability populating the stable, proton-rich isotopes of heavy elements.





**Figure 1.** Nucleosynthesis processes. Black squares denote stable nuclei. Colors indicate the nuclear half-lives: blue - above 10 s, green - 1 ms to 10 s, orange - below 1 ms.

The complete network describing the  $\gamma$ -process involves nearly 2,000 nuclei and 20,000 reactions. Since a vast majority of those reactions cannot be measured, the models have to rely on theoretical predictions for the reaction rates, such as the statistical Hauser-Feshbach (HF) model [16]. The HF model in turn depends on the description of the statistical parameters of the nuclei, such as the level density (LD), optical model potential (OMP) and the  $\gamma$ -ray strength function ( $\gamma$ SF). With a variety of models for the statistical inputs, the reaction rates obtained from HF calculations can span up to an order of magnitude, thus limiting the predictive power of the network calculations. However, experimental efforts can constrain those models by providing systematic measurements of the reaction cross sections that can then be used to constrain the inputs for the HF models.

The reactions relevant for the astrophysical  $\gamma$ -process can be studied via their inverse, i.e.,  $(p, \gamma)$  and  $(\alpha, \gamma)$  as the temperature range of the  $\gamma$ -process corresponds to projectile energies of 1-6 MeV and 3-12 MeV for proton and  $\alpha$  capture reactions, respectively. In this work, the first results from a  $\gamma$ -ray summing detector at the University of Notre Dame aiming at constraining the HF predictions are presented. Cross sections for two capture reactions will be presented with a comparison to the measurements found in the literature and to the NON-SMOKER [17] calculations based on the HF model.

## 2. $\gamma$ -summing technique

The proton and  $\alpha$  capture cross sections depend strongly on the projectile energy and decrease rapidly by orders of magnitude within the Gamow window as the projectile energy decreases. Thus, very efficient experimental techniques are required to extend the measurements towards the low energy part of the Gamow window.

The results presented in this paper were obtained using the  $\gamma$ -summing technique. The technique is a well established method used for cross section measurements [18, 19, 20, 21]. It requires a large volume  $\gamma$ -ray detector covering almost a  $4\pi$  solid angle so that all the  $\gamma$  rays



**Figure 2.** HECTOR: High Efficiency TOtal absorption spectrometeR.

from the deexcitation cascade following the projectile capture are detected. Since the  $\gamma$  rays cannot be resolved by the large crystal due to its long response time, they are all summed into the so-called sum peak. When the entry state populated by the captured projectile decays into the ground state, the energy of the sum peak can be expressed as

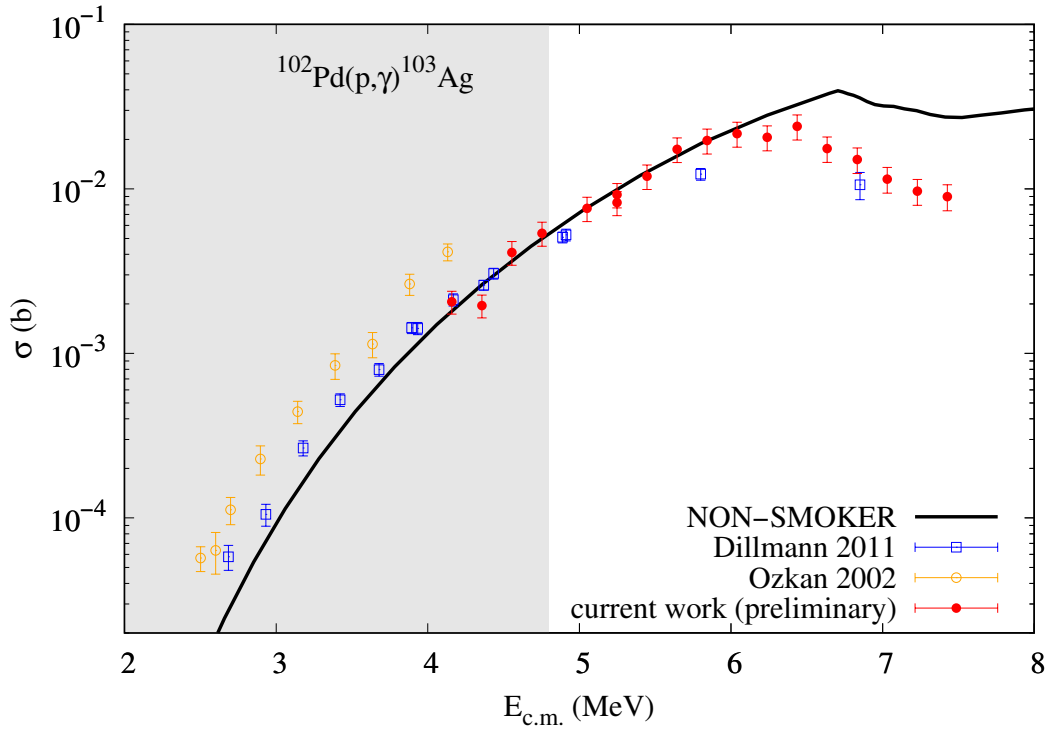
$$\gamma_{\Sigma} = E_{\text{entry}} - E_{g.s.} = E_{CM} + Q, \quad (1)$$

where the  $E_{\text{entry}}$  and  $E_{g.s.}$  are the energy of the entry and ground state, respectively,  $E_{CM}$  is the projectile energy in the center-of-mass system and  $Q$  is the reaction Q-value.

The method has several advantages over the alternative technique (i.e., using the angular distribution of the emitted  $\gamma$  rays). Since the detector covers nearly 100% of the solid angle there is no need for angular distribution corrections, which greatly reduces the uncertainty. Additionally, the angular distribution method requires identification of all the  $\gamma$  rays feeding the ground state to account for all the possible branching paths of the decay of the entry states. Frequently, the  $\gamma$ -decay branchings are not known very well or the intensity of the  $\gamma$  rays is low and they cannot be resolved from the background, which may result in underestimation of the measured cross section. This is not the case with the summing technique, where each decay branch will be summed to the same energy ( $\gamma_{\Sigma}$ ). The only peak structure in the spectrum that needs to be analyzed is the sum peak with the area proportional to the measured cross section.

### 3. Experimental procedure

The experiments were performed at the Nuclear Science Laboratory of the University of Notre Dame using a  $\gamma$ -summing detector, HECTOR. The High Efficiency TOtal absorption spectrometeR is an array of sixteen  $4'' \times 8'' \times 8''$  NaI(Tl) crystals, each read out by two photomultipliers (see Fig. 2). Each segment of HECTOR is housed by a 1 mm aluminum casing and the crystals are assembled to form a 16-inch cube. A 60 mm bore hole through the



**Figure 3.**  $^{102}\text{Pd}(p,\gamma)^{103}\text{Ag}$  cross section obtained with HECTOR (solid red circles) compared with previous results of Dillmann et al. [23] (open blue squares) and Ozkan 2002 [24] (open yellow circles). Solid black line denotes the cross section from the NON-SMOKER website [25]. The gray shaded area indicates the Gamow window.

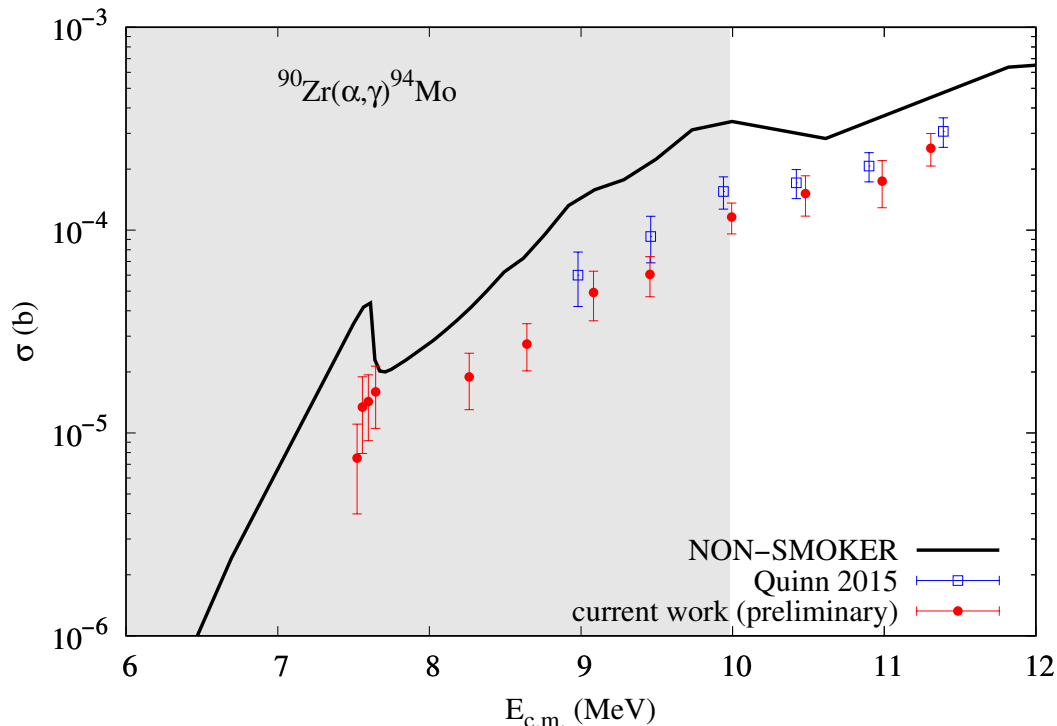
array allows for placing the target in the center of the array without compromising the solid angle covered by the detector. Details of the detector can be found in [22].

Highly enriched targets of  $^{102}\text{Pd}$  (78(1)% enriched) and  $^{90}\text{Zr}$  (98(1)% enriched) were used during the experiment. The  $^{102}\text{Pd}$  was bombarded with 1-10 nA proton beam, while a 10-25 nA beam of  $\alpha$  particles was impinging on the  $^{90}\text{Zr}$  target. In each case, the target was placed in the center of the detector to maximize the  $\gamma$ -summing efficiency.

The beam pipe within the setup was electrically insulated and served as a Faraday cup for measurement of the beam current. The charge deposited in the Faraday cup was collected by a charge integrator and recorded within the data acquisition system for continuous monitoring of the beam intensity. The energy range covered during the experiment was 4-7.5 MeV and 7.5-11.5 MeV for proton and  $\alpha$  beam, respectively.

#### 4. Results

The data analysis was performed in accordance with the method described in detail in [22]. For each beam energy, the integral under the sum-peak in the spectrum was obtained and the background from the incomplete summation was subtracted. The  $\gamma$ -summing efficiency was determined using a Geant4 simulation of the HECTOR array. The target thickness has been determined using the Rutherford backscattering technique. The uncertainty in the cross sections includes the statistical and systematic uncertainty of the sum-peak integral, 5% uncertainty in the target thickness and in the total beam current, and 10% uncertainty in the summing efficiency. The preliminary results are shown in Figures 3 and 4, for the  $^{102}\text{Pd}(p,\gamma)^{103}\text{Ag}$  and



**Figure 4.**  $^{90}\text{Zr}(\alpha,\gamma)^{94}\text{Mo}$  cross section obtained with HECTOR (solid red circles) compared with previous results of Quinn et al. [26] (open blue squares). Solid black line denotes the cross section from the NON-SMOKER website [25]. The gray shaded area indicates the Gamow window.

$^{90}\text{Zr}(\alpha,\gamma)^{94}\text{Mo}$  reactions, respectively.

In the case of  $^{102}\text{Pd}(p,\gamma)^{103}\text{Ag}$  reaction, two previous measurements were found in the literature. The first one from Ozkan et al. [24] was performed using the activation technique, the second one by Dillmann et al. [23] utilized in-beam  $\gamma$ -ray detection using Ge detectors. There is a discrepancy of about a factor of two between the two data sets. The current measurement shows a very good agreement with the data from Dillmann et al. and extends the covered energy range towards higher energies. For comparison, the cross section obtained from NON-SMOKER is also shown in Figure 3. The model seems to under-predict the cross section at lower energies while it overestimates the capture cross section at energies above 6.5 MeV. In the energy range of 4-6.5 MeV a good agreement between the current work, data from Dillmann et al. and NON-SMOKER can be observed.

The  $^{90}\text{Zr}(\alpha,\gamma)^{94}\text{Mo}$  reaction has previously been measured using the  $\gamma$ -summing technique by Quinn et al. [26]. Very good agreement between the previous measurement and current work can be seen in Figure 4. Additionally, the current measurement extends the experimentally covered energy range down to 7.5 MeV. NON-SMOKER overestimates the experimental cross sections by a factor of 2-3.

## 5. Conclusions

The first results from a  $\gamma$ -summing detector, HECTOR, at the University of Notre Dame were presented. Two measurements of capture reactions:  $^{102}\text{Pd}(p,\gamma)^{103}\text{Ag}$  and  $^{90}\text{Zr}(\alpha,\gamma)^{94}\text{Mo}$  were discussed and compared with the previous measurements found in the literature and with NON-

SMOKER calculations. In the case of the  $^{102}\text{Pd}(p,\gamma)^{103}\text{Ag}$  reaction, a good agreement with the previous measurement of Dillmann et al. [23] was found. For the  $^{90}\text{Zr}(\alpha,\gamma)^{94}\text{Mo}$  reaction, the current results are in a very good agreement with the results of Quinn et al. [26] who utilized the same experimental technique. The results serve as a proof-of-principle for the newly commissioned detector.

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