# First results from HECTOR: High EffiCiency TOtal absorption spectrometeR for γ-process nucleosynthesis studies

Journal of Physics: Conference Series **1668** (2020) 012038 doi:10.1088/1742-6596/1668/1/012038

# First results from HECTOR: High EffiCiency TOtal absorption spectrometeR for $\gamma$-process nucleosynthesis studies

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**Abstract.** The nucleosynthesis path of the $\gamma$-process is predominantly governed by the branching points at which the flow of the initial ($\gamma$,n) is redirected by either ($\gamma$,p) or ($\gamma$,$\alpha$) reactions. In this work, the inverse reactions, proton and $\alpha$ capture on $^{108}$Cd were studied in order to aid in verification of the $^{112}$Sn isotope as a potential branching point in the $\gamma$-process. The results of the first measurement with a $\gamma$-summing detector, HECTOR, are compared with previous measurements found in the literature and with NON-SMOKER predictions. The results of this work will provide input for Hauser-Feshbach calculations to obtain the $\gamma$ induced reaction rates.

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

A majority of nuclei above iron are produced during two nucleosynthesis scenarios: the s- and r-processes [1, 2, 3], which are a combination of neutron capture and $\beta$-decay (Figure 1). 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 [4]. Several processes have been proposed to explain the origin of these 35 p-nuclei [5]; however, the most favorable scenario to-date is the $\gamma$-process [6].

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 [4, 7], thus, the $\gamma$-process has to take place in explosive environments, such as, type II [6, 7, 8, 9] or type Ia supernovae (SN) [10, 11, 12, 13, 14]. In these explosive environments, a high flux of $\gamma$ rays is produced, which then passes through the volume of the star with the explosion shockwave and interacts with the pre-existing seed nuclei, 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.

The details of the reaction flow of the $\gamma$-process are governed primarily by the so-called branching points, i.e., nuclei for which at given astrophysical conditions the ($\gamma$,n) reactions

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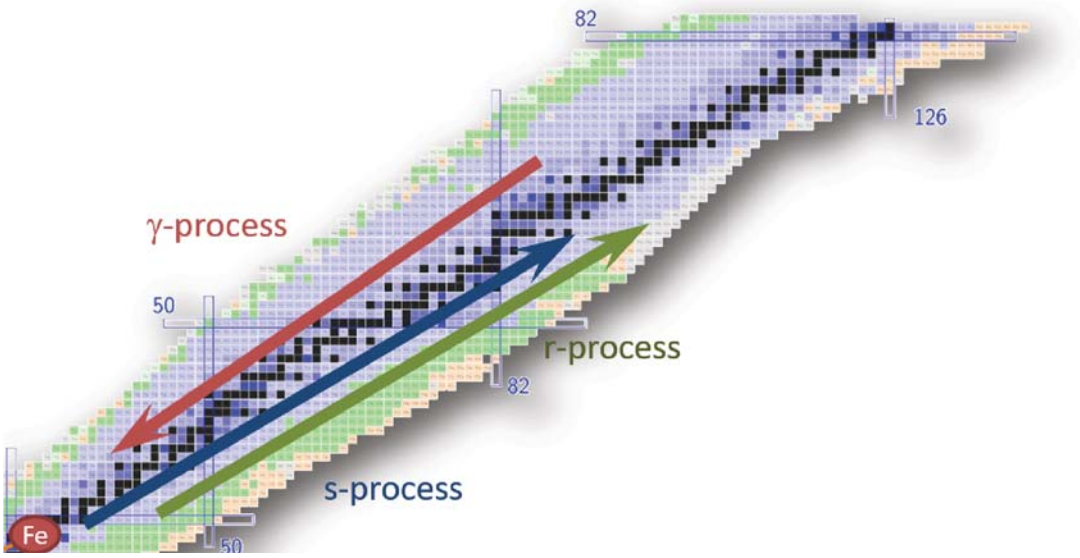


**Figure 1.** Major nucleosynthesis processes responsible for production of elements beyond iron. Black squares denote stable nuclei. Colors indicate the nuclear half-lives: black - stable isotopes, blue - above 10 s, green - 1 ms to 10 s, orange - below 1 ms.

no longer dominate and either ($\gamma$,p) or ($\gamma$,$\alpha$) redirect the flow towards lower-Z nuclei. In the study by Rauscher [15], a list of branching points that are most impactful for the $\gamma$-process nucleosynthesis was compiled. The aim of the current work was to verify that $^{112}$Sn is a branching point in the $\gamma$-process. It was suggested in [15] that at $^{112}$Sn the ($\gamma$,$\alpha$) reaction becomes dominant over ($\gamma$,n) and the reaction flow is redirected towards $^{108}$Cd. In this work, the inverse reaction $^{108}$Cd($\alpha$,$\gamma$)$^{112}$Sn was measured in order to experimentally constrain the $\gamma$-induced one. Additionally, $^{108}$Cd(p,$\gamma$)$^{109}$In was measured to provide constraints for the statistical model prediction of cross sections in the A$\sim$100 mass region to indirectly constrain the ($\gamma$,n) reaction as well.

## 2. $\gamma$-summing technique

After a capture of a projectile to a target nucleus, a compound nucleus in an excited state is formed. At energies relevant for the $\gamma$-process, this entry state will deexcite to the ground state via emission of $\gamma$ rays. The total energy carried away by the $\gamma$ rays can be expressed as:

$$E_{total} = E_{entry} - E_{g.s.} = E_{CM} + Q, \tag{1}$$

where the $E_{entry}$ 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. When the target is surrounded by a $4\pi$ high-efficiency $\gamma$-ray detector, all the $\gamma$ rays from each deexcitation cascade will be detected and summed together. As a result, a sum-peak at energy $E_{total}$ is recorded with intensity proportional to the reaction cross section. Such an experimental approach is referred to as the summing technique. The technique is a well established method used for cross section measurements [16, 17, 18, 19, 20].

## 3. Experimental procedure

The experiments were performed at the Nuclear Science Laboratory of the University of Notre Dame using a $\gamma$-summing detector, HECTOR [20]. HECTOR, The High EffiCiency TOtal

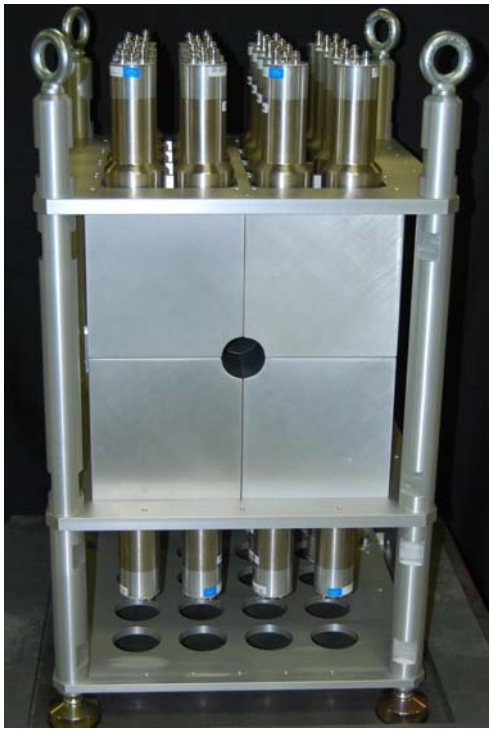

**Figure 2.** HECTOR: High EffiCiency TOtal absorption spectrometeR.

absorption spectrometeR is an array of sixteen $4'' \times 8'' \times 8''$ NaI(Tl) crystals, each read out by two photomultipliers (see Figure 2). Each segment of HECTOR is housed in a 1 mm aluminum casing and the crystals are assembled to form a 16-inch cube. A 60 mm bore hole through the 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 [20]. The preliminary results of the proof-of-principle measurements of $^{102}$Pd(p,$\gamma$)$^{103}$Ag and $^{90}$Zr($\alpha$,$\gamma$)$^{94}$Mo reactions using HECTOR were discussed in [21].

In the current work, a highly enriched (88%) 2 mg/cm$^2$ self-supported target of $^{108}$Cd was placed in the center of HECTOR and bombarded with a few tens of nA of proton and alpha beam. The beam pipe, target holder and the target itself were electrically isolated from the rest of the setup and served as a Faraday cup for measurement of the beam current. Since the whole system was utilized as a Faraday cup, no suppression voltage was necessary. 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 4.0-7.0 MeV and 8.5-11.5 MeV for proton and $\alpha$ beam, respectively.

## 4. Results

The data analysis was performed in accordance with the method described in detail in [20]. 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.

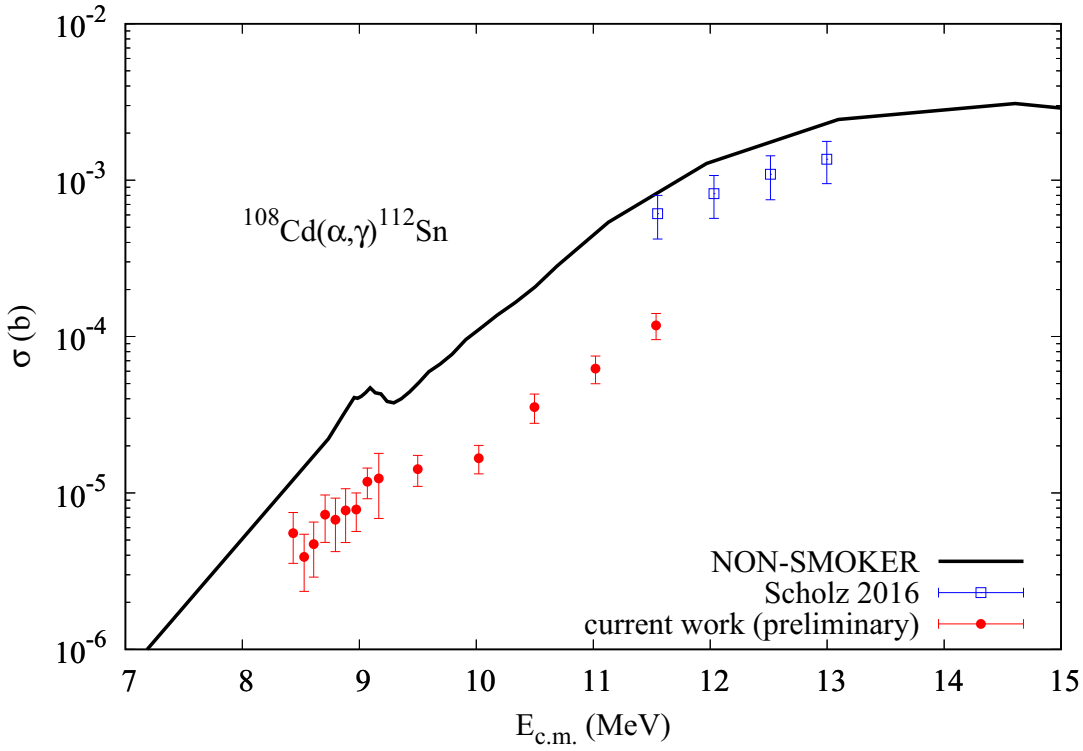


**Figure 3.** Current cross section data for the $^{108}$Cd($\alpha$,$\gamma$)$^{112}$Sn reaction (solid red circles) compared with the data of Scholz et al. [22] (open blue squares) and predictions of the NONSMOKER code [23].

*4.1. The $^{108}$Cd($\alpha$,$\gamma$)$^{112}$Sn reaction*

The preliminary results of this work for the $^{108}$Cd($\alpha$,$\gamma$)$^{112}$Sn reaction are shown in Figure 3. This is the first measurement of this reaction that spans energies below the ($\alpha$,n) threshold. The cross sections obtained in this work are approximately a factor of 2 to 5 lower than those predicted by NON-SMOKER [15] which is typical for $\alpha$-capture reactions in this mass region.

The results of Scholz et al. [22] are much closer to the NON-SMOKER values and are about a factor of two higher than the current results at the overlapping energy point. The origin of this discrepancy is still under investigation; one possible explanation is overlap of the measured $\gamma$ ray with other $\gamma$ rays in the data of Scholz et al.

*4.2. The $^{108}$Cd(p,$\gamma$)$^{109}$In reaction*

In Figure 4, the preliminary results for the total proton capture cross section are reported, that include both capture to the ground and to the first excited state in $^{109}$In. The results of this work are in an excellent agreement with those of Gyurky et al. [24]. Both the data sets in the overlapping energy range provide cross sections slightly lower than those of Skakun et al. [25]. At higher energies the current results are about a factor of two lower than those predicted by NON-SMOKER and reported in [25].

## 5. Conclusions

The results from a $\gamma$-summing detector, HECTOR, at the University of Notre Dame were presented. Two measurements of capture reactions: $^{108}$Cd($\alpha$,$\gamma$)$^{112}$Sn and $^{108}$Cd(p,$\gamma$)$^{109}$In were discussed and compared with the previous measurements found in the literature and with NON-

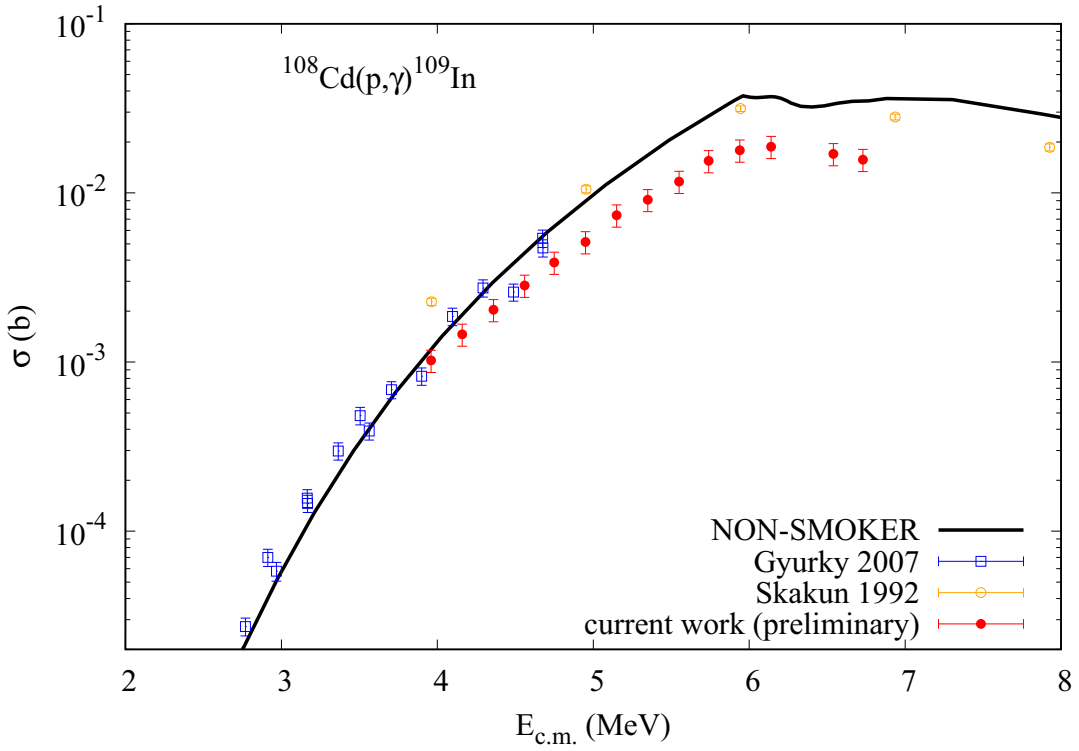


**Figure 4.** Current cross section data for the $^{108}$Cd(p,$\gamma$)$^{109}$In (solid red circles) compared with data from Gyurky et al. [24] (open blue squares) and Skakun et al. [25] (open yellow circles) and predictions of the NON-SMOKER code [23].

SMOKER calculations. In the case of the $^{108}$Cd(p,$\gamma$)$^{109}$In reaction, a good agreement with the previous measurement of Gyurky et al. [24] was found, which resolved the discrepancy between the results of [24] and [25]. For the $^{108}$Cd($\alpha$,$\gamma$)$^{112}$Sn reaction, the current results are a factor of two lower than the results of Scholz et al. [22].

The measurements presented here will be utilized to constrain the Hauser-Feshbach predictions of the ($\gamma$,$\alpha$) and ($\gamma$,n) reaction channels to determine if $^{112}$Sn is a branching point in the $\gamma$-process reaction flow.

## 6. Acknowledgments

This work was supported by NSF under grants No. PHY-1614442, PHY-1713857 (Nuclear Science Laboratory) and PHY-1430152 (JINA-CEE).

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