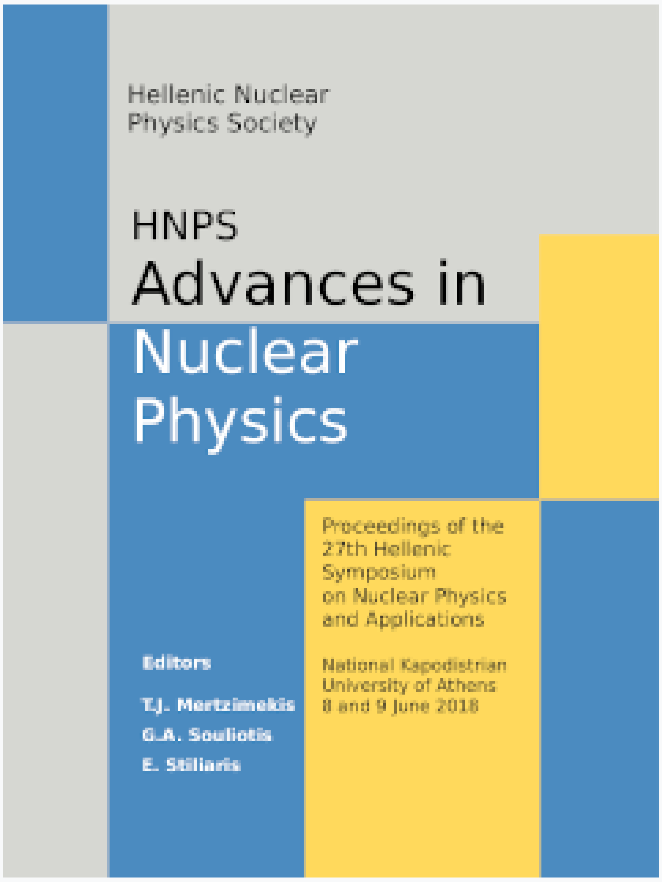
HNPS Advances in Nuclear Physics

Vol 26 (2018)

HNPS2018



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doi: [10.12681/hnps.1818](https://doi.org/10.12681/hnps.1818)

On the Experimental Investigation of the Angular Distributions in the Reaction ^{112}Cd$(p,\gamma)^{113}$In

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Abstract Some of the mid–weight nuclei lie in the region of the isotopic chart where the astrophysical *p*-process has a prominent role in the nucleosynthetic scenarios. Experimentally deduced reaction cross section data can provide stringent tests for the astrophysical models, especially at low energies. In this framework, the reaction ^{112}Cd$(p,\gamma)^{113}$In has been studied experimentally at four proton beam energies $2.8 \leq E_p \leq 3.4$ MeV, partly inside the astrophysically interesting Gamow window. Proton beams were provided by the 5.5 MV T11 Van de Graaff Tandem Accelerator of the Institute of Nuclear Physics of the National Center for Scientific Research (NCSR) "Demokritos". In–beam spectroscopy was carried out with an array of four HPGe detectors sitting on a rotating table. In total, eight (8) different angles were used to record gamma–ray spectra. Special focus was given on constructing the angular distribution of each gamma–ray feeding the ground state of ^{113}In directly, so as to determine the reaction cross sections from the in–beam data, exclusively. The resulting cross sections were compared to Hauser–Feshbach calculations using the code TALYS v1.9.

Keywords Cross Section, Angular Distribution, (p,γ) Reaction, TALYS

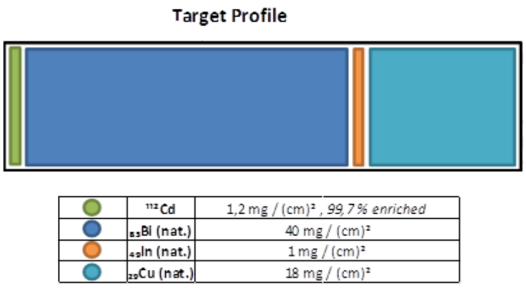
INTRODUCTION

One of the main subjects of Nuclear Astrophysics is understanding the mechanisms behind the generation of isotopes inside powerful stellar environments. The *p*–process, which is responsible for the *p*–nuclei abundances that appear in the observed solar system, comprised an extended network of nuclear reactions (e.g. *p*–process: ≈20'000 reactions). Styding those *p*–nuclei, such as ^{113}In, requires knowledge of proton–capture cross sections at low energies. Due to the vast network of nuclear reactions involved statistical models are often employed relying on experimental data, which are often scarce. In this work, the proton capture by ^{112}Cd is studied experimentally at energies of astrophysical interest. The experimental results are compared to theoretical calculations with TALYS v1.9 employing the Hauser–Feshbach model.

EXPERIMENTAL DETAILS

The reaction ^{112}Cd$(p,\gamma)^{113}$In was studied with proton beams accelerated at energies of 2.8, 3.0, 3.2 and 3.4 MeV by the 5.5 MV T11 Van de Graaff Tandem Accelerator at NCSR "Demokritos". The protons were collimated and impinged on a thin isotopic target of ^{112}Cd (1.2 mg/cm^2, 99.7% enriched) backed by three additional layers (Table 1). The target was mounted in a ladder inside a vacuum chamber tilted by 30° with respect to the beam to avoid any shadowing effects by the target frame.

The γ rays from the de–exciting ^{113}In nuclei (Table 2) were detected by four high–efficiency HPGe detectors. The detectors were placed on a goniometric table at specific angles (Fig. 1) to obtain sufficient information on the angular distribution of the γ rays. A 15° rotation of the goniometric table, driven by a remotely–controlled motor, enabled collection of data at four addition angles. Analysis of spectra was performed using the SpectrW analysis software [1].



	^{112}Cd	1,2 mg / (cm)² , *99,7 % enriched*
	$_{83}$Bi (nat.)	40 mg / (cm)²
	$_{49}$In (nat.)	1 mg / (cm)²
	$_{29}$Cu (nat.)	18 mg / (cm)²

Table 1. Target composition

E_{level} (keV)	E_γ (keV)	$t_{1/2}$	Multipolarity
391.70	391.70	99.48 min (IT)	M4
1024.28	1024.30	3.60 ps	E2
1131.48	1131.50	0.97 ps	E2
1191.12	1191.10		M1,E2
1509.01	1509.04	0.20 ps	

Table 2. Main γ rays of ^{113}In feeding ground state

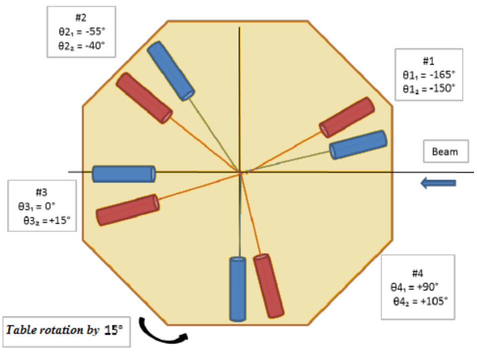


Figure 1. A sketch of the experimental setup

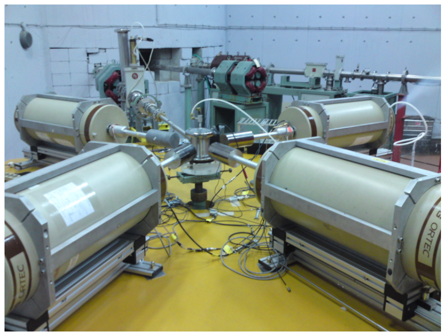


Figure 2. The HPGe detectors

RESULTS AND DISCUSSION

Angular Distributions

In–beam data were collected at two angle sets accounting for a total of eight (8) angles of detection (Fig. 1). After measuring the number of counts N in a detector at an angle θ having absolute detection efficiency ε for γ–ray E^γ, the absolute yield for a particular beam energy E_p is:

$$Y\left(E_i^\gamma, E_j^p, \theta_k\right) = \frac{N\left(E_i^\gamma, E_j^p, \theta_k\right)\omega\left(E_j^p, \theta_k\right)}{\varepsilon_{abs}(E_i^p, \theta_k)Q\left(E_j^p\right)}$$

The angular distribution W(θ) can be extracted by fitting a function of the form:

$$W(\theta) = A_0\{1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)\}$$

corresponding to an E2 de–excitation. Here A_k (k=0,2,4) are free parameters and P_k k–order Legendre polynomials. The experimental results and the corresponding fitted curves are illustrated in Fig. 3.

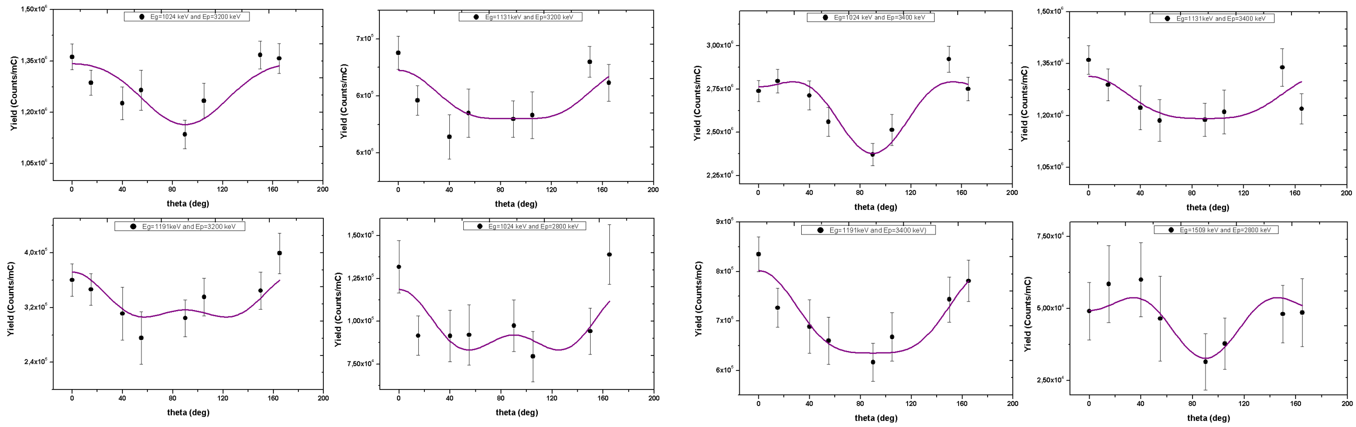


Figure 3. Experimentally deduced angular distributions for the γ–ray decays listed in Table 2. The isomeric decay (E_γ=391.7 keV, $t_{1/2}$=99 min) is excluded.

Cross Sections

The in–beam cross section, σ, for the ^{112}Cd$(p,\gamma)^{113}$In reaction is determined by the sum of all partial cross sections σ_i of transitions feeding the ground state of ^{113}In,

$$\sigma = \sum_{i=1}^{N} \sigma_i = \frac{A}{N_p N_A \xi} \sum_{i=1}^{N} (A_0)_i$$

where A is the atomic mass of the target, N_p is the number of projectile particles, N_A is the Avogadro number and ξ is the target thickness in mg/cm^2. The deduced experimental cross sections were compared to Hauser–Feshbach (H-F) calculations using TALYS code [2].

The H–F formula uses global models of optical model potentials (OMP), nuclear level densities (NLD) and γ strength functions (γSF). The results from the comparison between theory and experiment are shown in Fig. 4.

E_{beam} (keV)	$\sigma_{in-beam}$ (μb)
2800	4.6 ± 0.4
3000	20.7 ± 2.4
3200	50.6 ± 1.6
3400	106.4 ± 2.2

Table 3. Total in–beam cross sections of ^{112}Cd$(p,\gamma)^{113}$In

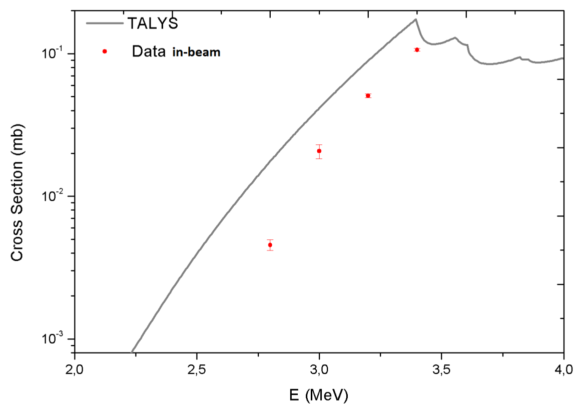


Figure 4. Experiment vs. TALYS

CONCLUSIONS

The resulting in–beam cross sections were compared to Hauser–Feshbach calculations using the default settings of code TALYS v1.9. An overall good agreement was found in the trend despite some missing strength between the experimental and theoretical values, which is a subject for further investigation. The angular distributions agree with what is expected for E2 multipolarities, confirming the spin values suggested in literature. Additional analysis is in progress to study the isomeric decay of ^{113}In with the activation method, which will complement the current results.

ACKNOWLEDGEMENTS

We would like to thank the staff of the Tandem Accelerator Laboratory for their assistance during the experiment and Ms. Marilena Lykiardopoulou for providing us the detectors' efficiency data.

References

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[2] A. Koning, S. Hilaire and M. Duijvestijn. *TALYS: Nuclear Reaction Simulator*