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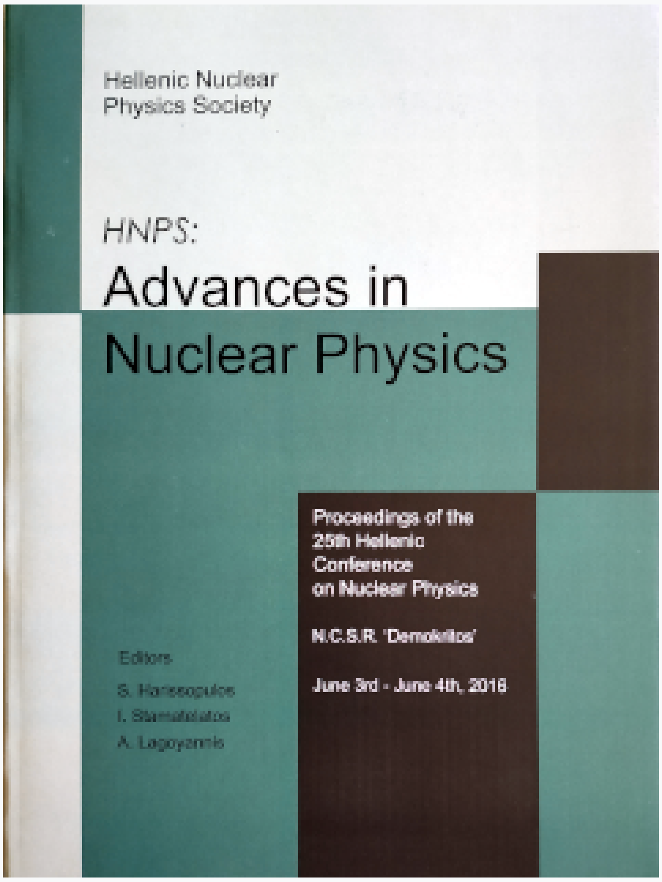

Experimental Investigation of radiative proton-capture reactions relevant to Nucleosynthesis

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Experimental Investigation of radiative proton-capture reactions relevant to Nucleosynthesis

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Abstract One of the primary objectives of the field of Nuclear Astrophysics is the study of the elemental and isotopic abundances in our solar system. Although a lot of progress has been made regarding a large number of nuclides, there is still a number of neutron-deficient nuclei, ie the *p* nuclei, which cannot be created via the *s* and *r* processes. These processes are responsible for the production of the bulk of heavy nuclides. The pre-explosive or explosive phases of massive stars are considered potential loci for *p* nuclides production via various combinations of photodisintegrations and nucleon captures, along with β^+ decays and electron captures.

For the study of the vast network of nuclear reactions (over 20'000) that are responsible for observed isotopic abundances, the statistical model of Hauser-Feshbach is employed. The model requires the knowledge of nuclear reaction cross sections, quantities that can be measured in the laboratory. In this work, we report on recent experimental attempts to measure such cross sections in radiative proton-capture reactions involving ^{107,109}Ag near the astrophysically relevant energy window. Measurements have been performed at the Tandem Accelerator Laboratory of the N.S.C.R. "Demokritos". The results are compared to various theoretical models, using the TALYS and EMPIRE codes, in an attempt to provide experimental input to astrophysical models.

Keywords Nucleosynthesis, p process, nuclear reactions, cross section, TALYS

INTRODUCTION

Heavier elements can be produced by two distinct neutron-capture processes [1,2]. The one is the slow neutron-capture process (*s* process), with a lifetime for β-decay t_β shorter than the competing neutron-capture time t_n. Consequently, the elements produced by the *s* process run through the valley of stability. The *s* process timescale is of the order of t_n ~10^3 y and happens in stellar environments where the neutron density is of the order of $d_n = 10^{18}$ cm^{-3}. The other neutron-capture process is called *r* process, where *r* stands for rapid, and requires $t_n << t_\beta$. The *r* process produces nuclei far from the valley of stability, neutron-rich and unstable. The typical duration of the *r* process is of a few seconds, in a very dense neutron environment (d_n ~10^{20}-10^{25} cm^{-3}), and takes place, for example, in the helium burning stages of red giants.

However, the *s* and *r* process fail to produce a number of naturally occurring neutron deficient nuclei. Thus, it is essential that another process should be introduced for the explanation of the origin of these nuclei. This process was introduced in [1] and is called the *p* process. The *p*-process isotopes or *p* nuclei are those elements which are characterized by mass number A>74, lie at the neutron-defficient side of the valley of stability and are

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bypassed by the neutron capture chains (*s* and *r* processes), which are responsible for the production of the bulk of heavy elements. The nuclei which are synthesized by the *p* process, although stable, have the significant feature that are much less abundant than the ones produced by s and r processes, by a factor ranging from 0.001 to 0.1.

The *p* process practically involves every process that leads to the synthesis of a *p* nucleus. It is widely assumed that massive stars can produce *p* nuclei through photodisintegration of pre-existing intermediate and heavy nuclei. This is called the *γ* process and occurs in pre-explosive or explosive O/Ne burning, depending on the mass of the star. Photodisintegrations are an alternative way to make *p* nuclei, either by producing them through the destruction of their neutron-richer isotopes through sequential (γ,n) reactions, which are the predominant photodisintegration processes for most stable nuclei, or by flows from heavier elements via (γ,p) and (γ,α) reactions and *β*-decays. Thus, cross section measurements of proton-capture reactions, as well as of their inverse ones (γ,p), are equally important for the study of the *p* process.

The present work is focused on the reactions $^{nat}Ag(p,\gamma)^{108,110}Cd$. Similar studies of proton-capture reactions can be found in Refs. [3-12]. The study of ^{108}Cd is of special astrophysical interest because it is characterized by a very small abundance, compared to those of most of the heavier elements. Furthermore, its predicted solar abundance is found to be underproduced, compared to the observed one [13].

Cross sections of such reactions can be estimated theoretically, using the statistical Hauser-Feshbach model [14]. In this model, there are three important parameters that should be used as input in order to calculate the cross section. These are the *optical potential*, which describes the interaction of the reactants, the *nuclear level density* which describes the energy levels of a nucleus at high excitation energies, and the *γ-ray strength function*, used for the determination of the exit channel transmission coefficient. Having this knowledge, the cross section can be then estimated by the following equation:

where i_α, I_α are the spins of the reactants in the entrance channel α, and are transmission coefficients.

Another useful quantity used in nuclear astrophysics is the *astrophysical S factor*, defined by the relation:

where is the *Sommerfeld parameter*. The astrophysical *S* factor varies smoothly with energy compared to the cross section and allows for extrapolation to experimentally inaccessible energies. In the present work, the *S* factors regarding the reactions $^{107,109}Ag(p,\gamma)^{108,110}Cd$ have been determined for each beam energy.

EXPERIMENTAL DETAILS

The study of the reactions $^{nat}Ag(p,\gamma)^{108,110}Cd$ was performed at the Tandem Van de Graaff Accelerator, at N.C.S.R. “Demokritos”. The Tandem accelerator is ideal for the study of such reactions, as it can produce proton beams within the energy range from 300 keV up to

10 MeV. The reactions were studied for three beam energies E_p: 2.2, 3.5 and 4 MeV. These energies are nicely located inside the astrophysically relevant energy window, namely the *Gamow window*, which was found to be 1.6 MeV < E_p < 4.7 MeV for the present case.

A target of natural silver, constituting of ^{107}Ag (51.8%) and ^{109}Ag (48.2%), has been used for the particular experiment. The target thickness was determined by means of the Rutherford Backscattering Technique [15], and was found equal to 458 μg cm^{-2}, a value very close to its nominal one (420 μg cm^{-2}). The target was oriented at an angle of 30° with respect to the beam, to avoid masking of the detector at 90° by the target aluminum frame.

The emitted γ rays were detected by three HPGe detectors of 100% relative efficiency. The detectors were placed at 0°, 90° and 165°, as illustrated in Fig. 1. All detectors were calibrated with an ^{152}Eu point-like source placed in the target position, before and after the experiment. Detector efficiencies were also carefully deduced from these spectra.

The cross section of each reaction can be estimated by measuring the intensity of each photopeak feeding the ground state of the produced nucleus. For the case of the reaction ^{107}Ag(p,γ)^{108}Cd, only the $2^+ \rightarrow 0^+$ transition (E_γ=633 keV [16]) could be observed and measured, and is shown on Fig. 2. In the same manner, the only measurable transition for the reaction ^{109}Ag(p, γ)^{110}Cd was the $2^+ \rightarrow 0^+$ transition (E_γ=658 keV [16]).

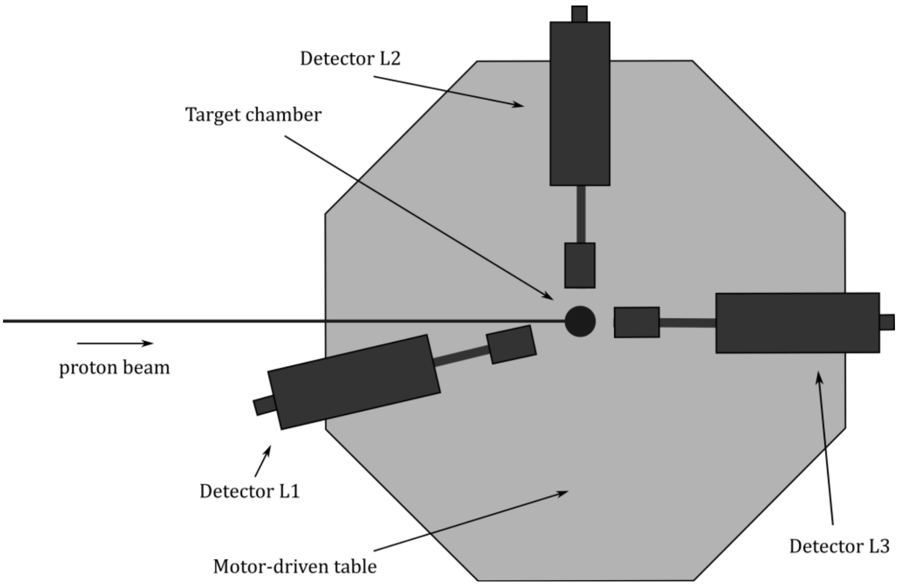

Fig. 1: The detecting setup. Three HPGe detectors are placed in the angles of 0^o, 90^o and 165^o

RESULTS

Having measured the intensity of the required transitions, one can deduce the angular distribution of the radiation for a fixed beam energy. Despite the original plan to have more detector angles during measurement, so that a more reliable angular distribution could be established, the very low cross sections of the reactions resulted in running out of experimental beam time. In Fig. 4, the angular distributions are shown for each beam energy.

After having determined the angular distribution for each reaction, the cross section can then be calculated directly, by estimating its mean value, a representative of the total number of reactions. The cross section results, along with the respective *S* factors are shown in Fig. 4.

Table 1: Models used for the theoretical calculations of the cross sections of the studied reactions (KD:Koning-Delaroche [19], KU: Kopecky-Uhl [21], BGD: Bauge-Delaroche-Girod[22], DG: Demetriou-Goriely [23], GH: Goriely-Hilaire [24], HFB:Hartree-Fock-Bogoliubov [25])

Combination	Optical Potential Model	Nuclear Level Density Model	γ-ray strength function model
TALYS 1	KD	CTM [20]	KU
TALYS 2	BDG	DG	Hartree-Fock-BCS [24]
TALYS 3	GH	Goriely-Hilaire	HFB
TALYS 4	BDG	Temperature Dependent HFB [26]	Goriely's Hybrid Model [27]
EMPIRE	KD	EGSM [28]	Plujko MLO1 [29]

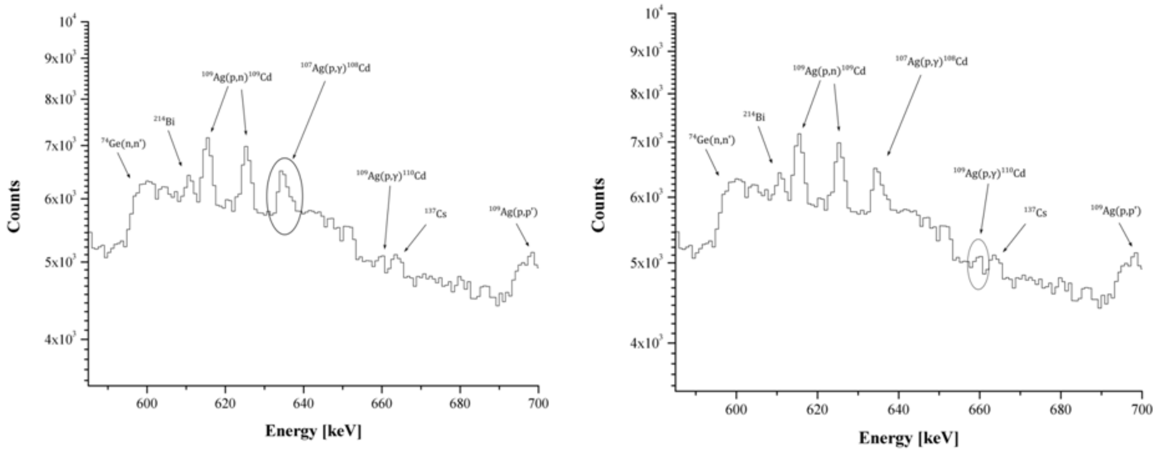

Fig. 2: Part of the obtained spectrum obtained by the detector at an angle of 90^{o} degrees and for a beam energy of 4 MeV.

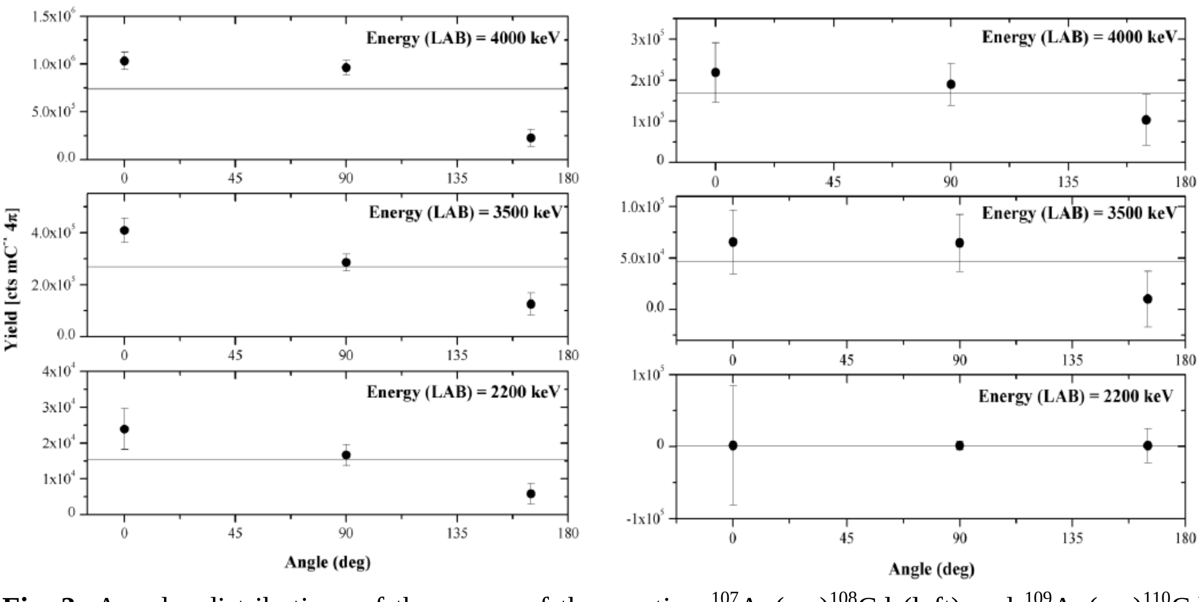

Fig. 3: Angular distributions of the γ rays of the reaction ^{107}Ag(p,γ)^{108}Cd (left) and ^{109}Ag(p,γ)^{110}Cd (right). The distribution pattern was assumed to be flat.

The experimental results were compared to theoretical calculations of the cross sections for the particular (p,γ) reactions carried out with TALYS v1.6 [17] and EMPIRE (MALTA) [18] codes, using various models for the three input parameters of the Hauser-Feshbach model. The full list of combinations are tabulated in Table 1 and the results of calculations are shown in Fig. 4.

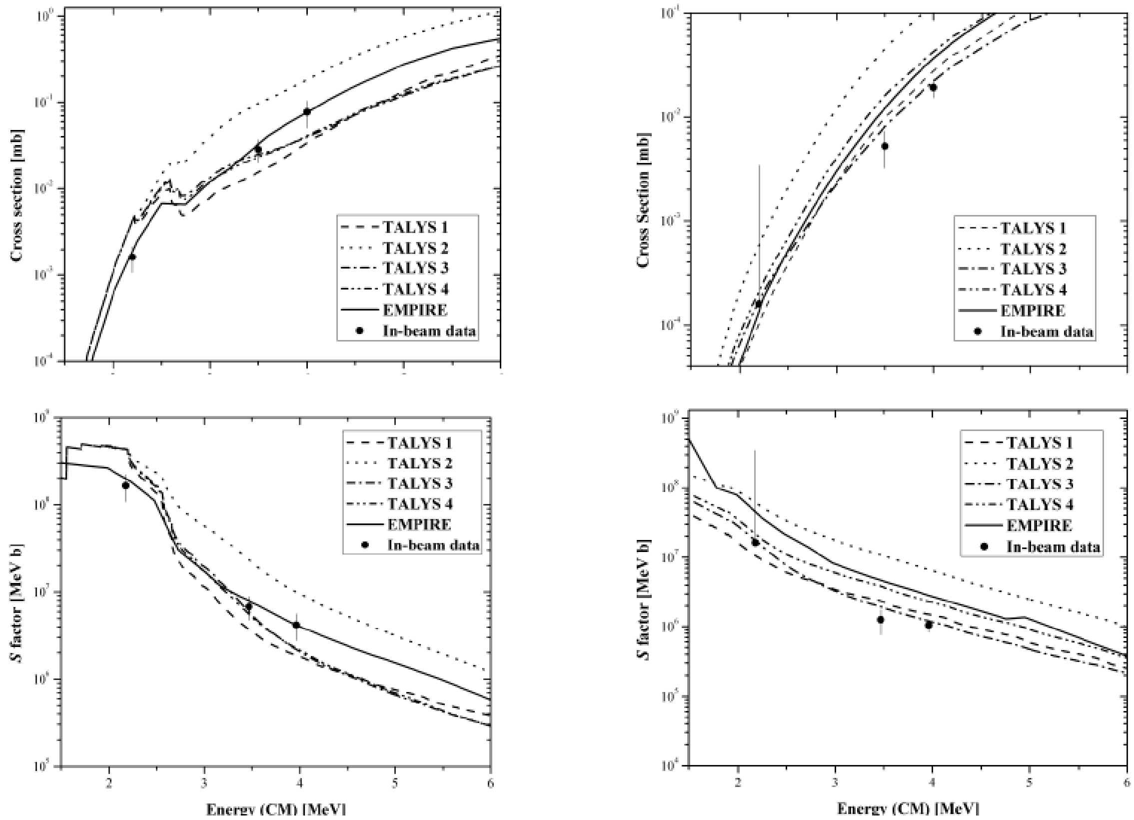

Fig. 4: Total cross section and *S* factor results for the studied reactions. Comparison is given between experimental data and the theoretical calculation of cross sections and *S* factors.

DISCUSSION AND CONCLUSIONS

In the framework of the present work, an experimental attempt to study two proton-capture reactions, $^{107}Ag(p,\gamma)^{108}Cd$ and $^{109}Ag(p,\gamma)^{110}Cd$, was carried out. These reactions are of special interest to astrophysics, as they are relevant to the *p* process. The experimental measurements of the cross sections were performed at the Tandem Accelerator Laboratory of N.C.S.R. Demokritos, at three proton beam energies: 2.2, 3.5 and 4 MeV. These values fall inside the range of astrophysically relevant energies, concerning the O/Ne shell of a massive star, either in its explosive or its pre-explosive state, as the dominant astrophysical site of *p* process. The resulting cross sections and astrophysical S factors of the particular reactions, as well as those of their inverse reactions, can be used as input for the determination of the reaction rate, a necessary parameter used in the theoretical calculations of reaction networks featuring the *p* process.

The cross section of the above reactions were determined experimentally by measuring their absolute yield *Y* with three 100% HPGe detectors placed at three angles, i.e. 0°, 90° and 165° with respect to the beam. Angular distributions have been studied to provide data and infer the absolute cross sections. The experimental results were compared with Hauser-Feshbach theoretical calculations which included various combinations of models describing the three input parameters necessary for the calculation of relevant transmission coefficients. The codes TALYS and EMPIRE were used in this study. In general, despite the overall good agreement between theoretical predictions and experimental data, further investigation is required, both experimentally (more detailed angular distributions), as well as theoretically (e.g. sensitivity analysis). Our results for the reaction ^{109}Ag(p,γ)^{110}Cd suffered low statistics, but can remain as a reference point for any future study.

The scarce experimental data existing today underline the importance to perform careful measurements of cross sections in this mass region, where *p* nuclei contribute immensely to the nucleosynthetic mechanisms taking place in highly-dynamic, explosive stellar environments. Experimental results are expected to set stringent tests to models in terms of the Hauser-Feshbach theory currently being the dominant theoretical description of such stellar environments.

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