

Radiative proton–capture reactions with $^{112,114}\text{Cd}$ at astrophysically important energies

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Abstract. The reaction network in the neutron-deficient part of the nuclear chart around $A \approx 100$ contains several nuclei of importance to astrophysical processes, such as the p -process. This work reports on the results from recent experimental studies of the radiative proton–capture reactions $^{112,114}\text{Cd}(p, \gamma)^{113,115}\text{In}$. Experimental cross sections for the reactions have been measured for proton beam energies residing inside the respective Gamow windows for each reaction, using isotopically enriched ^{112}Cd and ^{114}Cd targets. Two different techniques, the in–beam γ -ray spectroscopy and the activation method have been implemented, where the latter is considered mandatory to account for the presence of low-lying isomers in ^{113}In ($E \approx 392$ keV, $t_{1/2} \approx 100$ min), and ^{115}In ($E \approx 336$ keV, $t_{1/2} \approx 4.5$ h). Following the measurement of the cross sections, the astrophysical S factors have been subsequently deduced.

1 Introduction

The origin of a group of 35 neutron–deficient nuclides, spanning from ^{74}Se to ^{196}Hg , commonly referred to as p nuclei, has been a long–standing puzzle in nuclear astrophysics. The solar abundances of these nuclei are one to two orders of magnitude lower than those of the respective s and r nuclides in the same mass regime. Various astrophysical sites and nucleosynthesis scenarios have been proposed to account for the production of these nuclei, with the main production mechanism being referred to as the p -process [1].

Due to the vastness of the p -process reaction network, the Hauser–Feshbach statistical model [2] is often employed to estimate the reaction rates for the majority of these reactions. Experimental input is critical in the attempt to constrain the model parameters, and better understand the driving mechanisms behind the p -process. Such is the aim of this work, which reports on cross section measurements of the radiative proton–capture reactions with $^{112,114}\text{Cd}$, for energies inside the astrophysical important Gamow window [1] (1.6–4.8 MeV for both reactions [3]). These reactions lead to the production of ^{113}In , nowadays widely accepted not to be a “pure” p nucleus, having non–negligible s - and r -process components [4], and the slightly heavier ^{115}In , a nucleus also studied for its medical applications [5].

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2 Experimental details

The proton beams, ranging from $E_p = 3.0\text{--}4.0$ MeV, were provided by the 5.5 MV T11 Tandem Accelerator of NCSR “Demokritos”. The detector setup consisted of 3 HPGe detectors, angled at 55° , 90° and 165° with respect to the beam direction (a picture of the setup is shown in Fig. 1). Isotopically enriched (99.7%) ^{112}Cd and ^{114}Cd targets were used for the study of the radiative proton–capture reactions $^{112,114}\text{Cd}(p, \gamma)^{113,115}\text{In}$, using two different techniques, namely, in–beam γ –spectroscopy (described in detail in Refs. [3, 7, 8]) and the activation method [3, 8, 9], where the latter was deemed necessary to account for the presence of low–lying isomers in $^{113,115}\text{In}$ [6].



Figure 1: Picture of the detector setup used in the experiments.

3 Analysis and Results

Transitions feeding the ground state that were observed in the in–beam spectra of our experiments are marked with *’s in Fig. 2, and were used to determine the in–beam ground state cross section (σ_{gs}). The same procedure was followed for the in–beam measurement of the isomeric transitions, by measuring the photopeaks marked with #’s in the in–beam spectra (Fig. 2).

The full contributions of the isomeric transitions were determined by means of the activation technique, described in detail in Refs. [3, 8, 9]. Finally, the total cross sections were determined as:

$$\sigma_T = \sigma_{gs} + \sigma_{is} \quad (1)$$

where σ_T , σ_{gs} , σ_{is} are the total, ground state and isomeric cross sections, respectively. Subsequently, the astrophysical S factors were deduced through:

$$S(E) = E\sigma_T(E) \exp(-2\pi\eta) \quad (2)$$

where η is the Sommerfeld parameter.

The experimental results were compared with data existing in the literature, as well as with theoretical calculations with the TALYS code [10], using all the available combinations of Optical Potentials (OMP), Nuclear Level Densities (NLD) and γ –Strength Functions

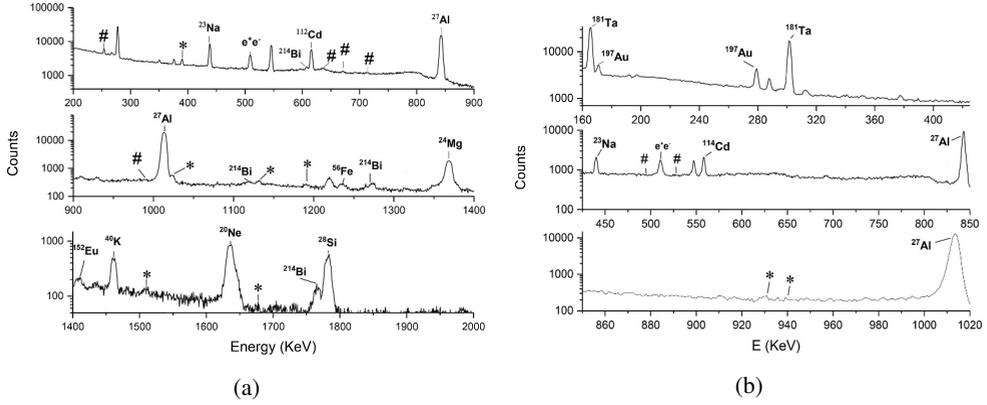


Figure 2: (a) Horizontal split-view (0.2–2.0 MeV) of a typical in-beam spectrum for the reaction $p+^{112}\text{Cd}$. Transitions to the gs of ^{113}In are marked with an (*). Transitions to the isomeric state are marked with (#). Additional photopeaks arising from background radiation or other beam induced reactions are also marked. (b) Horizontal split-view (0.16–1.02 MeV) of a typical in-beam spectrum for the reaction $p+^{114}\text{Cd}$.

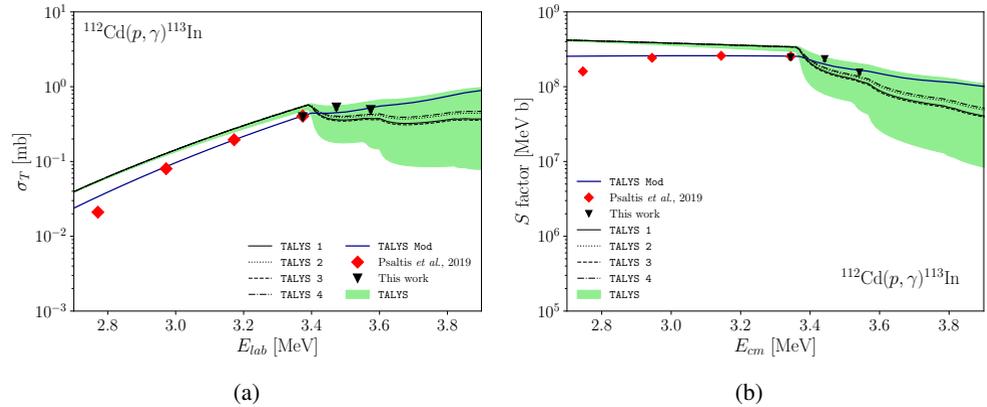


Figure 3: Total cross sections and astrophysical S factors for the reaction $^{112}\text{Cd}(p, \gamma)^{113}\text{In}$ (for details see text).

(γSF), with their default parameters, reaching a total of 96 combinations. The minimum and maximum value for each energy step was used to create the green shaded area in Figs. 3 and 4. The best data matching combinations of models, using their default parameters are also shown in these figures, labeled TALYS 1–4. The set of modified model parameters, achieving the best simultaneous agreement with all of the experimental data, is also plotted (labeled TALYS Mod. in Figs. 3, 4).

4 Conclusions

The experimental data presented in this work for the reaction $^{112}\text{Cd}(p, \gamma)^{113}\text{In}$ are in excellent agreement with those of the earlier work of Psaltis et al. [8], for the 3.4 MeV energy point,

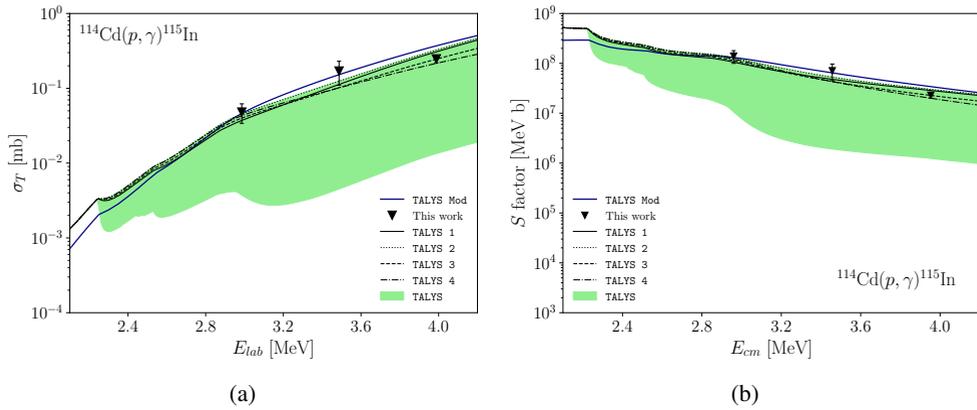


Figure 4: Same as in Fig. 3, for the reaction $^{114}\text{Cd}(p, \gamma)^{115}\text{In}$.

extending the measurements above the neutron emission threshold for the reaction ($E_{th} = 3.397$ MeV [6]), while still inside the Gamow energy window of astrophysical importance.

At the same time, the experimental data for both reactions studied in this work are in good agreement with the theoretical predictions of the TALYS v1.95 code, with the TALYS Mod. combination leading to a significantly improved agreement between theory and experiment for all of the studied channels, in a simultaneous fashion.

Further experimental and theoretical work is required for a firm insight at the driving mechanisms behind the p -process nucleosynthesis, in an energy region where the experimental data, even for stable nuclei, remain scarce.

Acknowledgements

AZ and AC acknowledge support by the Hellenic Foundation for Research and Innovation (HFRI) and the General Secretariat for Research and Technology (GSRT) under the HFRI PhD Fellowship grant (GA. No. 101742/2019 and 74117/2017, respectively).



References

- [1] C. Iliadis, *Nuclear Physics of Stars* (John Wiley & Sons, 2015)
- [2] W. Hauser and H. Feshbach, *Phys. Rev.* **87**, 366 (1952)
- [3] P. Vasileiou et al., *Nucl. Phys. A* **1015**, 122298 (2021)
- [4] M. Pignatari et al., *Int. J. Mod. Phys. B* **25** (04), 1630003 (2016)
- [5] F. Tárkányi et al., *Radiochim. Acta* **93**, 561–569 (2005)
- [6] Nudat3, National Nuclear Data Center, www.nndc.bnl.gov/nudat3/
- [7] A. Khaliel et al., *Phys. Rev. C* **96**, 035806 (2017)
- [8] A. Psaltis et al., *Phys. Rev. C* **99**, 065807 (2019)
- [9] G. Gyürky et al., *Eur. Phys. J. A* **55**, 41 (2019)
- [10] A. Koning et al., TALYS manual, v1.95 Edition, www.talys.eu (2020)