Experimental investigations of proton–capture reactions with ^{112,114}Cd at energies of astrophysical interest

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Introduction – Motivation

- The *p* process reaction network involves roughly 20000 reactions among 2000 nuclei. Most of these reactions need to be estimated by means of the Hauser–Feshbach statistical model

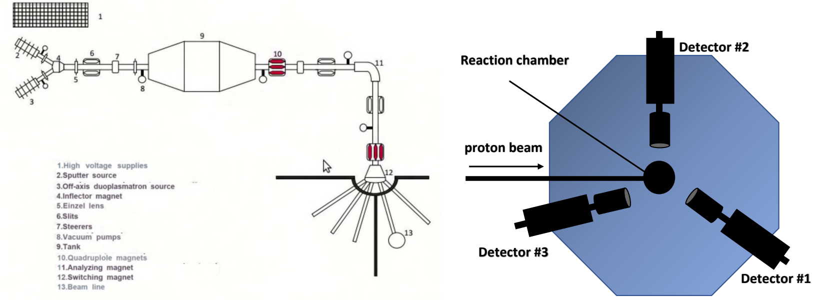
- The study of the experimental cross sections of radiative capture reactions is important for:

    1. Constricting the theoretical model parameters, improving theoretical predictions for currently unmeasured reactions
    2. Calculating photodisintegration decay constants, providing us with insight on the reaction flow in the examined mass regime

Introduction – Motivation

- The ^{113}In is nowadays accepted not to be a "pure" p nucleus, having non–negligible s and r process contributions
- ^{114}Cd involved in the s process, no total proton–capture cross section experimental data available for low energies (~ 3 MeV) for this nucleus
- Experimental cross sections, for energies of astrophysical importance (i.e. inside the Gamow window for these reactions, $\sim 1.6 - 4.8$ MeV for both reactions, corresponding to $T_9 \sim 1.7 - 3.3$ GK) provide valuable input for the determination of the reaction flow in this mass region

Experimental Setup



(a) (b)

Figure: Schematic representation of the T11 5.5 MV Tandem Accelerator of NCSR "Demokritos" (a), and the detector array (3HPGe detectors, at 55°, 90° and 165°) w/ respect to the beam (b). Isotopic (99.7%) ^{112}Cd and ^{114}Cd were used in the experiments.

Analysis and Results

Evaluation of the Cross Section – The In–beam and Activation Methods

- **In–beam** (σ_{gs}): Measurement of prompt γ–ray transitions feeding the ground state in the in–beam spectra, summing to σ_{gs}

- **Activation** (σ_{is}): Measurement of the decays of the residual nuclei after the end of the target irradiation. This method is employed to account for the contributions of the isomeric transitions to the reaction cross section.

Analysis and Results

Total Cross Sections – Astrophysical S factors

- Total cross section:

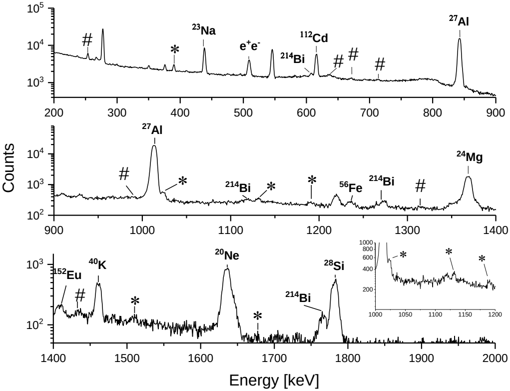
$$\sigma_T = \sigma_{gs} + \sigma_{is} \tag{1}$$

- Astrophysical S factor:

$$S(E) = E\sigma(E)e^{2\pi\eta}, \text{ with } \eta = \frac{Z_a Z_X e^2}{\hbar \upsilon} \textit{ (Sommerfeld Parameter)} \tag{2}$$

Analysis and Results

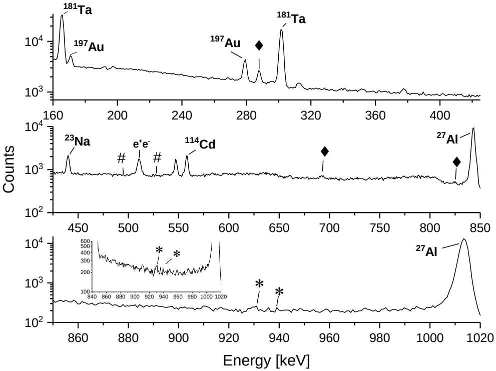
In–beam Spectra – The Reaction ^{112}Cd+p



E [MeV]	Origin
255.134	$^{112}\mathrm{Cd}(p,\gamma)^{113}\mathrm{In}_{is}$ (#)
391.698	$^{112}\mathrm{Cd}(p,\gamma)^{113}\mathrm{In}_{is}$ ($*$)
617.517	$^{112}\mathrm{Cd}(p,p'\gamma)$
638.03	$^{112}\mathrm{Cd}(p,\gamma)^{113}\mathrm{In}_{is}$ (#)
672.40	$^{112}\mathrm{Cd}(p,\gamma)^{113}\mathrm{In}_{is}$ (#)
714.9	$^{112}\mathrm{Cd}(p,\gamma)^{113}\mathrm{In}_{is}$ (#)
989.0	$^{112}\mathrm{Cd}(p,\gamma)^{113}\mathrm{In}_{is}$ (#)
1024.3	$^{112}\mathrm{Cd}(p,\gamma)^{113}\mathrm{In}_{gs}$ ($*$)
1131.5	$^{112}\mathrm{Cd}(p,\gamma)^{113}\mathrm{In}_{gs}$ ($*$)
1191.1	$^{112}\mathrm{Cd}(p,\gamma)^{113}\mathrm{In}_{gs}$ ($*$)
1509.04	$^{112}\mathrm{Cd}(p,\gamma)^{113}\mathrm{In}_{gs}$ ($*$)
1675.5	$^{112}\mathrm{Cd}(p,\gamma)^{113}\mathrm{In}_{gs}$ ($*$)

Analysis and Results

In–beam Spectra – The Reaction ^{114}Cd+p



E [MeV]	Origin
287.734	$^{114}\mathrm{Cd}(p,n)^{114}\mathrm{In}$ (♦)
492.351	$^{114}\mathrm{Cd}(p,\gamma)^{115}\mathrm{In}_{is}$ (#)
527.901	$^{114}\mathrm{Cd}(p,\gamma)^{115}\mathrm{In}_{is}$ (#)
558.456	$^{114}\mathrm{Cd}(p,p'\gamma)$
692.934	$^{114}\mathrm{Cd}(p,n)^{114}\mathrm{In}$ (♦)
825.000	$^{114}\mathrm{Cd}(p,n)^{114}\mathrm{In}$ (♦)
933.808	$^{114}\mathrm{Cd}(p,\gamma)^{115}\mathrm{In}_{gs}$ (∗)
941.420	$^{114}\mathrm{Cd}(p,\gamma)^{115}\mathrm{In}_{gs}$ (∗)
336.241	$^{114}\mathrm{Cd}(p,\gamma)^{115}\mathrm{In}_{is}$

Theoretical Calculations

- The results are compared with the existing experimental data and the theoretical predictions of the latest `TALYS (v1.95)` code
- 96 different combinations (=2 OMPs×6 NLDs×8 γSF, default options) were used for the theoretical calculations. For each energy, the maximum and minimum was determined (colored area in the graphs)

OMP	**NLD**	**γSF**
1. Koning–Delaroche	1 CTM	1. Kopecky–Uhl
2. Bauge–Delaroche–Girod	2. BSF	2. Brink–Axel
	3. GSM	3. HFBCS
	4. Goriely Tables	4. HFB
	5. Hilaire Tables	5. Goriely Hybrid
	6. TDHFB, Gogny force	6. Goriely TDHFB
		7. TDRMF
		8. Gogny D1M HFB +QRPA

Table: Models used for the calculations of the cross sections with **TALYS**.

Results

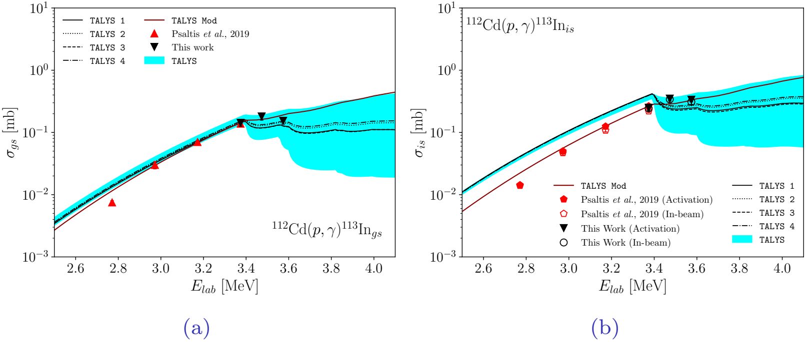
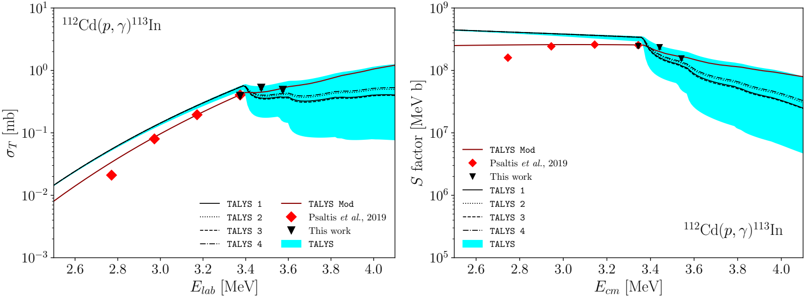


Figure: Cross Sections for the reactions ^{112}Cd$(p,\gamma)^{113}$In$_{gs}$ (a) and ^{112}Cd$(p,\gamma)^{113}$In$_{is}$ (b)[1].

[1] https://doi.org/10.1016/j.nuclphysa.2021.122298

Results

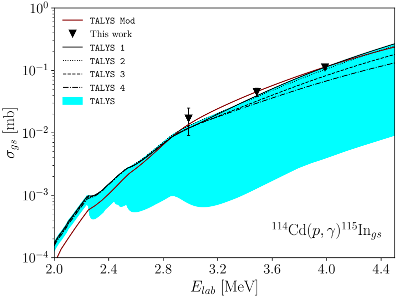


(a) (b)

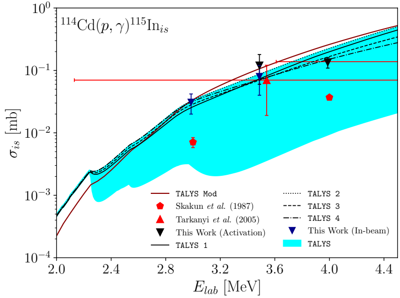
Figure: Total cross sections (a) and astrophysical S factors (b) for the reaction ^{112}Cd$(p,\gamma)^{113}$In[1].

[1] https://doi.org/10.1016/j.nuclphysa.2021.122298

Results



(a)

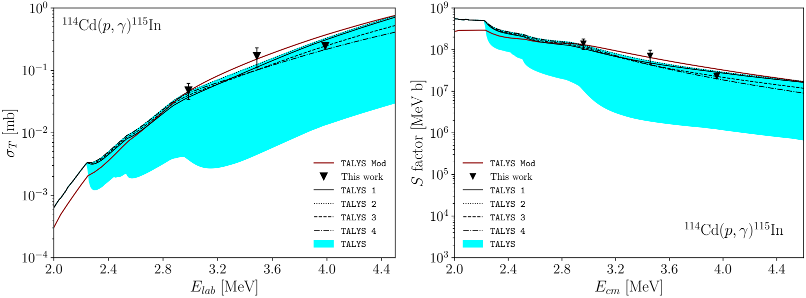


(b)

Figure: Cross Sections for the reactions ^{114}Cd$(p,\gamma)^{115}$In$_{gs}$ (a) and ^{114}Cd$(p,\gamma)^{115}$In$_{is}$ (b)[1].

[1] https://doi.org/10.1016/j.nuclphysa.2021.122298

Results



(a) (b)

Figure: Total cross sections (a) and astrophysical S factors (b) for the reaction ^{114}Cd$(p,\gamma)^{115}$In[1].

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Conclusions

For the reactions ^{112}Cd$(p,\gamma)^{113}$In$_{gs,is,tot}$:

- Good agreement with the theoretical predictions of **TALYS**, despite some overestimation of the theoretical isomeric cross section for the 3.4 MeV energy point
- Excellent agreement with the data from the earlier work of Psaltis *et al.* for the 3.4 MeV energy point.
- Results extended to energies above the neutron emission threshold for the reaction ($E_{th} = 3.397$ MeV), while inside the Gamow window, for the first time

For the reactions ^{114}Cd$(p,\gamma)^{115}$In$_{gs,is,tot}$:

- Cross sections for the g.s. transition measured for the first time, using in–beam γ–spectroscopy
- Results are in agreement with the theoretical predictions of **TALYS**
- Better agreement with the experimental data of Tarkányi *et al.*, despite their higher energy uncertainties, on which the current results improve significantly

Conclusions

- An attempt was carried out to determine the **TALYS** model parameter combination achieving the best *simultaneous* description of all of the studied reaction channels
- The proposed parameter combination (labeled **TALYS Mod** in graphs) leads to a significantly improved description of the experimental data, especially for the isomeric cross sections

Certainly, further investigation is required in this region of the nuclear chart, both experimentally and theoretically, so as to:

- Improve knowledge on the reaction networks
- Provide firm insight on the driving mechanisms behind p process nucleosynthesis
- Constrict the theoretical model parameters, in an energy region where a scarcity of experimental data, even for stable nuclei, still persists

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End of Presentation

Thank You

The Gamow Window

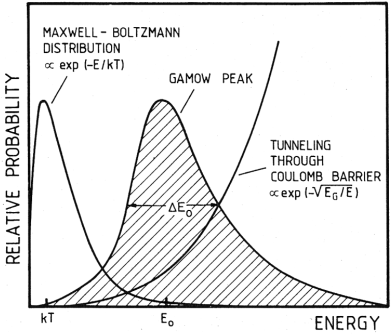

Figure: Schematic representation of the Gamow window, ΔE_0, corresponding to nuclear burning reactions, for the case of charged particle–induced reactions.

Analysis and Results

Evaluation of the Cross Section – The In–beam Method

- Measurement of transitions feeding the ground state in the in–beam spectra
- The cross section is found by summing all of the partial cross sections, σ_i, feeding the g.s.:

$$\sigma_{gs} = \sum_{i=0}^{N} \sigma_i = \frac{A}{N_p N_A \delta} \sum_{i=0}^{N} (A_0)_i \tag{3}$$

where $(A_0)_i$ is the total number of photons of energy E_i^{γ} emitted in the reaction

Analysis and Results

Evaluation of the Cross Section – The Activation Method (1/2)

- This method is employed in order to account for the contributions of the isomeric transitions to the reaction cross section
- The number of produced radioactive nuclei alive at the end of the irradiation of the target with a beam of constant current, ϕ_b [particles s^{-1}], is:

$$\mathcal{N}_{prod} = \sigma N_X \phi_b \frac{1 - e^{-\lambda t_{irrad}}}{\lambda} \tag{4}$$

where $N_X = \delta N_A / A$ is the surface number density of target nuclei X, $\lambda = \ln 2 / T_{1/2}$ the decay constant

Analysis and Results

Evaluation of the Cross Section – The Activation Method (2/2)

- The number of decays after a given counting time, t_c, is:

$$\mathcal{N}_{decay} = \mathcal{N}_{prod} e^{-\lambda t_w} (1 - e^{-\lambda t_c}) \quad (5)$$

where t_w the waiting time elapsed between end of irradiation and beginning of counting

- The isomeric cross section is evaluated with the use of Eqs. (4), (5) as:

$$\sigma_{is} = \frac{\mathcal{N}_{decay} \lambda e^{\lambda t_w}}{N_X \phi_p I_\gamma (1 - e^{-\lambda t_{irrad}})(1 - e^{-\lambda t_c})} \quad (6)$$

where I_γ is the probability for γ–ray emission ($I_\gamma \approx 0.649$, 0.458 for the isomeric states of ^{113,115}In, respectively)