

Reaction rates of the $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$ and $^{115}\text{In}(\gamma, n)^{114\text{m}}\text{In}$

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Abstract. The integral yields of the $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$ ($J^\pi=9/2^+ \rightarrow J^\pi=4^+$) and $^{115}\text{In}(\gamma, n)^{114\text{m}}\text{In}$ ($J^\pi=9/2^+ \rightarrow J^\pi=5^+$) photonuclear reactions were measured in the bremsstrahlung end-point energy range from the respective thresholds up to 14 MeV by a conventional activation/decay technique using the $^{197}\text{Au}(\gamma, n)^{196}\text{Au}$ reaction cross sections as the standard for the absolute photon intensity determination. The metallic indium samples of the natural and enriched compositions were irradiated by the bremsstrahlung beams from thin tantalum converters of the electron linear accelerator of NSC KIPT (Kharkiv) and the microtron of IEP (Ughhorod). The integral reaction yields were determined from the activities of the nuclei-products measured by the high resolution γ -ray spectrometry technique with Ge(Li)- and HPGe-detectors. The reaction rates for the Planck spectrum of a thermal photon bath were derived for the ground state target nuclei and compared to the predictions of the statistical model of nuclear reactions.

1. Introduction

Naturally occurred weak-abundant proton-rich isotopes of a group named as *p*-nuclei can not be reached by the stellar slow (*s*) and rapid (*r*) neutron capture processes synthesizing the overwhelming majority of middle and heavy nuclei. Proton capture reactions (*p*-process) and photodisintegration of *s*- and *r*-process seed nuclei (γ -process) are considered as most probable mechanisms of the *p*-nuclei synthesis. The large network of low energy nuclear reaction rates (derived from the cross sections) is required for the *p*-nuclei natural abundance simulation and parametrization of the statistical theory of nuclear reactions called to supply non-measurable reaction cross sections.

The γ -process temperatures of $T_9=2-3$ (T_9 is the temperature in 10^9 Kelvin) are provided by the oxygen- and neon-rich layers of type II supernovae and the stellar reaction rates are determined by the product of the Planck spectrum of the black-body radiation characteristic for the thermal interior of a star and the photonuclear reaction cross section [1, 2]. As a result, the significant astrophysical energy range is the region of (1.5–2.0) MeV immediately above the photonuclear reaction threshold. Electron accelerators were earlier used as powerful sources of bremsstrahlung for measurements of photonuclear reaction cross sections. However over the years major portion of photonuclear reaction cross section measurements was fulfilled at larger energies.

The integral yields and derived the (γ, n)-reaction rates for the nuclei of the indium isotopes near the threshold energies would be useful for the problem of the *p*-nuclei stellar synthesis and parametrization of the statistical theory of nuclear reactions.

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2. Experimental measurements

We used the photoactivation/decay measurement technique with high resolution gamma-spectrometry. The irradiation procedures were performed by using two facilities: one electron linear accelerator of NSC KIPT (Kharkiv) and the other microtron of IEP (Uzhgorod). The electron beam of Kharkiv linac was bent through an angle 15° and passing the 50- μm titanium foil striked to the 100- μm tantalum converter generating bremsstrahlung flux. Having passed the converter the electrons were bent sideward with a sweeping magnet and the Schiff distribution bremsstrahlung flux cut by the 8-mm lead collimator hit the targets under investigation. The Uzhgorod microtron did not have a photon collimator. The Kharkiv and Uzhgorod accelerators were operated with the average beam currents of $(20\div30) \mu\text{A}$ and not more than $10 \mu\text{A}$ respectively.

The high-purity metallic indium disks of natural isotopic composition with masses of around 500 mg and the ^{113}In enriched (up to 66 %) foil of $60 \text{ mg}\cdot\text{cm}^{-2}$ surface density and 18 mm diameter were irradiated as targets. The indium targets were sandwiched with gold foils. The $^{197}\text{Au}(\gamma, n)^{196}\text{Au}$ reaction was used as a standard for determination of the photon beam intensity [3]. An ionization chamber was used for monitoring of the beam current fluctuations. The target isotopes, reactions with their thresholds and properties of the radioactive decays of the residual nuclei are summarized in Table.

Table. Target nuclei (spins-parities), reactions and spectroscopic data of the residual indium nuclei used in the data analysis [4].

Target nucleus (Spin-parity)	Reaction, Threshold, MeV	Residual nucleus	Half-life	E_γ , keV	$I_\gamma(\Delta I_\gamma)$, %
^{113}In (9/2 ⁺)	(γ, n) 9.597	$^{112\text{m}}\text{In}$ (4+)	20.56 m	157	13.2 (3)
		$^{112\text{g}}\text{In}$ (1+)	14.97 m	617	4.6
^{115}In (9/2 ⁺)	(γ, n) 9.230	$^{114\text{m}}\text{In}$ (5+)	49.51 d	190	15.56 (15)
		$^{114\text{g}}\text{In}$ (1+)	71.9 s		
^{197}Au	(γ, n) 8.071	^{196}Au	6.183 d	333 356	22.9 (5) 87

The spin-parities of the ground state ^{113}In and ^{115}In target nuclei are 9/2⁺ and the (γ, n) -reactions can result two long-lived isomers in each residual nuclei. However large difference between the spins of the target and residual nuclei ground states (see Table) does small contributions by-passed production cross sections of the 1⁺ states of the ^{112}In and ^{114}In nuclei. So the production cross sections of the $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$ and $^{115}\text{In}(\gamma, n)^{114\text{m}}\text{In}$ reactions are practically the total cross sections of the (γ, n) -reactions in the near threshold energy range and it is confirmed by isomeric ratio measurements [5].

3. Results

Figure 1 shows the integral yields of the (γ, n) -reactions calculated by the activation equation for the ^{113}In and ^{115}In targets as the functions of the bombarding end point energy. The data are normalized to the $^{197}\text{Au}(\gamma, n)^{196}\text{Au}$ reaction yields [3]. The dark and light points represent the data from the Kharkiv and Uzhgorod accelerators respectively. The near threshold energy dependence of the (γ, n) -reaction cross section can be expressed [6] as the functional form $\sigma_{(\gamma, n)} = \sigma_0 \left(\frac{E_\gamma - E_{thr}}{E_{thr}} \right)^{l+1/2}$, where E_γ and E_{thr} are the

γ -ray and threshold energies, respectively, and l the angular momentum of the emitted neutron. It gives an opportunity to compare our results with experimental, evaluated or theoretical data of other authors if available. Having collated the integral yields of the reactions under study and the $^{197}\text{Au}(\gamma, n)^{196}\text{Au}$ reaction with parametrization [3] we found the average weighted values of the σ_0 parameter to be equal to 61 mb and 54 mb for the $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$ and $^{115}\text{In}(\gamma, n)^{114\text{m}}\text{In}$ reactions respectively in the case of the s- wave emission of neutrons. Figure 2 plots the fitted cross sections of these reactions together with the

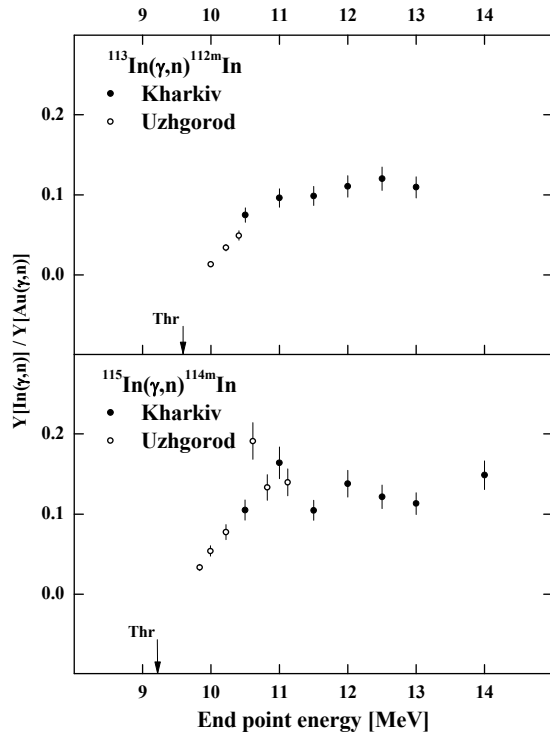


Figure 1. Integral yields of the $^{113}\text{In}(\gamma,n)^{112m}\text{In}$ (upper panel) and $^{115}\text{In}(\gamma,n)^{114m}\text{In}$ (lower panel) reactions relative to the $^{197}\text{Au}(\gamma,n)^{196}\text{Au}$ reaction ones. The dark and light points correspond to the Kharkiv and Uzhgorod measurements respectively. The arrows show the reaction thresholds.

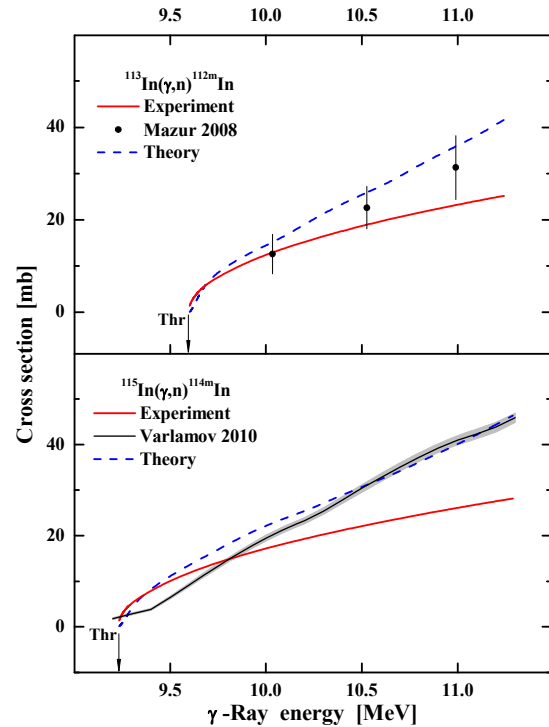


Figure 2. Fitted cross sections (red solid curves) of the $^{113}\text{In}(\gamma,n)^{112m}\text{In}$ (upper panel) and $^{115}\text{In}(\gamma,n)^{114m}\text{In}$ (lower panel) reactions deduced from our measured integral yield data, the literature data (points with error bars in upper panel and shading in lower panel) and theoretical predictions (blue dash curves).

previously evaluated and theoretical data. The red (solid) curves represent our results and the blue (dash) ones correspond to the theoretical values calculated with the NON-SMOKER code [7]. Three points with the error bars in upper panel represent the results of one of our authors (V. M.) with his co-workers [5] for the $^{113}\text{In}(\gamma,n)^{112m}\text{In}$ reaction. The shade band in lower panel depicts the cross section data evaluated by Varlamov et al [8].

From the evaluated in this way the near and above threshold (γ,n) -reaction cross sections the reaction rates $\lambda_{(\gamma,n)}$ for the ground state indium isotope nuclei in a stellar photon bath were calculated using the equation:

$$\lambda_{(\gamma,n)} = \int_0^\infty c n_\gamma(E) \sigma_{(\gamma,n)}(E) dE,$$

where c is the speed of light and $n_\gamma(E)$ the number of photons per unit volume and energy (the Planck distribution).

In addition to this conventional analysis the method of superposition of several bremsstrahlung spectra [1,2] to approximate the thermal Planck spectrum was used for determination of the reaction rates with no assumption of the (γ,n) cross section energy dependence.

The reaction rates of the $^{113}\text{In}(\gamma,n)^{112m}\text{In}$ and $^{115}\text{In}(\gamma,n)^{114m}\text{In}$ reactions derived from the experimental integral yields by the conventional analysis together with the NON-SMOKER code theoretical predictions are presented in Figure 3. The ratios of the experimental results and theoretical

predictions are shown in the inserts of the graphs. Theory overestimates the reaction rates not more than 20 % for the first reaction and does not go out of the experimental uncertainties for the second one. The superposition method gives similar results.

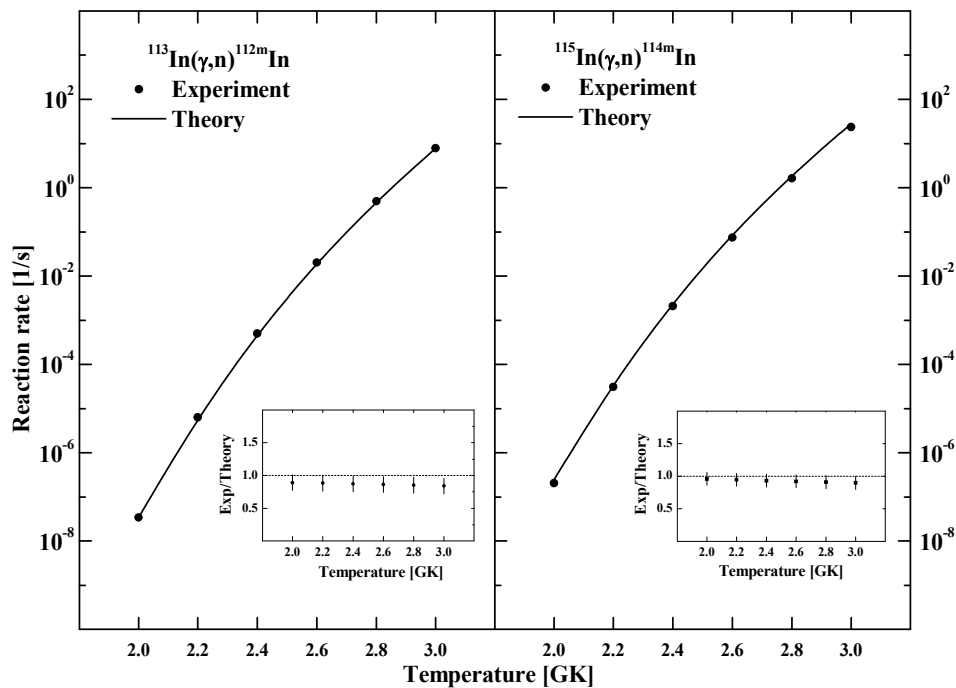


Figure 3. Experimental (points) and the NON-SMOKER code (curves) reaction rates of the $^{113}\text{In}(\gamma,n)^{112m}\text{In}$ (left panel) and $^{115}\text{In}(\gamma,n)^{114m}\text{In}$ (right panel). The inserts present the ratio of the experimental and theoretical values

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