

ENERGY DEPENDENCE OF CROSS SECTION OF PHOTONUCLEAR REACTIONS ON INDIUM ISOTOPES

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Experimental isomeric yield ratios for the $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$ reactions on the betatron B25/30 bremsstrahlung gamma beam of energy range 12...25 MeV are measured. Effective cross-sections of (γ, n) -reactions with $^{112\text{m}}\text{In}$ and $^{114\text{m}}\text{In}$ isomers output are calculated. The Penfold-Leiss and Tikhonov methods are applied to solve the Volterra integral equation. The obtained experimental cross-sections are compared with theoretical calculations using the TALYS-1.6 code.

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INTRODUCTION

The purpose of the majority of physical researches that are carried spent on brake beams electronic accelerators, – studying of power dependence of cross sections of different photonuclear processes. As the spectrum received from the accelerator γ -quantum's has continuous character, therefore in experiment not cross section is measure of reaction, it is so-called output. The output is intensity photonuclear to the process, the doze attributed to unit γ -quantum's that have passed through a target with researched substance at various values of the top border of a brake spectrum [1 - 3].

The yield of reaction is directly connected with effective cross section of reaction by integral equation of the first kind:

$$Y(E_{\gamma\text{max}}) = \int_{E_m}^{E_{\gamma\text{max}}} \sigma(E)\Phi(E, E_{\gamma\text{max}})dA, \quad (1)$$

where E_m and $\sigma(E)$ are the threshold and the cross section of a reaction; $E_{\gamma\text{max}}$ is the maximal energy of a bremsstrahlung γ -spectrum; $\Phi(E, E_{\gamma\text{max}})$ is an energy E of spectrum of γ -quanta (Shiff's spectrum [4]).

The cross section of the reaction can be received from experimental data about yield as a result of the solution of an inverse problem (1). For the numerical solution of this integral equation different mathematical methods were developed. The most widespread methods are «a difference of photons», «the least structure» Cook's method [5], «an inverse matrix» (Penfold-Leiss method) [6], «regularizations» (Tikhonov method) [7]. Penfold-Leiss and Tikhonov methods have different forms of the effective photon spectrum – the hardware function of the method. Except the direct solution of the inverse problem there are other methods for determination of information about the cross section, namely, a combination of reaction outputs and a method of reduction.

The conditions of well-posed problem given by Hadamar [8] should have the properties: 1) a solution exists in space of possible values; 2) the solution should be the unique; 3) the solution's behavior changes continuously with the initial conditions.

This paper deals with the determination of the experimental cross sections of (γ, n) -reaction on isotopes of indium with the formation of isomers $^{112\text{m}}\text{In}$ and $^{114\text{m}}\text{In}$.

1. CROSS SECTION OF REACTION $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$

With the bremsstrahlung gamma beam of the betatron B25/30 (UzhNU, Uzhgorod) there was measured

isomeric ratios of the yields for the reaction $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$. The energy of electron beam was changed in the interval 12...25 MeV with a step of 1 MeV. Isomeric state of the nucleus $^{112\text{m}}\text{In}$ decays with a half-life of 20.9 m, emitting γ -rays with energy 155 keV (the quantum yield is 13%). β^+ -decay of the ground state ($T_{1/2}=14.4$ m) is accompanied by the emission of γ -rays with energies 511, 606, and 618 keV, with the quantum yields 44, 1.2, 5.3%, respectively. Time of irradiation of targets and time for measurement were 10...20 m, and time for cooling was 5...10 m.

Nuclear-physical parameters of the isomers $^{112\text{m}}\text{In}$ and $^{114\text{m}}\text{In}$ are specified in Table 1, where E_m is a threshold (γ, n) -reaction; $T_{1/2}$ is a half-life period; E_γ is energy of γ -ray that radiates the isomer; J_m , and J_g are the total angular momentum of the isomeric and the ground state; "+" or "-" is the state parity.

Table 1

Nuclear-physical characteristics of investigated isomers

Isomer	E_m , MeV	$T_{1/2}$	E_γ , keV	J_m^P	J_g^P
$^{112\text{m}}\text{In}$	9.58	20.9 m	155	4^+	1^+
$^{114\text{m}}\text{In}$	9.03	43 ms	310	8^-	1^+

Experimental results for yields ratio of reaction $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$ are shown in Table 2.

Table 2

Isomeric ratios Y_m/Y_g of reaction $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$

E , MeV	Y_m/Y_g	$\Delta(Y_m/Y_g)$
12	1.86	0.32
13	2.34	0.30
14	2.52	0.21
15	2.91	0.12
16	2.83	0.17
17	2.76	0.08
18	2.62	0.10
19	2.44	0.05
20	2.6	0.04
21	2.39	0.12
22	2.48	0.05
23	2.41	0.06
24	2.45	0.08
25	2.51	0.06

According to the obtained isomeric ratio of yields Y_m/Y_g it is possible to calculate the cross sections of isomeric state excitation in the reaction $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$. For this we need to use the known values of total cross section of (γ, n) -reaction [9]. We used the connection between the yields and the integral cross-sections σ_{int} :

$$K(E_{\gamma_{\max}}) = \frac{Y^{113m} \text{In}(\hat{A}_{\gamma_{\max}})}{Y^{113g} \text{In}(\hat{A}_{\gamma_{\max}})} \cong \frac{\sigma_{\text{int}}^{113m} \text{In}(\hat{A}_{\gamma_{\max}})}{\sigma_{\text{int}}^{113g} \text{In}(\hat{A}_{\gamma_{\max}})}, \quad (2)$$

$$\sigma_{\text{int}} = \int_{E_p}^{E_{\text{nop}}} \sigma(E_{\gamma}) dE_{\gamma} = \frac{Y(E_{\max})(E_{\max} - E_m)}{\int_{E_p}^{E_{\text{nop}}} \Phi(E, E_{\gamma_{\max}}) dE_{\gamma}}, \quad (3)$$

where E_m – energy of isomeric level.

It should be noted that for solving the integral equation (1) by Tikhonov's method ones use Schiff's spectrum $\Phi(E, E_{\gamma_{\max}})$ as a core of integral equation. In Fig. 1 the cross sections obtained by Penfold-Leiss (PL) and Tikhonov's (T) methods are shown. The difference between them is 4...5%.

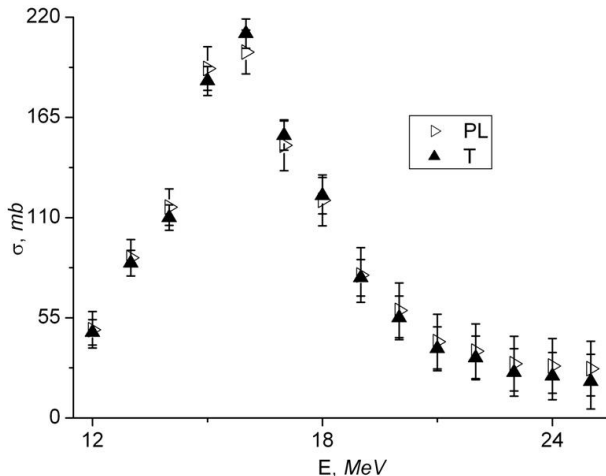


Fig. 1. Energy dependence of cross section of reaction $^{113}\text{In}(\gamma, n)^{112m}\text{In}$

It is possible to use package TALYS-1.6 [10, 11] for the simulation of nuclear reaction $^{113}\text{In}(\gamma, n)^{112m}\text{In}$. When calculating cross sections in TALYS-1.6 the density level model was selected for a given nuclide (ldmodel parameter). In the package there are three phenomenological level-density models and two variants for microscopic level densities. In particular: ldmodel 1 is Fermi-gas model with a constant temperature; ldmodel 2 is Fermi-gas model with reverse shift; ldmodel 3 is generalized superfluidity model; ldmodel 4 is microscopic level densities from Goriely's table [10]; ldmodel 5 is microscopic level densities from Hilaire's table [10].

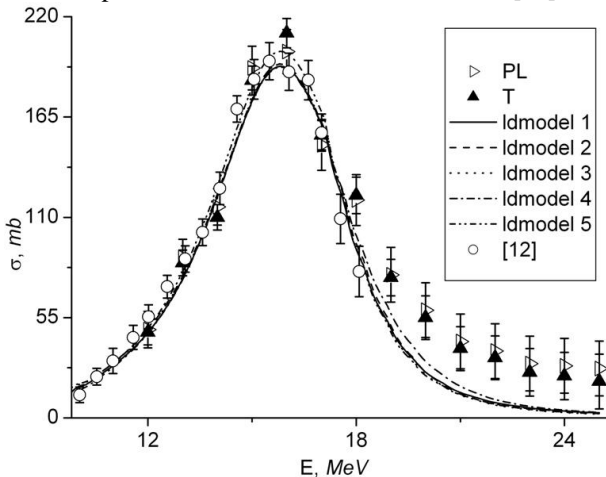


Fig. 2. Energy dependence of cross section of reaction $^{113}\text{In}(\gamma, n)^{112m}\text{In}$

On the consolidated Fig. 2 our experimental data of cross section for reaction $^{113}\text{In}(\gamma, n)^{112m}\text{In}$ (see Fig. 1) and experimental data [12] are shown in comparison with theoretical calculations in the package TALYS-1.6.

Table 3

The results of processing the peaks of cross section for reaction $^{113}\text{In}(\gamma, n)^{112m}\text{In}$ by Gauss function

Model	χ^2	S	E_{\max} , MeV	Γ , MeV	σ_{\max} , mb
ldm-1	3.44	883.0	15.7	3.9	180.0
ldm-2	3.47	907.1	15.7	4.0	181.5
ldm-3	3.31	895.7	15.7	4.0	181.7
ldm-4	2.45	904.8	15.8	4.0	178.5
ldm-5	3.67	914.0	15.7	3.9	188.3
[12]	1.46	852.0	15.7	3.9	174.5
PL	0.71	741.0	15.9	3.6	161.8
T	1.69	744.5	15.9	3.6	166.8

The results of fitting of the calculated cross section peaks for the reaction $^{113}\text{In}(\gamma, n)^{112m}\text{In}$ in the package TALYS-1.6 are shown in Table 3, where the following designations are used: χ^2 per degree of freedom of function; S is the area under the peak in the MeV·mb; Γ is the full width at half maximum; ldm-1 (5) are the numbers of the density level model for the nuclide. As an approximating function the Gauss function was chosen

$$y = y_0 + \frac{A}{w\sqrt{\pi/2}} e^{-2(x-x_c)^2/w^2}. \quad (4)$$

Additionally it was fitting the same picks by the Breit-Wigner function (Table 4):

$$y = y_0 + \frac{2A}{\pi} \frac{w}{4(x-x_c)^2 + w^2}, \quad (5)$$

obtained parameters of which are given in Table 5. Analyzing the data of Tables 3 and 4, it is seen that adjustment of the peak by the Breit-Wigner formula (5) gives better results than Gaussian by the formula (4).

Table 4

The results of processing the peaks of cross section for reaction $^{113}\text{In}(\gamma, n)^{112m}\text{In}$ by Breit-Wigner function

Model	χ^2	S	E_{\max} , MeV	Γ , MeV	σ_{\max} , mb
ldm-1	2.45	1575	15.7	4.7	213.9
ldm-2	2.62	1627	15.7	4.8	216.2
ldm-3	2.94	1600	15.7	4.7	216.1
ldm-4	1.28	1632	15.8	4.9	213.2
ldm-5	3.60	1624	15.7	4.6	223.4
[12]	0.72	1749	15.7	5.1	219.5
PL	0.47	1243	15.8	4.2	190.1
T	0.85	1277	15.9	4.1	198.6

Consequently, the experimental results for the cross section of the reaction $^{113}\text{In}(\gamma, n)^{112m}\text{In}$ matches with the calculated one in the package TALYS-1.6 in the region of maximum.

For energies of 18...25 MeV there is some difference between the results of theory and experiment. It can be explained by the fact that the TALYS-1.6 is not included nappy processes, but reaction $^{113}\text{In}(\gamma, 2n)^{112}\text{In}$

contributes to experimental results, which begins with the threshold 16.3 MeV. Some calculation results of the above reactions is given in [13].

Table 5

The parameters of Breit-Wigner formula from fitting the peaks of cross section for reaction $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$

Parameter	[12]	PL	T
y_0	-20.65 ± 7.2	15.81 ± 9.0	11.44 ± 7.3
A	1749 ± 157	1243 ± 168	1277 ± 126
x_C	15.7 ± 0.1	15.8 ± 0.1	15.9 ± 0.1
w	5.1 ± 0.4	4.2 ± 0.5	4.1 ± 0.3

2. CROSS SECTION FOR REACTION $^{115}\text{In}(\gamma, n)^{114\text{m}}\text{In}$

On the yields [14] in work [15] was calculated cross section of the reaction $^{115}\text{In}(\gamma, n)^{114\text{m}}\text{In}$. Using the package TALYS-1.6 we calculated the cross section for reaction $^{115}\text{In}(\gamma, n)^{114\text{m}}\text{In}$ in the energy range of 10...25 MeV. The results obtained for five models of the density levels of the nuclide (ldmodel 1-5) are shown in Fig. 3. For ldmodel 1-3 values of cross section in the max are close (42...45 mb), but differ from the experimental ones to 1.17 times.

The result of processing of peaks of the cross section energy dependence for the reaction $^{115}\text{In}(\gamma, n)^{114\text{m}}\text{In}$ is given in Table 6. Fitting the peak by Gaussian gives better results than the fitting by Breit-Wigner formula.

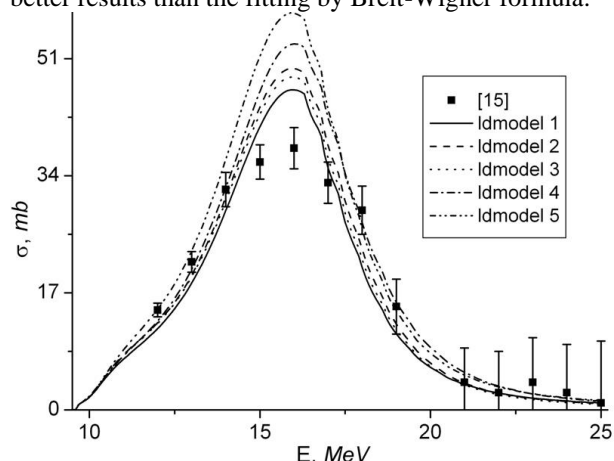


Fig. 3. Energy dependence of cross section of reaction $^{115}\text{In}(\gamma, n)^{114\text{m}}\text{In}$

Table 6

The results of processing the peaks of cross section for reaction $^{115}\text{In}(\gamma, n)^{114\text{m}}\text{In}$

Model	χ^2	S	E_{max} , MeV	Γ , MeV	σ_{max} , mb
ldm-1	2.60	203.9	15.6	3.8	42.3
ldm-2	2.74	223.0	15.7	3.9	45.4
ldm-3	2.88	216.2	15.7	3.9	44.2
ldm-4	2.64	240.9	15.8	4.0	48.1
ldm-5	3.46	255.4	15.7	3.9	52.5
[15]	2.37	232.7	15.7	5.1	36.4

CONCLUSIONS

The paper presents the results of experimental studies of the isomeric relations of the yields for the reaction $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$, which recreated the energy depend-

ence of the cross section for the reaction $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$. Energy behavior of the cross section for reaction has a characteristic shape of the giant dipole resonance in the area of 15.8 MeV.

Experimental data cross section (γ, n) -reaction on indium isotopes with the formation of isomers $^{112\text{m}}\text{In}$ and $^{114\text{m}}\text{In}$ are compared with theoretical calculations in the package TALYS-1.6. The analysis shows that both experimental and theoretical calculations of the energy dependence of the cross sections are described better by the Breit-Wigner function.

The obtained experimental results of the cross section for the reaction $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$ can fill the nuclear data bases of isomeric states which are used as constants in nuclear applications, for example, for γ -activation analysis.

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ЭНЕРГЕТИЧЕСКАЯ ЗАВИСИМОСТЬ СЕЧЕНИЙ ФОТОЯДЕРНЫХ РЕАКЦИЙ НА ИЗОТОПАХ ИНДИЯ

В.И. Жаба, И.И. Гайсак, А.М. Парлаг, В.С. Бохинюк, М.М. Лазорка

На тормозном пучке бетатрона Б25/30 в области энергий 12...25 МэВ проведено измерение изомерного отношения выхода реакции $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$. По экспериментальным значениям энергетических выходов рассчитаны сечения (γ, n) -реакции на изотопах индия с образованием изомеров $^{112\text{m}}\text{In}$ и $^{114\text{m}}\text{In}$. Для расчетов применены методы Пенфольда-Лейсса и Тихонова. Полученные экспериментальные данные сравниваются с теоретическими расчетами в TALYS-1.6.

ЕНЕРГЕТИЧНА ЗАЛЕЖНІСТЬ ПЕРЕРІЗІВ ФОТОЯДЕРНИХ РЕАКЦІЙ НА ІЗОТОПАХ ІНДІЮ

В.І. Жаба, І.І. Гайсак, О.М. Парлаг, В.С. Бохинюк, М.М. Лазорка

На гальмівному пучку бетатрона Б25/30 в області енергій 12...25 МеВ проведено вимірювання ізомерно-го відношення виходу реакції $^{113}\text{In}(\gamma, n)^{112\text{m}}\text{In}$. За експериментальними значеннями енергетичних виходів розраховано перерізи (γ, n) -реакції на ізотопах індію з утворенням ізомерів $^{112\text{m}}\text{In}$ і $^{114\text{m}}\text{In}$. Для розрахунків застосовано методи Пенфольда-Лейсса і Тіхонова. Отримані експериментальні дані порівнюються з теоретичними розрахунками в TALYS-1.6.