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STUDY OF THE ISOMERIC RATIOS IN PHOTONUCLEAR REACTIONS OF NATURAL INDIUM INDUCED BY BREMSSTRAHLUNGS WITH END-POINT ENERGIES IN THE GIANT DIPOLE RESONANCE REGION

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We have determined the isomeric ratios in $^{113}\mathrm{In}\,(\gamma,n)\,^{112m,g}\mathrm{In}$ and $^{113}\mathrm{In}\,(\gamma,2n)\,^{111m,g}\mathrm{In}$ photonuclear reactions of natural indium induced by bremsstrahlungs with end-point energies in the giant dipole resonance (GDR) region. The investigated samples were irradiated at the electron accelerator Microtron MT-25 of the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna. The gamma spectra of the samples irradiated were measured with a spectroscopic system consisting of an 8192-channel analyzer and a high-energy resolution (180 keV at gamma ray 1332 keV of ^{60}Co) HP(Ge) semiconductor detector Canberra. The GENIE2000 (Canberra) computer program was used for data processing. The results were discussed and compared with those of other authors. For both the mentioned reactions, the isomeric ratios in the bremsstrahlung energy range from 19 to 24 MeV in this work are new measurements.

На микротроне МТ-25 ЛЯР ОИЯИ проведено исследование изомерных отношений в фотоядерных реакциях $^{113}\mathrm{In}\,(\gamma,n)\,^{112m,g}\mathrm{In}$ и $^{113}\mathrm{In}\,(\gamma,2n)\,^{111m,g}\mathrm{In}$ в области гигантского дипольного резонанса. Гамма-спектры облученных образцов измерены HPGe полупроводниковым детектором (с энергетическим разрешением 180 кэВ на гамма-линию 1332 кэВ стандартного источника ^{60}Co). Их обработка выполнена с помощью компьютерной программы GENIE2000 (Canberra). Проведены обсуждение и сравнение полученных данных с результатами других авторов. Для отмеченных выше реакций представлены новые данные по изомерным отношениям в диапазоне энергий 19–24 МэВ.

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INTRODUCTION

Nuclear reactions have become powerful tools for studying properties and characteristics of nuclei. Using different particles, for example, photon, proton, neutron and so on, as projectile, one was able to determine a series of general properties of nuclei. The investigation of the properties of excited states in a nuclear reaction such as the probability of level population, the energy and spin distributions, and the different decay modes allows one to obtain

important information about level structure and nuclear reaction mechanism. It is especially effective when the excited states last for a sufficiently long period of time as the isomeric and ground states. Some of the mentioned properties can be delivered through investigating the characteristics of the nuclear reaction products and partly from the information on the spin distribution of the excited nuclei, which can be obtained from the yield ratio of the reaction products in isomeric and ground states, the so-called isomeric ratio [1–5]. Because of this, the measurement of the isomeric ratio has become one of the most effective directions in the study of nuclear reaction and structure. Up to now, most investigations have been concentrated on nuclear reactions with proton and neutron, and the data for photonuclear reactions is not complete. The study of nuclear reactions at bremsstrahlung photon beam in the giant dipole resonance (GDR) region has definite advantages. The reasons for that are the following:

a) In the GDR region the most probable mechanism of interactions is the process of successive emission of one or several nucleons from the compound nucleus. In this region the electromagnetic interaction is well known and absorption of $E1$ gamma ray is dominant, therefore, the theoretical consideration will be simplified.

b) Although the cross section of photonuclear reaction is very low, the bremsstrahlungs are an intense source of photons produced by powerful electron accelerators; and the cross section of photonuclear reaction presents a wide maximum. As a result, the reaction yield is significant.

c) At the same time, the study of photonuclear reaction is of considerable interest due to the significant difference from nuclear reaction induced by other projectiles. This difference is connected to the fact that in photonuclear reaction the states are excited which are usually difficult to be produced in other reaction types.

The investigation of the isomeric ratios induced by bremsstrahlung above the giant dipole resonance region shows that in this case the isomeric pairs are formed by a complex reaction as spallation $(\gamma, xnyp)$, and the reaction mechanism is very complicated [6–10]. The more simple the investigated reaction, the more definite the obtained information. The examples of such simple reactions are one-step reactions (γ, n) and (γ, p) in the GDR region. Up to the present, the isomeric ratios have been investigated in nuclear reactions induced by different projectiles, for example, by photon [11], fast and thermal neutrons [12, 13], proton [14], tritium [15], alpha [16], heavy ions [17], as well as by fission products [18, 19]. In the previous works, we have studied the isomeric ratios in different nuclear reactions such as $(n, 2n)$, (γ, n), (γ, p), $(\gamma, 2n)$, (γ, np) in the GDR region [20–29] and in higher energy region [30]. The results of the study on (γ, n) photonuclear reaction in the GDR region were considered in the framework of the statistical model method proposed by Huizenga and Vandenbosch [1, 2]. The study provided valuable nuclear data and led to the interesting conclusions about the structure and mechanism of photonuclear reactions [20–30].

The aim of this work is to completely measure the isomeric ratios in photonuclear reactions of natural indium in the GDR region. The rationale of the study was the incompleteness and discrepancy of the data in the GDR region and the lack of the data beyond this region. There are very few works devoted to the investigation on photonuclear reaction of natural indium [31–34]. Natural indium consists of two isotopes ^{115}In and ^{113}In with abundances of 95.77 and 4.23%, respectively. It is interesting to note that two isomeric pairs ^{112m,g}In and ^{111m,g}In were observed in $^{113}\mathrm{In}\,(\gamma, n)\,^{112m,g}\mathrm{In}$ and $^{113}\mathrm{In}\,(\gamma, 2n)\,^{111m,g}\mathrm{In}$ photonuclear reactions of natural indium with bremsstrahlungs with end-point energies in the GDR region.

Through the mentioned photonuclear reactions from odd–even nucleus ^{113}In with spin $9^+/2$ are formed odd–odd nucleus ^{112}In and odd-even ^{111}In with different isomeric and ground states. Therefore, it is expected to obtain new information on the probability of level population and other properties of the residual nuclei by measurement of the isomeric ratios.

EXPERIMENTAL

Target Preparation. The samples for investigation were prepared from natural indium foil with purity of 99.99% in disk form with 1 cm diameter. Table 1 presents the parameters of the investigated samples. Table 2 shows the decay characteristics of isomeric pairs ^{112m,g}In and ^{111m,g}In, which have been observed in photonuclear reactions of natural indium with bremsstrahlungs in the GDR region. The data were taken from [35, 36].

Table 1. **Parameters of the investigated samples**

Sample number	Bremsstrahlung end-point energy, MeV	Sample mass, g	Sample diameter, cm	Average irradiated electron beam, μA	Sample irradiation time, min
1	14.0	0.1276	1.0	15.0	15
2	15.0	0.1311	1.0	15.0	15
3	16.0	0.1285	1.0	15.0	15
4	17.0	0.1327	1.0	15.0	15
5	18.0	0.1195	1.0	15.0	15
6	19.0	0.1223	1.0	14.0	15
7	20.0	0.1271	1.0	14.0	15
8	21.0	0.1196	1.0	14.0	15
9	22.0	0.1232	1.0	14.0	15
10	23.0	0.1195	1.0	14.0	15
11	24.0	0.1115	1.0	14.0	15

Table 2. **The decay characteristics and gamma rays which were used for calculating the isomeric ratio of natural indium**

Nuclear reaction	Reaction product	Spin	Abun., %	Half-life	Reaction threshold, MeV	Gamma-ray energy, keV	Gamma-ray intensity, %	Isom. trans. coeff. IT, %
^{113}In (γ, n) ^{112m}In	^{112m}In	4^+	4.23	20.56 min	9.58	156.6	13.2	100
^{113}In (γ, n) ^{112g}In	^{112g}In	1^+		14.97 min	9.43	617.3	4.60	
^{113}In $(\gamma, 2n)$ ^{111m}In	^{111m}In	$1^-/2$	4.23	7.6 min	17.28	537.2	87.0	100
^{113}In $(\gamma, 2n)$ ^{111g}In	^{111g}In	$9^+/2$		2.83 d	17.28	171.3	90.24	

Target Irradiation. The sample irradiation in the GDR region was performed at the electron accelerator Microtron MT-25 of the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna. The average electron beam and the irradiation time for the investigated samples are shown in Table 1. The description of this accelerator and

its characteristics are presented in [37]. The essential advantage of the Microtron is the small energy spread of the accelerated electrons (30–40 keV) at high beam intensity (up to an average power of 600 W). This allows the measurement of the isomeric ratio at strictly definite end-point energy bremsstrahlung. As an electron–photon converter was used W disk 4 mm thick, cooled by water. To absorb low-energy electrons passing the converter in the irradiation target, an aluminum screen 20 mm thick was placed behind the converter. The bremsstrahlung end-point energy of this accelerator can be varied stepwise from 10 to 25 MeV, i.e., over the GDR region.

Gamma-Spectra Measurement. The gamma spectra of the samples irradiated were measured for different cooling and measurement times at different distances from the detector with a spectroscopic system consisting of an 8192-channel analyzer and a high-energy resolution (180 keV at gamma ray 1332 keV of ^{60}Co) HP(Ge) semiconductor detector Canberra. The GENIE2000 (Canberra) computer program was used for data processing. The efficiencies of the detectors were determined with a set of standard single gamma-ray sources calibrated to 1–2%. Figure 1 shows the efficiency of the used detector measured at a distance of 5 cm.

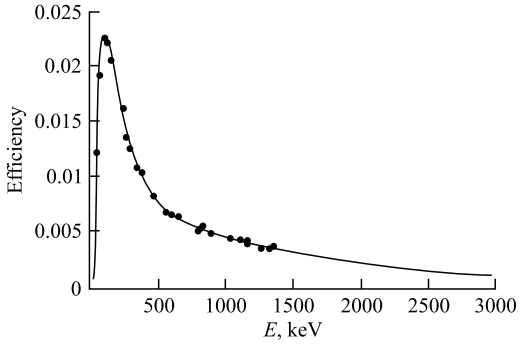

Fig. 1. The efficiency of the HP(Ge) semiconductor detector measured at a distance of 5 cm

Isomeric Ratio Determination. Usually the isomeric ratio in a nuclear reaction is determined by the measurements of the areas under photopeaks characterizing the isomeric and ground states. The equations that describe the decay of these states can be written as follows:

$$\begin{aligned} \frac{dN_m}{dt} &= N_0\phi\sigma_m - \lambda_m N_m, \\ \frac{dN_g}{dt} &= N_0\phi\sigma_g - \lambda_g N_g + P\lambda_m N_m, \end{aligned} \tag{1}$$

where m and g are the isomeric and ground states; N_0 is the target nuclei number; $\phi(E)$ is the bremsstrahlung photon flux; σ is the reaction cross section; N is the number of reaction product nuclei; λ is the decay constant, and P is the isomeric transition coefficient.

Resolving the system of equations (1) in dependence on irradiating, cooling and measurement times, we could determine the isomeric ratio IR by the expression

$$\frac{1}{\mathrm{IR}} = \frac{\dfrac{S_g\varepsilon_m I_m}{S_m\varepsilon_g I_g}\Lambda_3\Lambda_6\Lambda_9 - \Lambda_1\Lambda_5\Lambda_8 - \Lambda_3\Lambda_5\Lambda_8 - \Lambda_3\Lambda_6\Lambda_7}{\Lambda_2\Lambda_5\Lambda_8}. \tag{2}$$

Here S, ε and I are the areas, efficiencies and intensities of the gamma rays of interest; $\Lambda_i\,(i = 1{-}9)$ are factors connected to the irradiating, cooling and measurement times as follows:

$$\Lambda_1 = \frac{P}{\lambda_g}\left[\left(1-\mathrm{e}^{-\lambda_g t_1}\right) - \frac{\lambda_g}{\lambda_m-\lambda_g}\left(\mathrm{e}^{-\lambda_g t_1}-\mathrm{e}^{-\lambda_m t_1}\right)\right], \quad \Lambda_2 = \frac{1}{\lambda_g}\left(1-\mathrm{e}^{-\lambda_g t_1}\right),$$

$$\Lambda_3 = \frac{1}{\lambda_m}\left(1-\mathrm{e}^{-\lambda_m t_1}\right), \quad \Lambda_4 = \frac{P\lambda_m}{\lambda_m-\lambda_g}\left(\mathrm{e}^{-\lambda_g t_2}-\mathrm{e}^{-\lambda_m t_2}\right), \quad \Lambda_5 = \mathrm{e}^{-\lambda_g t_2}, \quad \Lambda_6 = \mathrm{e}^{-\lambda_m t_2},$$

$$\Lambda_7 = P\left[1-\frac{\lambda_m\lambda_g}{\lambda_m-\lambda_g}\left(\frac{\mathrm{e}^{-\lambda_g t_3}}{\lambda_g}-\frac{\mathrm{e}^{-\lambda_m t_3}}{\lambda_m}\right)\right], \quad \Lambda_8 = \left(1-\mathrm{e}^{-\lambda_g t_3}\right), \quad \Lambda_9 = 1-\mathrm{e}^{-\lambda_m t_3},$$

where t_1, t_2 and t_3 are irradiation, cooling and measurement times, respectively.

In the case of bremsstrahlung, the isomeric ratio is defined as the ratio of the yield of the isomeric state to that of the ground state:

$$\mathrm{IR} = \frac{\mathrm{No}\int\limits_{E_{\mathrm{th}}^m}^{E_\gamma^m}\sigma_m(E)\,\phi(E)\,dE}{\mathrm{No}\int\limits_{E_{\mathrm{th}}^g}^{E_\gamma^m}\sigma_g(E)\,\phi(E)\,dE}, \tag{3}$$

where E_γ^m is the bremsstrahlung end-point energy; $\phi(E)$ is the bremsstrahlung photon flux; No is the number of the target nuclei; $\sigma_m(E)$ and $\sigma_g(E)$ are the cross sections of the isomeric and ground states, respectively; E_{th}^m and E_{th}^g are the threshold energies for the isomeric and ground states, respectively.

RESULTS AND DISCUSSION

In our experiment the isomeric ratio was determined by using the expression (2) as the average value $\overline{\mathrm{IR}}$ of those data calculated from various combinations of a series of gamma spectra measured for different times of cooling and measurement. The relative error was determined by the following formula:

$$\varepsilon(\overline{\mathrm{IR}}) = \frac{\sigma(\overline{\mathrm{IR}})}{\overline{\mathrm{IR}}} = \frac{\sqrt{\sum\limits_{i=1}^{n}\sigma_i^2(\mathrm{IR})/n}}{\overline{\mathrm{IR}}}, \tag{4}$$

where $\sigma_i\,(\mathrm{IR})$ is the error of the isomeric ratio calculated for i, combination of measurements, and n is the number of combinations of the measurement.

Figure 2 shows typical gamma spectra of natural indium irradiated by 24.0 MeV bremsstrahlung measured with the HP(Ge) semiconductor detector at a distance of 5 cm. The gamma rays characterizing the isomeric and ground states of isomeric pairs ^{112m,g}In and ^{111m,g}In are

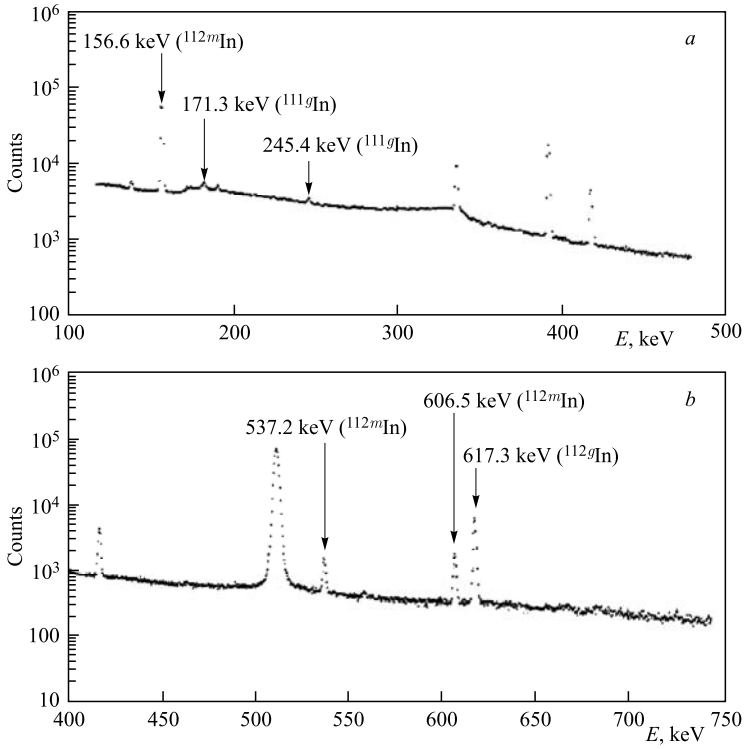

Fig. 2. A typical gamma spectrum of natural indium irradiated by 24 MeV end-point energy bremsstrahlung

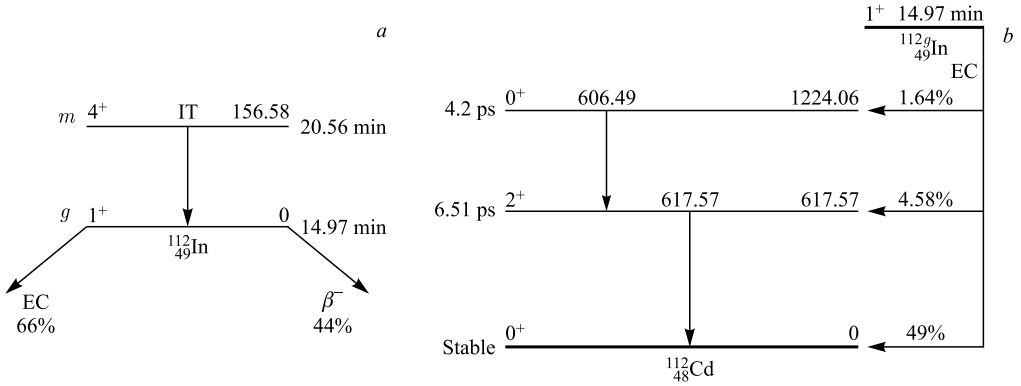

Fig. 3. The decay scheme of isomeric pair ^{112m,g}In

marked on these spectra. Other gamma rays arose from different products of the interaction between natural indium and the bremsstrahlung.

Figures 3, *a*, *b*, taken from [31, 32], present the decay scheme of isomeric pair ^{112m,g}In. It can be seen from Fig. 3, *a* that the isomeric state ^{112m}In decays to the ground state ^{112g}In by

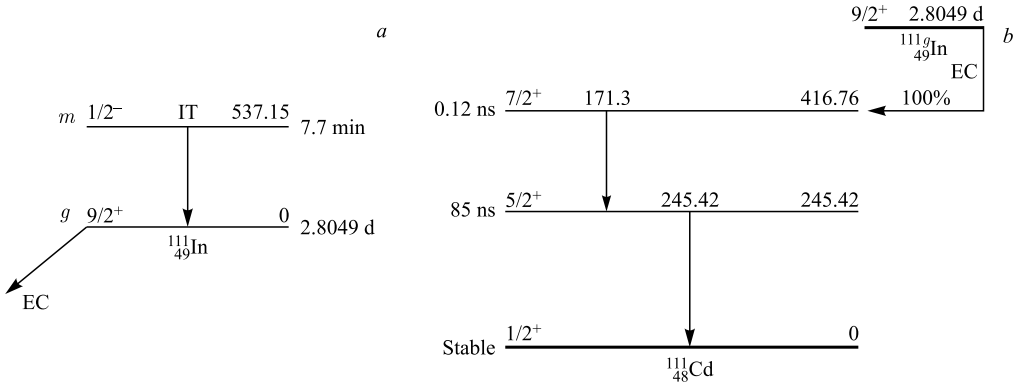

Fig. 4. The decay scheme of isomeric pair ^{111m,g}In

isomeric transition IT = 100% with 155.6 keV gamma ray and the ground state ^{112g}In decays to stable ^{112}Sn by beta emission (44%) and to ^{112}Cd by EC process (56%). The simplified decay scheme of ^{112g}In to ^{112}Cd by EC process is shown in Fig. 3, *b*. There are two most intense cascade gamma rays of 606.7 and 617.2 keV with intensities 1.10 and 4.60%, respectively. Therefore, for the determination of the isomeric ratio of the isomeric pair ^{112m,g}In, gamma rays of 155.6 and 617.2 keV were chosen due to their high intensites, which are shown in Table 2. Figures 4, *a*, *b* present the decay scheme of the isomeric pair ^{111m,g}In. It can be seen here that the isomeric state ^{111m}In decays to the ground state ^{111g}In by isomeric transition IT = 100% with gamma ray of 537.0 keV and the ground state ^{111g}In decays to stable ^{111}Cd by 100% EC process. The simplified decay scheme of ^{111g}In is shown in Fig. 4, *b*. There are two most intense cascade gamma rays of 171.3 and 245.4 keV with high intensities 90.24 and 94.00%, respectively. In this case, gamma rays of 537.0 and 171.3 keV were chosen for the isomeric ratio calculation of the isomeric pair ^{111m,g}In, as shown in Table 2.

Table 3. **Uncertainty sources in the isomeric ratio determination**

Sources of uncertainty	^{112m,g}In, %	^{111m,g}In, %
Measurement error:		
Statistical	0.1–0.6	0.2–0.8
Detector efficiency	1–2	1–2
Half-life	1–3	1–3
Branching ratio	2–5	2–5
Uncertainties related to the isomeric calculation	7.0	8.0
Systematic error:		
Sample to detector	1.0	1.0
Photopeak selection	2.0	2.0
Electron beam variation	1.0	1.0
Coincidence summing	1.0	1.0
Gamma-ray self-absorption	1.0	1.0
Irradiation and cooling time	1.0	1.0
Uncertainties related to systematics	3.0	3.0
Total uncertainties of the isomeric ratio determination	7.5	8.5

In the experiment, the counting loss arose from coincidence summing and gamma-ray self-absorption. The coincidence summing can be reduced or eliminated by taking proper distance between sample and detector and the self-absorption with optimum sample mass. These corrections were performed in the experiment by the methods used in [8–10]. The main error sources were discussed and estimated. These are shown in Table 3.

Table 4 shows the results of our experiment and those of other authors. We have to note that in this work the isomeric ratio was determined as the ratio of the yield of the high spin $Y_{\rm hs}$ to that of the low spin states $Y_{\rm ls}$, i.e., $\mathrm{IR} = Y_{\rm hs}/Y_{\rm ls}$. We also have to note that in [33, 34] for the isomeric ratio of ^{112m,g}In the authors gave the ratio of the yield of the isomeric state

Table 4. **The isomeric ratios in dependence on bremsstrahlung end-point energies**

Nuclear reactions	End-point energy, MeV	$\mathrm{IR} = Y_{\rm hs}/Y_{\rm ls}$	
		This work	Other work
$^{113}\mathrm{In}\,(\gamma, n)\,^{112m,g}\mathrm{In}$	14.0	1.645 ± 0.123	3.00 ± 0.19 [34]
	15.0	1.837 ± 0.159	2.85 ± 0.18 [34]
	16	2.123 ± 0.218	2.85 ± 0.18 [34]
	17.0	2.417 ± 0.181	2.70 ± 0.18 [34]
	18	2.664 ± 0.200	2.67 ± 0.17 [34]
			2.67 ± 0.17 [33]
	19.0	2.866 ± 0.215	
	20.0	3.572 ± 0.268	1.90^{*} [31]
	21.0	3.979 ± 0.298	
	22.0	4.295 ± 0.322	
	23.0	4.406 ± 0.330	
	24.0	4.365 ± 0.327	
	25.0		4.74 ± 0.10 [32]
	30		4.5 ± 0.5 [52]
			2.37^{*} [31]
			2.21 ± 0.21 [31]
			4.05 ± 0.05 [32]
			4.0 ± 0.5 [48]
	40.0		2.50^{*} [31]
$^{\rm nat}\mathrm{In}\,(\gamma, xn)\,^{112m,g}\mathrm{In}$	43.0		3.4 ± 0.3 [49]
	50.0		3.93 ± 0.31 [50]
	60.0		4.47 ± 0.33 [50]
	70.0		4.88 ± 0.33 [50]
$^{113}\mathrm{In}\,(\gamma, 2n)\,^{111m,g}\mathrm{In}$	19.0	7.032 ± 0.598	
	20.0	6.874 ± 0.584	
	21.0	6.683 ± 0.568	
	22.0	6.452 ± 0.548	
	23.0	6.271 ± 0.533	
	24.0	6.314 ± 0.536	
$^{\rm nat}\mathrm{In}\,(\gamma, n)\,^{111m,g}\mathrm{In}$	43.0		6.1 ± 0.4 [49]

*Values calculated with the aid of photon strength functions from [51].

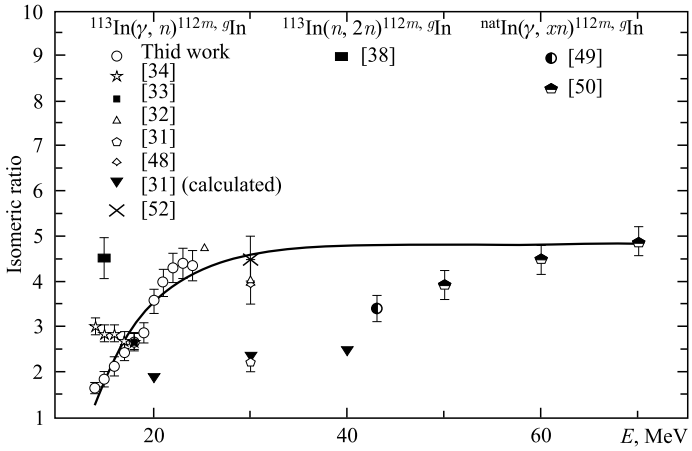

Fig. 5. The isomeric ratios in $^{113}\mathrm{In}\,(\gamma, n)\,^{112m,g}\mathrm{In}$ photonuclear reaction

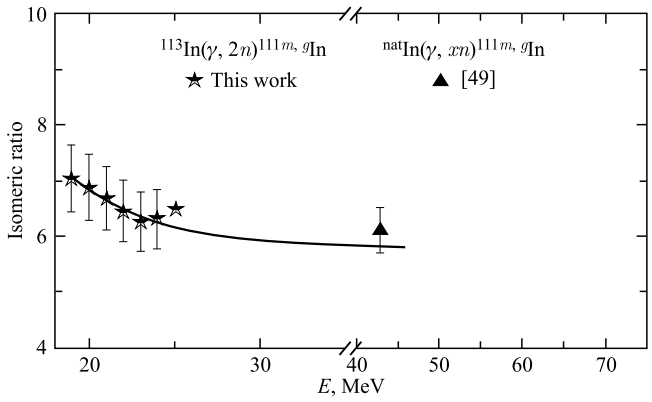

Fig. 6. The isomeric ratios in $^{113}\mathrm{In}\,(\gamma, 2n)\,^{111m,g}\mathrm{In}$ photonuclear reaction

to the sum of that for the isomeric and ground states i.e., $Y_m/(Y_m + Y_g)$. In order to make comparison, from this ratio we calculated the isomeric ratio $\mathrm{IR} = Y_m/Y_g$ and then the ratio of the yield of the high spin to that of the low spin states, which are shown in Table 4. The data for ^{112m,g}In in [31, 32] expressed as $\mathrm{IR} = Y_{\mathrm{hs}}/Y_{\mathrm{ls}}$ are also shown in this table. In [38], for the $^{113}\mathrm{In}\,(n, 2n)\,^{112m,g}\mathrm{In}$ reaction, the authors gave the value $\mathrm{IR} = Y_m/Y_g$. From this value we calculated the ratio of the yield of the high spin to that of the low spin states. Figure 5 depicts the dependences of the isomeric ratios of $^{113}\mathrm{In}\,(\gamma, n)\,^{112m,g}\mathrm{In}$ reactions on bremsstrahlung end-point energies and $^{113}\mathrm{In}\,(n, 2n)\,^{112m,g}\mathrm{In}$ at 14.9 MeV neutron. Figure 6 depicts the dependences of the isomeric ratios of $^{113}\mathrm{In}\,(\gamma, 2n)\,^{111m,g}\mathrm{In}$ reactions on bremsstrahlung end-point energies. There are no data available in the literature for this reaction.

One can see from formula (3) that for the case of photonuclear reaction with bremsstrahlung in the GDR region, the isomeric ratio increases (or decreases) with the increase of end-point energy, reaches maximum (or minimum) value at the end of this region and slightly changes for higher energies. The change of the isomeric ratio depends on the fact that the

yield of the isomeric state increases faster or slower than that of the ground state when the bremsstrahlung end-point energy increases. In ^{113}In (γ, n) ^{112m,g}In photonuclear reaction, the GDR region is from the threshold (i.e., about 10 MeV) to about 20–21 MeV, as seen in [34]. In ^{113}In $(\gamma, 2n)$ ^{111m,g}In photonuclear reaction, this region is similar to that of ^{115}In $(\gamma, 2n)$ ^{113m,g}In photonuclear reaction, i.e., from about 17.5 to about 28 MeV [45]. It is well known that ^{113}In is odd–even nucleus with spin $I = 9^+/2$ determined by the last odd proton $1g_{9/2}$ of fourth shell $1f_{7/2}$, $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, $1g_{9/2}$ [46]. As a result of ^{113}In (γ, n) ^{112m,g}In photonuclear reaction, odd–odd nucleus ^{112}In was formed and its spin is determined by the mentioned odd proton $1g_{9/2}$ and odd neutron $2d_{5/2}$ of fifth shell $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$ [46] and the isomeric pair ^{112m,g}In was formed with isomeric and ground state spins 4^+ and 1^+, respectively. Odd–even nucleus ^{111}In was formed from ^{113}In $(\gamma, 2n)$ ^{111m,g}In photonuclear reaction and its spin is determined by the last odd proton $1g_{9/2}$ of fourth shell $1f_{7/2}$, $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, $1g_{9/2}$ [46] and the isomeric pair ^{111m,g}In was formed with isomeric and ground state spins $1^-/2$ and $9^+/2$, respectively. From Table 4 and Figs. 5, 6 one can see the following facts:

a) There are very few data available in the existing literature for the isomeric ratios in photonuclear reactions with natural indium in the GDR region as well as in the higher energy range. We found only six papers [31–34, 48, 52], as shown in Table 4. One can see from this table the following: for the isomeric pair ^{112m,g}In, our results and the data from [34] are in agreement for 17 and 18 MeV in the error limit; for the energy range from 14 to 16 MeV our results are lower than those in [34], and for the energy range from 19 to 24 there are no data in the existing literature to make comparison. Therefore, it can be said that for the isomeric ratio of ^{113}In (γ, n) ^{112m,g}In photonuclear reaction, the results for the energy region from 19 to 24 MeV in this work are new measurements and in agreement with the data in [48, 52]. For 30 MeV the data in the literature are in big discrepancy. Table 4 and Fig. 5 also show the results of other authors [49, 50] for $^{\mathrm{nat}}$In (γ, xn) ^{112m,g}In photonuclear reaction. The isomeric ratio in this case, however, simultaneously came from two ^{113}In (γ, n) ^{112m,g}In and ^{115}In $(\gamma, 3n)$ ^{112m,g}In photonuclear reactions. The threshold energies of these reactions are about 9.5 and 26.0 MeV, respectively. One can see here that the data in [49] are insignificantly lower than those in [50] and our results are in good tendency with the data in [49, 50] as it is seen that beyond the resonance region the isomeric ratios are slightly changed.

b) The results of our experiments show that for the isomeric pairs ^{112m,g}In in the GDR region, the isomeric ratios increase with the increase of end-point energy, reach maximum value at the end of this region (20–21 MeV) and slightly change for higher energies. This fact was expected from formula (3), as mentioned above. This means that our results are logical. In principle, the isomeric ratios continue to increase with energy in the energy region higher than the GDR region. In Table 4 and Fig. 5 are also shown the data taken from [31] for the isomeric pair ^{112m,g}In calculated with the aid of photon strength functions [51] for 20, 30 and 40 MeV bremsstrahlung end-point energies. Although these values are significantly lower than the experimental ones, they are in the same tendency with our results, i.e., the isomeric ratio for ^{112m,g}In increases with the increase of bremsstahlung end-point energy.

c) For the isomeric pair ^{111m,g}In there are no data available in the existing literature. Therefore, we are unable to make any comparison and it can be said that our results for the isomeric ratio of ^{111m,g}In in the GDR region are new measurements. From Table 4 and Fig. 6 one can see that for ^{113}In$(\gamma, 2n)$ ^{111m,g}In photonuclear reaction, the isomeric ratio decreases with the increase of bremsstrahlung end-point energy from 19 to 24 MeV.

It is expected that this ratio will continue to decrease until 28 MeV, i.e., to the end of the GDR region of this reaction. The decrease of the isomeric ratio in this case means that the probability for population of low spin state $1^-/2$ increases faster than that of high spin state $9^+/2$ when the bremsstrahlung end-point energy increases. In Table 4 and Fig. 6 are also shown the results of other authors [49] for $^{\mathrm{nat}}\mathrm{In}\,(\gamma, xn)\,^{111m,g}\mathrm{In}$ photonuclear reaction. The isomeric ratio in this case, however, simultaneously came from two $^{113}\mathrm{In}\,(\gamma, 2n)\,^{111m,g}\mathrm{In}$ and $^{115}\mathrm{In}\,(\gamma, 4n)\,^{111m,g}\mathrm{In}$ photonuclear reactions. The threshold energies of these reactions are about 17.5 and 34.0 MeV, respectively. One can see that our results are in good tendency with the data in [49].

d) As a principle, the isomeric ratio of an isomeric pair, produced from different nuclear reactions, depends on the impulse of the projectiles. This is the influence of reaction channels on isomeric ratios, as demonstrated by the authors in [47]. The higher the impulse of the projectile, the higher the isomeric ratio. It is well known that $(n, 2n)$ and (γ, n) nuclear reactions form the same isomeric pair. However, for the same energies of neutron and photon, the impulse of neutron in $(n, 2n)$ reaction is higher than that of photon in (γ, n) reaction because the photon has zero rest mass. Therefore, the isomeric ratio in $(n, 2n)$ reaction is significantly higher than that in (γ, n) reaction. This fact can be seen in [20, 28, 29, 38, 39, 40–44]. For example, in [29] we obtained for (γ, n) photonuclear reactions at 14 MeV bremsstrahlung of isotopes ^{30}Ba, ^{32}Ba and ^{34}Ba the values of isomeric ratios 0.135 ± 0.011, 0.095 ± 0.008 and 0.065 ± 0.005, respectively, while the authors in [39] obtained the values 0.28, 0.19 and 0.29, respectively, for the isomeric ratios in $(n, 2n)$ reactions of the mentioned isotopes at 14.4 MeV neutron energy. In Fig. 5 we also show the isomeric ratios obtained by the authors in [38] for $^{113}\mathrm{In}\,(n, 2n)\,^{112m,g}\mathrm{In}$ reaction at neutron energy from 14.9 MeV and our results for $^{113}\mathrm{In}\,(\gamma, n)\,^{112m,g}\mathrm{In}$ photonuclear reactions at 15 MeV bremsstrahlung end-point energy. One can see that our data are significantly lower than those in [38]. This again confirms that our results are logical.

CONCLUSIONS

We have completely carried out the measurement of the isomeric ratios in $^{113}\mathrm{In}\,(\gamma, n)\,^{112m,g}\mathrm{In}$ and $^{113}\mathrm{In}\,(\gamma, 2n)\,^{111m,g}\mathrm{In}$ photonuclear reactions induced by bremsstrahlungs with end-point energies in the GDR region. The isomeric ratios in both the mentioned reactions in the bremsstrahlungs energy range from 19 to 24 MeV in this work are new measurements. The results provide complete and new data for this region and could contribute to the Nuclear Data.

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