Письма в ЭЧАЯ. 2009. Т. 6, № 2(151). С. 209–218

THE ISOMERIC RATIOS IN SOME PHOTONUCLEAR REACTIONS (γ, n), (γ, p), $(\gamma, 2n)$ AND (γ, np) INDUCED BY BREMSSTRAHLUNGS WITH END-POINT ENERGIES IN THE GIANT DIPOLE RESONANCE REGION

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We have determined the isomeric ratios in photonuclear reactions ^{116}Cd$(\gamma, n)^{115m,g}$Cd, ^{138}Ce$(\gamma, n)^{137m,g}$Ce, ^{153}Eu$(\gamma, n)^{152m,g}$Eu, ^{96}Mo$(\gamma, p)^{95m,g}$Nb, ^{118}Sn$(\gamma, p)^{117m,g}$In, ^{89}Y$(\gamma, 2n)^{87m,g}$Y, ^{106}Cd$(\gamma, np)^{104m,g}$Ag and ^{112}Sn$(\gamma, np)^{110m,g}$In induced by bremsstrahlungs with end-point energies in the Giant Dipole Resonance (GDR) region. The targets were irradiated at electron accelerator Microtron MT-25 of the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna. Gamma spectra of irradiated samples were measured with a spectroscopic system consisting of 8192-channel analyzer and high-energy resolution (180 keV at gamma ray 1332 keV of ^{60}Co) semiconductor detector CANBERRA. The results were discussed and compared with those of other authors.

Проведено исследование изомерных отношений в фотоядерных реакциях ^{116}Cd$(\gamma, n)^{115m,g}$Cd, ^{138}Ce$(\gamma, n)^{137m,g}$Ce, ^{153}Eu$(\gamma, n)^{152m,g}$Eu, ^{96}Mo$(\gamma, p)^{95m,g}$Nb, ^{118}Sn$(\gamma, p)^{117m,g}$In, ^{89}Y$(\gamma, 2n)^{87m,g}$Y, ^{106}Cd$(\gamma, np)^{104m,g}$Ag и ^{112}Sn$(\gamma, np)^{110m,g}$ в области гигантского дипольного резонанса. Работу проводили на микротроне МТ-25 ЛЯР ОИЯИ. Изомерные отношения определяли из серии гамма-спектров, измеренных HPGe-детектором с многоканальным анализатором. Проведены обсуждение и сравнение полученных данных с результатами других авторов.

PACS: 24.30.Cz; 25.20.Dc

INTRODUCTION

The investigations on the properties of excited states in nuclear reaction, including the characteristics and the probability of excitation, the energy and spin distributions, the different decay modes, allow one to obtain important information about interaction mechanism. It is very effective when there are excited states with sufficiently long lifetimes, i.e., the isomeric and ground states. One of the directions in these studies is to measure the ratios of probabilities of forming these states, the so-called isomeric ratio. The isomeric ratios furnish valuable information about the energy level structure of nuclei and the nuclear reaction mechanism

involved. On the other hand, the isomeric and ground states are formed simultaneously during nuclear reaction process in the same experimental conditions, so the isomeric ratios can be determined with high accuracy. By fitting the isomeric ratios calculated on the basis of a definite theoretical model to the experimental ones, it is possible to obtain information about the spin dependence of the nuclear density, in particular, the spin cut-off parameter σ and the level density parameter a. One of the important properties of photonuclear reactions in the giant dipole resonance region is that their cross sections are characterized with a wide maximum, so-called «giant resonance» and the most probable mechanism of interactions causes 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.

Up to now the study of the isomeric ratios in simple reactions (γ, γ') and (γ, n) is more complete and the contribution of preequilibrium and direct processes are shown [1–6]. The number of works devoted to the study on reactions (γ, p), (γ, np) and $(\gamma, 2n)$ with excitation of the isomeric states is significantly less and some of them can be seen in [7–12]. The reasons for that are the low reaction cross section and the higher threshold energy in comparison with (γ, n) reactions (in taking into account the Coulomb barrier for outflying protons). This leads to smaller yields of the mentioned reactions in comparison with (γ, n) reaction in the GDR region. Simultaneously, it is also expected that the contribution of direct and preequilibrium processes can be more significant in these types of reaction. Therefore, the study on the isomeric ratios in the mentioned reactions could furnish additional information on the spin level properties, the nuclear reaction mechanism involved as well as could contribute to the nuclear data source.

In this work we present the isomeric ratios measured in photonuclear reactions ^{116}Cd$(\gamma, n)^{115m,g}$Cd, ^{138}Ce$(\gamma, n)^{137m,g}$Ce, ^{153}Eu$(\gamma, n)^{152m,g}$Eu, ^{96}Mo$(\gamma, p)^{95m,g}$Nb, ^{118}Sn$(\gamma, p)^{117m,g}$In, ^{89}Y$(\gamma, 2n)^{87m,g}$Y, ^{106}Cd$(\gamma, np)^{104m,g}$Ag and ^{112}Sn$(\gamma, np)^{110m,g}$In in the GDR region. Recently we have also studied the isomeric ratio in photonuclear reactions induced by excitation energy higher than GDR region [13]. In this case more than two particles are emitted and the reaction mechanism is more complicated.

EXPERIMENTAL

The investigated samples were prepared of 99.99% purity metallic foils in disc form 1 cm in diameter from Sn, Mo and Cd and of 99.99% purity oxide powder packed in aluminium capsule 1 cm in diameter from CeO_2, Y_2O_3 and Eu_2O_3. The sample masses were 0.0797, 0.1997, and 0.5813 g for Sn, Mo and Cd and 0.8589, 0.29559 and 0.2198 g for Ce_2O_3, Y_2O_3 and Ei_2O_3, respectively.

The irradiations were carried out at bremsstrahlungs produced by electron accelerator Microtron MT-25 of the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna, Russia. The bremsstrahlung end-point energy can be varied stepwise from 10 to 25 MeV. The description of this accelerator and its main characteristics are presented in [14]. The essential advantage of this 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 measurement of the isomeric ratio of the studied nuclides at strictly definite end-point energy. As an electron–photon converter was used W disk 4 mm thick, cooled by water. For absorption of electrons entering the reaction cameras, an aluminium screen 20 mm thick was

placed behind the converter. The investigated samples were irradiated with bremsstrahlungs of end-point energies 18, 20 and 23.5 MeV, and the average accelerated electron beam was about 15 μA.

The gamma spectra of the irradiated samples were measured with a spectroscopic system consisting of HPGe detector CANBERRA with energy resolution of 1.8 keV at 1332 keV gamma ray of ^{60}Co, amplifier 2022 and 8192 multichannel analyzer connected to computer for data processing. The efficiency of the detector was determined by using a set of single gamma-ray sources calibrated to the error of 1–2%.

The decay characteristics and gamma rays of the investigated nuclei are taken from [15–17] and presented in Table 1. The irradiated targets were in natural chemical

Table 1. **The decay characteristics and gamma rays of the investigated nuclei**

Nuclear reaction	Reaction product	Spin	Abundance,%	Half-life	Reaction threshold, d, MeV	Coul. barrier, MeV	Gamma energy, keV, and intensity, %	Iso. trans. coef. IT, %
^{118}Sn$(\gamma,p)^{117m,g}$In	$^{117m}_{49}$In $^{117g}_{49}$In	$1^-/2$ $9^+/2$	24	1.93 h 42 min	10.33 10.01	7.98 7.98	315(16.94) 552(99.70)	47
^{112}Sn$(\gamma,np)^{110m,g}$In	$^{110m}_{49}$In $^{110g}_{49}$In	7^+ 2^+	0.95	4.9 h 69 min	17.59 17.59	7.77 7.77	658(98.5) 885(94.8) 658(97.9)	0
^{96}Mo$(\gamma,p)^{95m,g}$Nb	^{95m}Nb ^{95g}Nb	$1^-/2$ $9^+/2$	16.5	87 h 35 d	9.53 9.30	7.07 7.07	235(25.53) 766(99.82)	97.5
^{138}Ce$(\gamma,n)^{137m,g}$Ce	^{137m}Ce ^{137g}Ce	$11^-/2$ $3^+/2$	0.25	34.4 h 9.0 h	8.77 9.77		254(10.90) 168(0.43) 447(2.20)	99.2
^{153}Eu$(\gamma,n)^{152m,g}$Eu	^{152m}Eu ^{152g}Eu	8^- 0^-	52.23	96 min 9.3 h	8.69 8.59		90(72) 334(2.14) 121.8(6.31) 841(12.7) 963(10.5) 1389(0.75)	0
^{89}Y$(\gamma,2n)^{87m,g}$Y	^{87m}Y ^{87g}Y	$9^+/2$ $1^-/2$	100	13.2 h 80.3 h	21.19 20.62		318(7.8) 485(92.0)	98
^{106}Cd$(\gamma,np)^{104m,g}$Ag	^{104m}Ag ^{104g}Ag	2^+ 5^+	1.22	33.5 min 69.2 min	17.37 17.35	7.56 7.56	556(60.5) 556(92.0) 767.6(65.8) 785.7(9.5) 857.9(10.3) 923.3(6.9) 941.6(24.8)	0.07
^{116}Cd$(\gamma,n)^{115m,g}$Cd	^{115m}Cd ^{115g}Cd	$11^-/2$ $1^+/2$	7.58	44.8 d 53.38 min	8.86 8.69		934(1.70) 231(0.75) 260.8(2.00) 336.2(50.1) 527.7(30.8) 492.6(9.4)	0

Table 2. **The interference reaction of the investigated nuclei**

Chem. element	Reaction product	Interference reaction	Threshold, MeV	Coulomb barr., MeV	Abundance, %
Sn	$^{110m}_{49}$In	No			
	$^{110g}_{49}$In	No			
	$^{117m}_{49}$In	$^{119}_{50}\mathrm{Sn}(\gamma, np)^{117m}_{49}\mathrm{In}$	16.81	7.64	$\theta(^{119}\mathrm{Sn}) = 8.5$
	$^{117g}_{49}$In	$^{119}_{50}\mathrm{Sn}(\gamma, np)^{117g}_{49}\mathrm{In}$	16.49	7.64	
SnMo	$^{95m}_{41}$Nb	$^{97}_{42}\mathrm{Mo}(\gamma, np)^{95m}_{41}\mathrm{Nb}$	16.35	6.92	$\theta(^{97}\mathrm{Mo}) = 9.45$
	$^{95g}_{41}$Nb	$^{97}_{42}\mathrm{Mo}(\gamma, np)^{95g}_{41}\mathrm{Nb}$	16.12	6.92	
SnCe	^{137m}Ce	No			
	^{137g}Ce	No			
SnEu	^{152m}Eu	No			
	^{152g}Eu	No			
SnY	^{87m}Y	No			
	^{87g}Y	No			
SnCd	^{104m}Ag	No			
	^{104g}Ag	No			
	^{115m}Cd	No			
	^{115g}Cd	No			

form; therefore, during reaction process the interference reactions of the investigated nuclei can happen. These interference reactions are shown in [16] and presented in Table 2. In the case of (γ, p) and (γ, np) reactions, proton has, however, a positive charge and must have, according to the classical theory, sufficient energy to overcome the Coulomb barrier. This barrier was taken by the following formula [18, 19]:

$$E_b = 1.44\frac{Z_A z_a}{R_A + R_a}, \tag{1}$$

where R_A and R_a are the radiuses of residual nucleus and outflying particle and expressed in Fermi units (10^{-13} cm) and $R_A = 1.5{\cdot}10^{-13}A^{1/3}$ cm.

The isomeric ratios were determined by the activation method and the following formula as presented in [20]:

$$\frac{1}{R} = \frac{\dfrac{S_g \varepsilon_m I_m}{S_m \varepsilon_m I_g}\Lambda_3^m \Lambda_6^m \Lambda_9^m - \Lambda_1\Lambda_5\Lambda_8 - \Lambda_3\Lambda_5\Lambda_8 - \Lambda_3\Lambda_6\Lambda_8}{\Lambda_2^g \Lambda_5^g \Lambda_8^g}, \tag{2}$$

where m and g are the isomeric and ground states; I, ε and S are the intensity, the efficiency and the area under the photopeak, respectively; R is the isomeric ratio and $\Lambda_i (i = 1\text{–}9)$ are the factors connected to the times of irradiation, cooling and measurement.

RESULTS AND DISCUSSION

As mentioned above, the targets were in natural chemical form; therefore, the gamma spectra of the products of the reactions were observed in principle on high background of other reactions. This makes the identification more difficult and the experimental results less accurate.

In Figs. 1, 2 and 3 are shown only the typical gamma spectra of Sn, Mo and Cd targets irradiated by bremsstrahlungs produced from Microtron MT-25. Here are seen the photo-

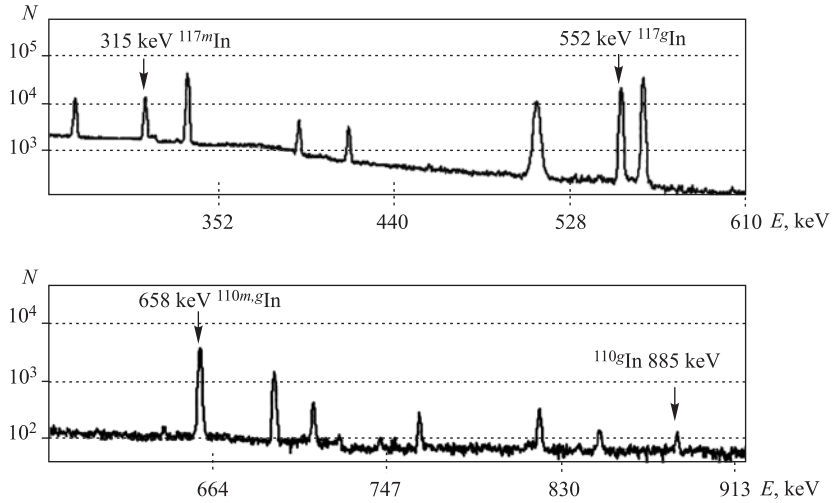

Fig. 1. Spectrum of Sn sample irradiated by 23.5 MeV bremsstrahlung for 60 min with cooling time of 200 min and measurement time of 60 min

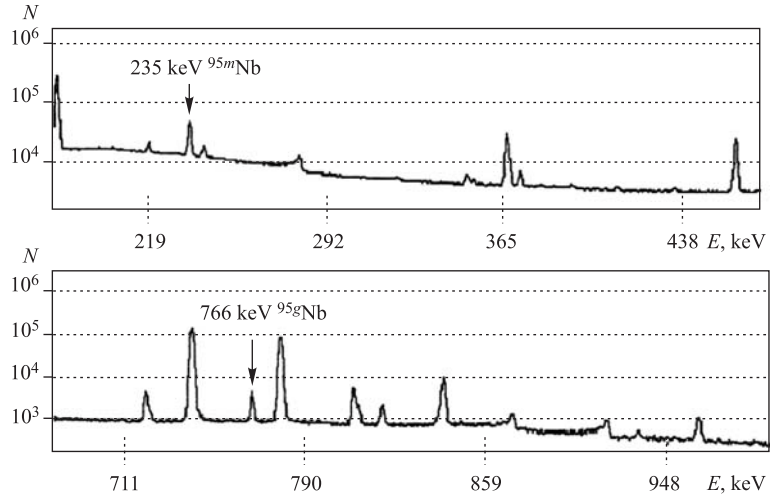

Fig. 2. Spectrum of Mo sample irradiated by 23.5 MeV bremsstrahlung for 120 min with cooling time of 1365 min and measurement time of 150 min

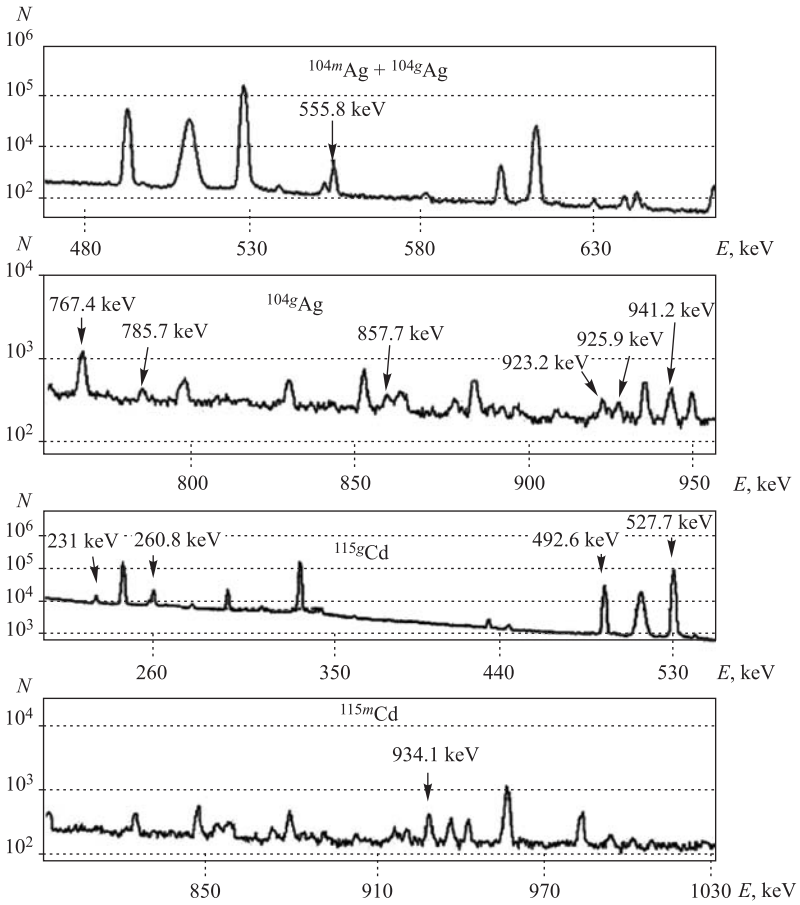

Fig. 3. Spectrum of Cd sample irradiated by 23.5 MeV bremsstrahlung for 120 min with cooling time of 260 min and measurement time of 60 min

peaks characterizing the isomeric pairs ^{117m,g}In, ^{110m,g}In, ^{104m,g}Ag, ^{115m,g}Cd and ^{95m,g}Nb appearing on very complicated backgrounds formed by various photonuclear reactions of other isotopes. In our experiments by choosing optimal sample masses and times of irradiation, cooling and measurement, we succeeded in the determination of the isomeric ratios for the investigated reactions with relatively good statistical errors. The isomeric ratio was determined as averaged value of values calculated from different combinations of series of gamma spectra measured for different times of cooling and measurement. In Table 3 are shown the isomeric ratios measured for the investigated reactions together with those of other authors for comparison and depicted in Fig. 4 [9, 10, 21–28].

As is seen from Table 2, the isomeric pairs ^{117m,g}In and ^{95m,g}Nb are formed not only from reactions ^{118}Sn$(\gamma, p)^{117m,g}$In and ^{96}Mo$(\gamma, p)^{95m,g}$Nb, but also by ^{119}Sn$(\gamma, np)^{117m,g}$In and ^{97}Mo$(\gamma, np)^{95m,g}$Nb, respectively. It is known that the reaction yields are expressed by $Y = \int_{E_{\rm th}}^{E_\gamma^m} N_0 \sigma(E)\, \phi(E) dE$ (here N_0 — the number of target nucleus, $\sigma(E)$ — the reaction

Table 3. **The isomeric ratios in different photonuclear reactions depending on bremsstrahlung end-point energies**

Nuclear reaction	Present work		Other works	
	End-point energy, MeV	Isomeric ratio	End-point energy, MeV	Isomeric ratio
^{138}Ce$(\gamma, n)^{137m,g}$Ce	18.2 20.0 23.5	0.154±0.015 0.179±0.018 0.227±0.023	70.0	0.32 [21]
^{153}Eu$(\gamma, n)^{152m,g}$Eu	18.2 23.5	$(1.018\pm0.1)\cdot10^{-2}$ $(1.999\pm0.2)\cdot10^{-2}$		
^{96}Mo$(\gamma, p)^{95m,g}$Mo	20.0 23.5	1.42±0.14 2.15±0.21	30.0	0.75 [22,23]
^{118}Sn$(\gamma, p)^{117m,g}$In	23.5	4.98±0.5	20.0 22.0 24.0	3.686±0.387[9] 9.5±2.7 [24] 3.8±0.3[10]
^{116}Cd$(\gamma, n)^{115m,g}$Cd	23.5 20.0	0.158±0.016 0.117±0.012	22.0 30.0 30.0	0.12±0.02[24] 0.27 [22, 23] < 0.25[25]
^{89}Y$(\gamma, 2n)^{87m,g}$Y	23.5	0.106±0.011	23.0 25.6 28.6 50.0 30.0 47.0 150.0	0.25±0.03 [26] 0.35±0.04 [26] 0.43±0.04 [26] 0.54±0.04 [26] 0.44 [22, 23] 0.32 [27] 0.71 [28]
^{106}Cd$(\gamma, np)^{104m,g}$Ag	23.5	10.438±1.041		
^{112}Sn$(\gamma, np)^{110m,g}$In	23.5	0.283±0.028		

cross section, $\Phi(E)$ — the bremsstrahlung photon flux, $E_{\rm th}$ — the reaction threshold energy and E_γ^m — the bremsstrahlung end-point energy). On the basis of the bremsstrahlung intensity distribution [29], taking into account the fact that the cross section of (γ, np) reaction is very low in comparison with that of (γ, p) reaction [30] and using the expression for the reaction yield, we have estimated that in the limit of the experimental errors the contribution of the yields of ^{119}Sn$(\gamma, np)^{117m,g}$In and ^{97}Mo$(\gamma, np)^{95m,g}$Nb reactions can be neglected in the yield of ^{118}Sn$(\gamma, p)^{117m,g}$In and ^{96}Mo$(\gamma, p)^{95m,g}$Nb.

It is known that the yield of (γ, p) reaction is lower than that of (γ, n) reaction about 10^2 times [31], the cross section of $(\gamma, 2n)$ reaction is much lower than that of (γ, n) reaction. (As an example, for the case of photonuclear reaction of ^{89}Y with 28 MeV bremsstrahlung $\sigma^{\rm int}(\gamma, 2n)/\sigma^{\rm int}(\gamma, n)$ ∼0.1 [32] and the cross section of (γ, np) reaction is also much lower in comparison with (γ, p) reaction [30].) Though the cross sections of the photonuclear reactions are very low, especially in (γ, p), (γ, np) and $(\gamma, 2n)$ reactions, the irradiation with bremsstrahlung produced by electron accelerators has significant advantages based on the fact that they are intense photon sources and the integrated cross section in the case is much higher

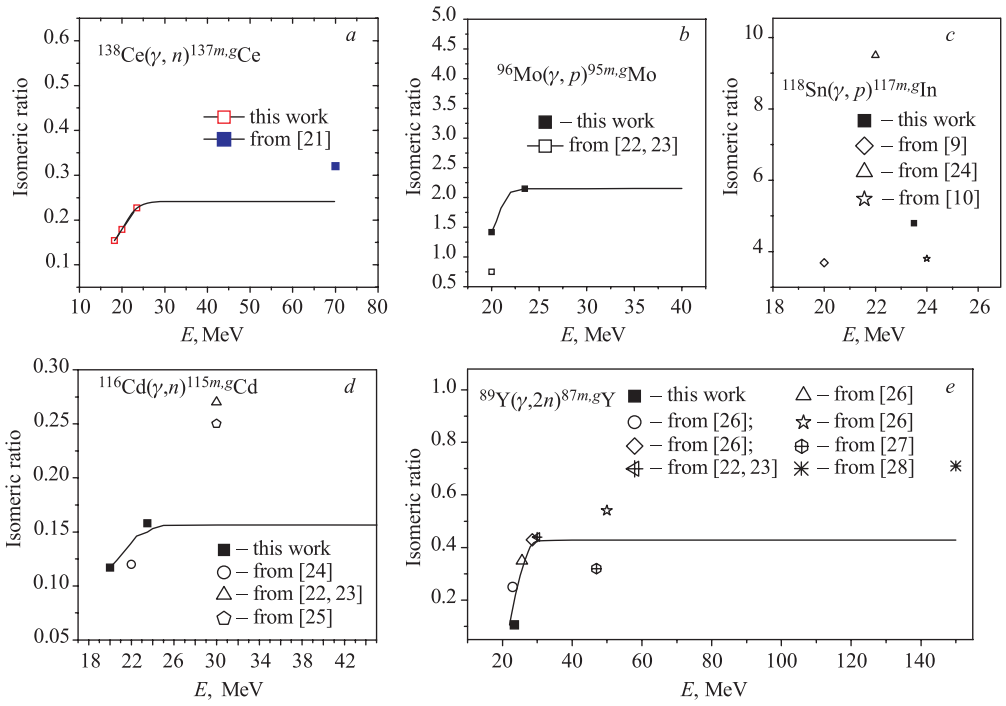

Fig. 4. The isomeric ratios of our experiment and other authors

than in monoenergetic photon. This leads to higher yields of the investigated reactions and makes the measurement of the isomeric ratios in our experiments succeeded.

One can see the characteristics of the isomeric and ground states of the investigated nuclei in Table 1. Here for isomeric pairs ^{110m,g}In, ^{137m,g}Ce, ^{152m,g}Eu, ^{87m,g}Y and ^{115m,g}Cd the isomeric states have high spins and the ground states have low spins and for isomeric pairs ^{117m,g}In, ^{95m,g}Nb and ^{104m,g}Ag, the isomeric states have low spins and the ground states have high spins. It is known that in almost cases the isomeric ratios are higher than unit when the isomeric states have lower spins and are lower than unit when the isomeric states have higher spins. This means that probability of population of the states with higher spins is lower than that of the states with lower spins. This fact is also observed in our case and confirms that our results are proper.

In the case of photonuclear reactions induced by bremsstrahlung, the isomeric ratio is the average value in the region from the reaction threshold to the end-point energy and can be expressed by the following formula:

$$R = \frac{\int\limits_{E_{\rm th}^{m}}^{E_{\gamma}^{m}} N_0 \sigma_m \phi\,(E)\; dE}{\int\limits_{E_{\rm th}^{g}}^{E_{\gamma}^{m}} N_0 \sigma_g \phi\,(E)\; dE}. \tag{3}$$

Therefore, from expression (3) it is expected that in the GDR region the isomeric ratio increases with the increasing end-point energy and reaches the maximum value at the end of this region and becomes unchanged for high energy. From [32] one can see that the end energy of GDR regions for reactions ^{138}Ce$(\gamma, n)^{137m,g}$Ce, ^{153}Eu$(\gamma, n)^{152m,g}$Eu,^{116}Cd$(\gamma, n)^{115m,g}$Cd, ^{89}Y$(\gamma, 2n)^{87m,g}$Y are about 22; 22; 22; 30, respectively, and for reactions ^{96}Mo$(\gamma, p)^{95m,g}$Nb, ^{118}Sn$(\gamma, p)^{117m,g}$In, ^{106}Cd$(\gamma, np)^{104m,g}$Ag and ^{112}Sn$(\gamma, np)^{110m,g}$In are much higher [30].

In Fig. 4 are depicted our experimental results together with those of other authors for ^{137m,g}Ce, ^{117m,g}In, ^{115m,g}Cd, ^{95m,g}Nb and ^{87m,g}Y. The results for ^{152m,g}Eu, ^{104m,g}Ag and ^{110m,g}In are not presented because of the lack of the data referenced in literature and we could not make any comparison. From Fig. 4 and on the basis of the above-mentioned arguments we can say that our results for ^{137m,g}Ce, ^{117m,g}In, ^{115m,g}Cd, ^{95m,g}Nb and ^{87m,g}Y are completely logical and in good agreement with those of other authors. We also would like to note that there are some discrepancies in the cases of ^{117m,g}In and ^{87m,g}Y as is seen from Fig. 4.

As is seen from Tables 1 and 2, for the case of reactions with emission of proton the Coulomb barrier plays an important role. In these reactions proton has to overcome not only the reaction threshold, but also the Coulomb barrier. The (γ, np) reaction happens even when the sum of the reaction threshold and Coulomb barrier is higher than the excitation energy. Therefore, the contribution of the direct and preequilibrium processes has to be taken into account for the reactions with emission of proton.

CONCLUSION

In conclusion, we would like to say that the isomeric ratios measured in this work for photonuclear reactions ^{116}Cd$(\gamma, n)^{115m,g}$Cd, ^{138}Ce$(\gamma, n)^{137m,g}$Ce, ^{153}Eu$(\gamma, n)^{152m,g}$Eu, ^{96}Mo$(\gamma, p)^{95m,g}$Nb, ^{118}Sn$(\gamma, p)^{117m,g}$In, ^{89}Y$(\gamma, 2n)^{87m,g}$Y, ^{106}Cd$(\gamma, np)^{104m,g}$Ag and ^{112}Sn$(\gamma, np)^{110m,g}$In are new results and could contribute to the nuclear data source. At the same time, the study of these reactions is of important significance for the nuclear reaction mechanism, especially for those reactions with emission of proton where the direct and preequilibrium processes have to be taken into account.

Acknowledgements. This work has been supported by the Vietnamese Council on Natural Science Research and by the grant RFBR – VAST No. 07-02-90005 from the Russian Academy of Sciences and the Vietnam Academy of Science and Technology.

The experiment has been performed at the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna. The authors would like to thank the working group on Microtron MT-25 for operating the irradiation facilities and the Chemical Department for providing the measurement system.

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Received on April 22, 2008.