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STUDY ON THE ISOMERIC RATIOS OF (γ, p) PHOTONUCLEAR REACTIONS WITH ISOTOPES $^{92}_{40}$Zr AND $^{183}_{74}$W IN THE GIANT DIPOLE RESONANCE REGION

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We have carried out the study on the isomeric ratios in (γ, p) photonuclear reactions with isotopes $^{92}_{40}$Zr and $^{183}_{74}$W in the giant dipole resonance (GDR) region. The targets were irradiated with bremsstrahlungs produced by electron accelerator Microtron MT-25 of the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna. Spectra of irradiated samples were measured with a spectroscopic system consisting of 8192-channel analyzer CANBERRA and high-energy resolution semiconductor detector CANBERRA. The results were discussed and compared with those of other authors.

Проведено исследование изомерных отношений в фотоядерных реакциях ^{92}Zr$(\gamma, p)^{91m,g}$Y и ^{183}W$(\gamma, p)^{182m,g}$Ta 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.

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INTRODUCTION

Nuclear reactions with emission of different particles become an important source of information on properties of the excited states of an investigated nucleus, namely on the nuclear reaction mechanism and the structure of newly formed nuclei.

The investigation on the properties of the excited states in nuclear reaction including the characteristics and the probability of the excitation, the energy and the spin distributions, the different decay modes allows one to obtain important information about interaction mechanism. However, the data in this field is not complete. Some of the mentioned properties can be delivered by investigating the characteristics of the products of nuclear reaction and in part of the information on the spin distribution of the excited nuclei as well as their deexcitation, which can be obtained from the yield ratio of the reaction products in different spin states. Because of these one of the directions in these studies is to measure the isomeric ratio, which is defined as the ratio of the cross-sections of producing isomeric and ground states in the final nucleus. This ratio depends on the spin of target nucleus and the intake angular momentum determined by the mass and the energy of projectile particles. Besides, the mechanism of reaction channel and the properties of the final nucleus in the region of the continuous spectrum of high excitation energy, as well as in low-lying discrete levels through which the isomeric and ground states formed, also strongly affect the isomeric ratio. On the other hand, as the isomeric and the ground states are produced in the same nuclear process, the experimental isomeric ratio can be determined with high accuracy. By fitting the theoretical model calculation isomeric ratio to the experimental one, it is possible to obtain important information on the nuclear structure. In particular, the spin cut-off parameter σ and the spin level density parameter a and the nuclear reaction mechanism involved.

In photonuclear reactions in the GDR region, the electromagnetic interaction well known as absorption of an $E1$ gamma ray leads the target nucleus with spin J_0 to an excited compound nucleus with spins $J_0 \pm 1\hbar$ and the theoretical calculation in this case will be simplified. One of the important properties of photonuclear reactions in this 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.

The more simple the investigated reactions, the more defined the obtained information. Samples of such simple reactions are the reactions with emission of one nucleon (γ, n) and (γ, p) in the GDR region. Up to now the study of excitation of the isomeric states in photonuclear reactions is more complete for the case of (γ, n) and (γ, γ') reactions, where the influence of the structure of low-lying levels in the final nucleus on the isomeric ratio and the contribution of preequilibrium and direct processes are shown in [1–8]. The number of works devoted to study on reaction (γ, p) with excitation of the isomeric states is significantly less [9–12]. 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 of the Coulomb barrier for outflying protons). This leads to smaller yields of (γ, p) reaction in comparison with (γ, n) reaction in the GDR region. At the same time, however, the study on the isomeric ratio in (γ, p) reaction presents a definite interest due to the significant difference from (γ, n) reaction. This difference is connected to the fact that in (γ, p) reaction other isomeric states are excited which are usually difficult to be produced in (γ, n) reaction. It is also expected that the contribution of direct and preequilibrium processes can be more significant in this type of reaction. Therefore, the study on the isomeric ratio in (γ, p) photonuclear reaction could furnish additional information on the spin level properties and the photonuclear reaction mechanism involved.

The aim of this work is to study the experimental isomeric ratios in (γ, p) reaction of nuclei $^{92}_{40}$Zr and $^{183}_{74}$W in the GDR region, and it is hopeful that the results could contribute to the nuclear data source.

1. EXPERIMENTAL

The targets for investigation were prepared from natural metalic foils Zr and W with 99.99% purity in circle form in diameter of 1 cm. There were three Zr samples with masses 0.1265, 0.1153, 0.1165 g and two W samples with masses 0.0637 and 0.3208 g prepared.

For irradiations of the target there were used bremsstrahlungs produced by electron accelerator Microtron MT-25 of the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research. The maximum energies can be varied stepwise from 10 to 25 MeV. The description of this accelerator and its characteristics is presented in [13]. As convertor of electron beam to bremsstrahlung photon flux a W disk with thickness of 4 mm, cooled with water, was used. Behind the convertor was placed an aluminium cylinder 20 mm thick for absorption of low-energy electrons entering the reaction cameras.

As is well known, the cross-section of electromagnetic interaction is very low, so the irradiation with bremsstrahlung of electron accelerators has significant advantages based on the fact that they are intense photon sources and the integrated cross-section in the case of bremsstrahlung irradiation is much more higher than in monoenergetic photon flux. This leads to higher yields in photonuclear reaction and makes the experimental results more accurate. In the case of Microtron MT-25, another essential advantage 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 nuclide production at strictly definite end point energy of bremsstrahlung.

In our experiment for the investigation of the isomeric ratios in photonuclear reaction with Zr target in the giant dipole resonance region, three samples of natural metallic Zr were irradiated at 23.5, 21.5 and 18 MeV bremsstrahlungs with average electron beams of 15, 15, 10 μA for irradiation times of 20, 10 and 30 min, respectively. For the case of W target, two samples of natural metal W were irradiated at 21.5 and 15 MeV bremsstrahlungs with average electrons beams of 15 and 12 μA for irradiation times of 10 and 40 min, respectively.

The gamma spectra of the irradiated samples were collected by a spectroscopic system consisting of high-energy resolution semiconductor HPGe – CANBERRA (1.8 keV at 1332 keV of ^{60}Co) and 8192-channel analyzer CANBERRA connected to computer for data processing. The efficiency of the detector was determined by using a set of single gamma ray sources calibrated to 1–2%.

Table 1. **The decay characteristics of the isomeric and ground states of interest**

Nuclear reaction	Nucleus product	Threshold, MeV*	Spin	Half-life	Energy, keV	Intensity, %
$^{92}_{40}$Zr (γ, p) ($\theta = 17.11\%$)	$^{91m}_{39}$Y	9.95	$9^+/2$	49.7 m	555.0	94.9
$^{92}_{40}$Zr (γ, p) ($\theta = 17.11\%$)	$^{91g}_{39}$Y	9.40	$1^-/2$	58.5 d	1205.0	0.30
$^{183}_{74}$W (γ, p) ($\theta = 14.40\%$)	$^{182}_{73}$Ta	7.72	10^-	15.8 m	146.7 171.7 184.9 318.3	29.6 47.0 23.5 10.3
$^{183}_{74}$W (γ, p) ($\theta = 14.40\%$)	$^{182}_{73}$Ta	7.21	3^-	115 d	100.0 152.0 156.0 222.0 1121.0 1188.0 1221.0 1230.0	14.04 7.0 2.74 7.4 37.0 16.5 27.4 11.6

* The Coulomb barrier is not included.

The isomeric and ground states were identified with the decay characteristics which are taken from [14, 15] and presented in Table 1. As in our previous works [5, 7, 8, 11], the experimental method in this study is the activation method based on measuring gamma spectra of formed products in dependence on energy and intensity of used bremsstrahlungs.

2. RESULTS AND DISCUSSION

As mentioned above, the targets were natural metal foils of Zr and W; therefore, the gamma spectra of the products of the reactions of interest were observed in principle on high background of other reactions. This makes the identification more difficult and the experimental results less accurate. For example, in Figs. 1 and 2 are shown the typical spectra

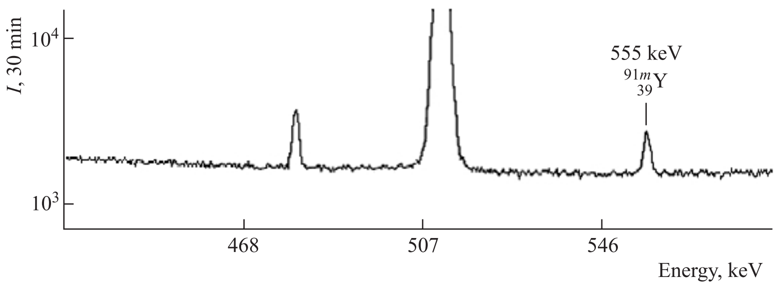

Fig. 1. Spectrum of Zr sample irradiated by 23.5 MeV bremsstrahlung for 120 min with cooling time of 165 min and measurement time of 30 min

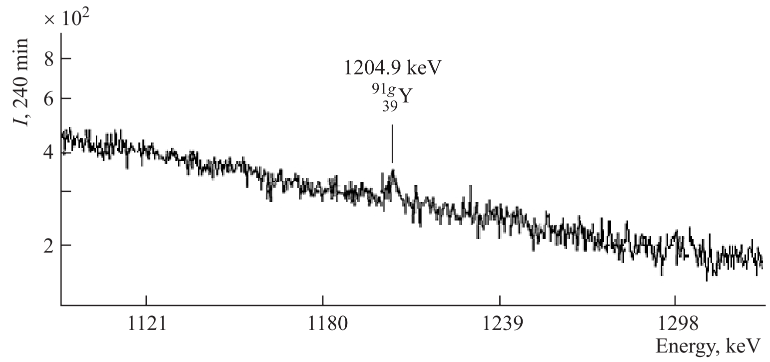

Fig. 2. Spectrum of Zr sample irradiated by 23.5 MeV bremsstrahlung for 120 min with cooling time of 1520 min and measurement time of 240 min

of Zr sample and in Fig. 3 and 4 are shown typical spectra of W sample. The isomeric ratio R is calculated from the gamma spectra of the irradiated samples by the following formula:

$$\frac{1}{R} = \frac{\frac{S_g \varepsilon_m I_m}{S_m \varepsilon_g I_g} \Lambda_3 \Lambda_6 \Lambda_9 - \Lambda_1 \Lambda_5 \Lambda_8 - \Lambda_3 \Lambda_5 \Lambda_8 - \Lambda_3 \Lambda_6 \Lambda_7}{\Lambda_2 \Lambda_5 \Lambda_8}, \tag{1}$$

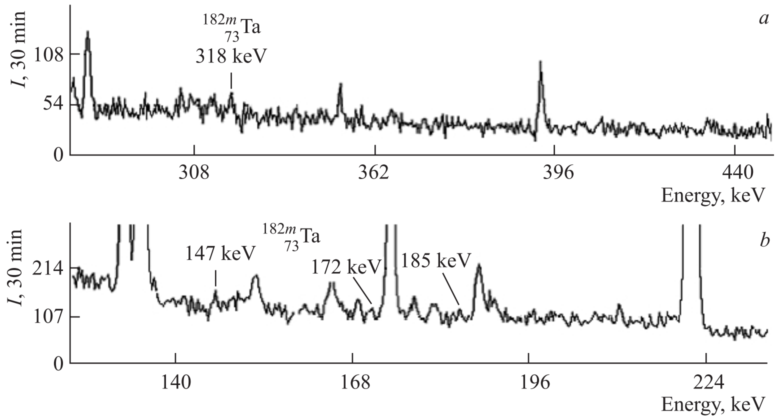

Fig. 3. Spectrum of W sample irradiated by 15 MeV bremsstrahlung for 40 min with cooling time of 9 min and measurement time of 30 min

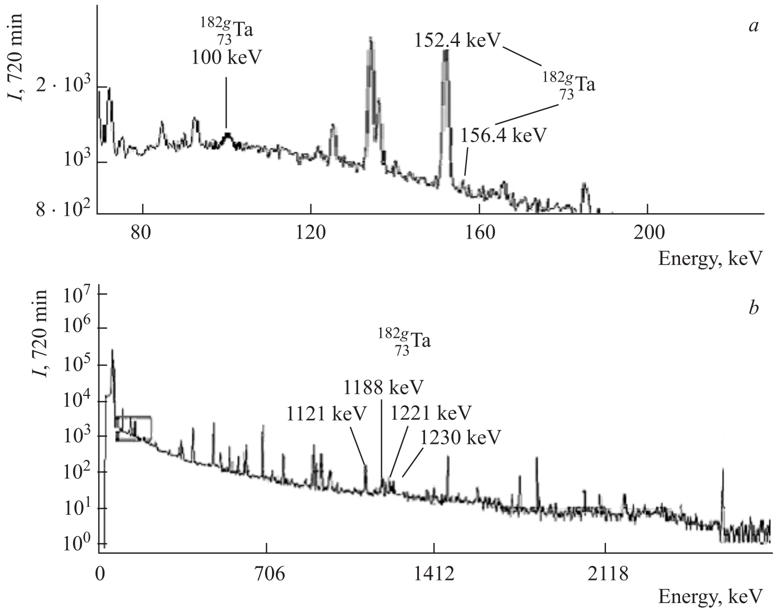

Fig. 4. Spectrum of W sample irradiated by 15 MeV bremsstrahlung for 40 min with cooling time of 4492 min and measurement time of 720 min

where S_m, S_g are the areas under the studied photopeaks; ε_m, ε_g are the efficiencies and I_m, I_g the intensities; Λ_1, Λ_2, $\ldots$, Λ_9 are the factors connected to the times of irradiation, cooling and measurement.

The calculation of isomeric ratio is most simple when it is supposed that the times of irradiation, cooling and measurement are the same for the isomeric and ground states. If it is necessary to study nuclei with very large difference in half-lives of the isomeric and ground states, then the times of irradiation, cooling and measurement will be different for these states.

In this case, formula (1) returns to

$$\frac{1}{R} = \frac{\dfrac{S_g \varepsilon_m I_m}{S_m \varepsilon_g I_g} \Lambda_3^m \Lambda_6^m \Lambda_9^m - \Lambda_1^g \Lambda_5^g \Lambda_8^g - \Lambda_3^g \Lambda_5^g \Lambda_8^g - \Lambda_3^g \Lambda_6^g \Lambda_7^g}{\Lambda_2^g \Lambda_5^g \Lambda_8^g}, \tag{2}$$

where m, g are marks for the isomeric and ground states. The detailed description of formulas (1) and (2) can be seen in [16].

In this study the isomeric ratio was determined as averaged value of values calculated from combinations of different series of gamma spectra. We can see that the photopeaks characterizing the isomeric and ground states of nuclei ${}^{91}_{39}\mathrm{Y}$ and ${}^{182}_{73}\mathrm{Ta}$ are very weak due to very low yields of (γ, p) photonuclear reaction. On the other hand, the half-lives of the isomeric states are very short. For these reasons the determination of the isomeric ratios in photonuclear reactions ${}^{92}_{40}\mathrm{Zr}(\gamma, p)^{91m,g}_{39}\mathrm{Y}$ and ${}^{183}_{74}\mathrm{W}(\gamma, p)^{182m,g}_{73}\mathrm{Ta}$ is very difficult and always of important significance for the nuclear reaction. 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 above-mentioned reaction with relatively good statistical errors.

The results of our experiments which have been determined with average errors of 12 and 10% for ${}^{183}_{74}\mathrm{W}$ and ${}^{92}_{40}\mathrm{Zr}$ respectively are shown in Table 2. The data for the isomeric ratios in these reactions are not available from literature except [17] for ${}^{183}_{74}\mathrm{W}$; therefore, it is not possible to make a comprehensive comparison between our results and those of other authors. However, in all cases the values of the isomeric ratios are very low in the reactions with excitation of high-spin isomers [16, 17]. It is very interesting to make the comparison of the isomeric ratios in (γ, p) photonuclear reactions with that in (γ, n) photonuclear reaction as shown in Table 2. One can see from this table that for the reaction products formed in both reactions with the same low and high spins or with the same spin difference, the isomeric ratios in (γ, n) photonuclear reactions are much higher than those in (γ, p) photonuclear reactions. It can be explained by the fact that due to the Coulomb barrier the excitation energies in (γ, n) photonuclear reaction products are higher as compared with that in (γ, p) photonuclear reaction product. Besides, in (γ, p) photonuclear reaction the direct and preequilibrium processes are dominant.

Table 2. **The experimental results of the investigated reactions**

Nuclear reactions	Bremsstrahlung energy and isomeric ratio			
	15 MeV	18 MeV	21.5 MeV	23.5 MeV
${}^{92}_{40}\mathrm{Zr}(\gamma, p)^{91m,g}_{39}\mathrm{Y}$		$2.2 \cdot 10^{-4}$	$7.6 \cdot 10^{-4}$	$9.1 \cdot 10^{-4}$
${}^{183}_{74}\mathrm{W}(\gamma, p)^{182m,g}_{73}\mathrm{Ta}$	$7.7 \cdot 10^{-4}$		$8.1 \cdot 10^{-4}$	$2.2 \cdot 10^{-4}$ [17]

As seen from Table 3, the isomeric ratios in the two (γ, p) reactions are very low. We know that the spin difference of the isomeric and ground states is significant (for ${}^{91m,g}\mathrm{Y}$ the spins are $9/2^+$ and $1/2^-$, for ${}^{182m,g}\mathrm{Ta}$ the spins are 10^- and 3^-; i. e., the spin differences are 4 and 7 for ${}^{91}\mathrm{Y}$ and ${}^{182}\mathrm{Ta}$, respectively). In the case of photonuclear reaction in the giant resonance region it is well known that the transfer momentum is very low; therefore, the probability for populating the high-spin states is smaller than that for the low-spin states. This means that the isomeric ratios must be low.

Table 3. **The isomeric ratios in (γ, p) and (γ, n) photonuclear reactions**

Nuclear reaction	High spin $\hbar$	Low spin $\hbar$	Spin difference $\hbar$	Isomeric ratio	Reference	Bremsstrahlung end-point, MeV
${}^{92}_{40}\mathrm{Zr}(\gamma, p){}^{91m,g}_{39}\mathrm{Y}$	$9^+/2$	$1^-/2$	4	$2.2 \cdot 10^{-4}$	This work	18
				$7.6 \cdot 10^{-4}$	This work	21.5
				$9.1 \cdot 10^{-4}$	This work	23.5
${}^{183}_{74}\mathrm{W}(\gamma, p){}^{182m,g}_{73}\mathrm{Ta}$	10^-	3^-	7	$7.7 \cdot 10^{-4}$	This work	15
				$8.1 \cdot 10^{-4}$	This work	21.5
${}^{121}\mathrm{Sb}(\gamma, n){}^{120m,g}\mathrm{Sb}$	8^-	1^+	7	$1.79 \cdot 10^{-2}$	[7]	15
				$5.16 \cdot 10^{-2}$	[7]	18
				$6.16 \cdot 10^{-2}$	[7]	20
				$6.12 \cdot 10^{-2}$	[7]	22
${}^{90}\mathrm{Zr}(\gamma, n){}^{89m,g}\mathrm{Y}$	$9^+/2$	$1^-/2$	4	$7 \cdot 10^{-1}$	[8]	16.5
				$7.5 \cdot 10^{-1}$	[8]	18
				$9.2 \cdot 10^{-1}$	[8]	20.5
${}^{140}\mathrm{Ce}(\gamma, n){}^{139m,g}\mathrm{Ce}$	$11^+/2$	$3^+/2$	4	$1.3 \cdot 10^{-1}$	[18]	18
${}^{132}\mathrm{Ba}(\gamma, n){}^{131m,g}\mathrm{Ba}$	$9^-/2$	$1^+/2$	4	$1.4 \cdot 10^{-1}$	[19]	18

Besides, we can also see that the isomeric ratios in the above-mentioned reactions in the region of giant dipole resonance change insignificantly in dependence on the excitation energies. This fact can also be explained with the low-momentum transfer in the (γ, p) photonuclear reactions.

CONCLUSION

In conclusion we would like to say that the study of the isomeric ratio of (γ, p) photonuclear reactions in the giant dipole resonance region is of definite interest because in this type of reactions such isomeric states are excited which are usually difficult to be produced by other reactions and it is expected that the contribution of direct and preequilibrium processes is more significant. These advantages allow the study of isomeric ratio in (γ, p) photonuclear reactions to provide additional information on the nuclear structure and reaction mechanism. In this meaning we hope that our results could contribute to the nuclear data treasure.

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