STUDY OF ISOMER RATIO IN $(n, 2n)$ AND (γ, n) REACTIONS ON THE ^{140}Ce NUCLEUS*

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The isomeric ratios of the yields of photoneutron reactions (γ, n) on a ^{140}Ce nucleus have studied in the energy range of 12–35 MeV with a step of 1 MeV. The resulting energy dependence has been obtained in the form of a saturation curve. The experiments have been carried out by the induced activity method. The cross sections for the excitation of the ^{139m,g}Ce isomeric states in the $(n, 2n)$ reaction on the ^{140}Ce nucleus at a neutron energy of 14.1 MeV have also been determined. Finally, the obtained experimental results have been compared with theoretical and numerical calculations performed using the TALYS-1.6 software package.

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1. Introduction

Nuclear reactions with various bombarding particles serve as an important source of information both on the mechanisms of nuclear reactions and on the properties of excited states of atomic nuclei. One of the directions of such research is the measurement of isomeric ratios, *i.e.*, the measurement of the ratio of yields and cross sections for the reactions of formation of residual nuclei in the isomeric and ground states. These ratios depend on the spin of the target nucleus and the introduced angular momentum, which is determined by the mass and energy of the bombarding particle, as well as on the mechanism of this reaction, the properties of excited states in both continuous and discrete regions. Using data on isomeric ratios of nuclear

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yields, one can study the mechanisms of nuclear reactions and the statistical properties of excited states of atomic nuclei [1–4]. In addition, data on the isomeric ratios of the yields are required for solving applied problems. In the present work, the energy dependence of the isomeric ratios of the yields of photonuclear reactions of the (γ, n) type on a ^{140}Ce nucleus is experimentally investigated in the energy range of 12–35 MeV with a step of 1 MeV. The cross sections for the excitation of the ^{139m,g}Ce isomeric states in the $(n, 2n)$ and (γ, n) reactions on the ^{140}Ce nucleus have also been determined. The isomeric ratios of the yields and cross sections of the $^{140}\mathrm{Ce}(\gamma, n)^{139m,g}\mathrm{Ce}$ reaction have been studied mainly in the energy range from the reaction threshold to 18 MeV. There are several works [5, 6] in which isomeric ratios are determined at fixed energies. In the energy region above 24 MeV, such a work has practically not been carried out. In the case of the $(n, 2n)$ reaction, despite numerous experiments carried out at 14.1 MeV, there are very little data on individual measurements of the cross sections of the isomeric and ground levels.

2. Experimental technique

The measurements of the isomeric ratios of the yields were carried out by the method of induced activity on the bremsstrahlung γ-beam of the high-current betatron SB-50 of the National University of Uzbekistan for electron energies from 12 to 35 MeV. Several series of irradiation were carried out. The irradiation time of the samples was 1.5–3 h. Cerium (cerium dioxide — CeO_2) in a natural mixture of isotopes was used as a target. To increase the dose rate, irradiation was carried out inside the accelerating chamber of the SB-50 high-current betatron at a distance of 12 cm from the tungsten inhibitory target, where the sample, located in a special container, was delivered using a K5-2A pneumatic transport unit. The delivery time of the sample to the place of irradiation by a pneumatic transport unit is ~ 4 s [7]. To study nuclear reactions of the $(n, 2n)$ type, the neutron generator NG-150 of the Institute of Nuclear Physics of the Academy of Sciences of the Republic of Uzbekistan was used, which implements fast neutron fluxes with energies of 14.1 MeV [8]. Cerium dioxide (CeO_2) samples weighing 2–3 g in the form of 15 mm tablets in diameter prepared by pressing were used as targets. To exclude the effect of background neutrons (thermal neutrons), the samples were packed in 1 mm thick cadmium screens. In addition, as a monitor, aluminium foil was attached to the front and back of the samples. Irradiation time was 60–120 min. The induced γ-activity of the targets was measured on a Canberra gamma-spectrometer, consisting of a germanium detector HP Ge (with a relative efficiency of 15%, a resolution for the ^{60}Co 1332 keV line — 1.8 keV) and a DSA 1000 digital analyzer with the Genie 2000 software package. The detection efficiency of γ-quanta of decay was determined using the standard calibration sources of ^{152,154}Eu and ^{133}Ba. Measurements were performed in standard geometry, in which the detector was calibrated for efficiency. The measurement time for the induced γ-activity of the targets was 3–120 min. The identification of radioactive isotopes formed as a result of nuclear reactions such as (γ, n) and $(n, 2n)$ on the ^{140}Ce nucleus was carried out by the energies of gamma peaks in the spectra, as well as their half-lives. The nuclear physical characteristics of the nuclei products of the (γ, n) and $(n, 2n)$ reactions, necessary for processing the measurement results, were taken from [9, 10] and are given in Table I, where I_π is the spin and parity of the level, $T_{1/2}$ is the half-life of the nucleus, I_γ is the intensity of γ-quanta of a given energy for decay, p is the branching coefficient of the γ-transition.

TABLE I

Nuclear physical characteristics of nuclei products of the (γ, n) and $(n, 2n)$ reaction on nuclei.

Reaction product	J^π	$T_{1/2}$	E_γ [MeV]	I_γ	p
^{139m}Ce	$11/2^-$	$54s$	754.2	93	1
^{139m}Ce	$3/2^+$	$137d$	165.8	81	—

Isomeric ratios of yields will be calculated using the formula [11]

$$d = \frac{Y_\mathrm{m}}{Y_\mathrm{g}} = \left[\frac{\lambda_\mathrm{g} F_\mathrm{m}(t)}{\lambda_\mathrm{m} F_\mathrm{g}(t)} \left(C \frac{N_\mathrm{g} I_\mathrm{m} \varepsilon_\mathrm{m}}{N_\mathrm{m} I_\mathrm{g} \varepsilon_\mathrm{g}} - p \frac{\lambda_\mathrm{g}}{\lambda_\mathrm{g} - \lambda_\mathrm{m}} \right) + p \frac{\lambda_\mathrm{m}}{\lambda_\mathrm{g} - \lambda_\mathrm{m}} \right]^{-1} , \quad (1)$$

where

$$F_\mathrm{m}(t) = [1 - \exp(-\lambda_\mathrm{m} t_0)] \exp(\lambda_\mathrm{m} t_\mathrm{p}) [1 - \exp(\lambda_\mathrm{m} t_\mathrm{m})] , \quad (2)$$

$$F_\mathrm{m}(t) = [1 - \exp(-\lambda_\mathrm{g} t_0)] \exp(\lambda_\mathrm{g} t_\mathrm{p}) [1 - \exp(\lambda_\mathrm{g} t_\mathrm{m})] , \quad (3)$$

and indexes 'm' and 'g' are corresponding to metastable and ground states; C is the coefficient taking into account the miscalculations of the recording equipment and the position of the pulses; N_m, N_g — the number of registered acts of decay of the isomeric and ground states, respectively; I will be the intensity of γ-quanta of a given energy for decay; ϵ is the efficiency of the spectrometer; p is the branching factor of the γ-transition; t_0, t_p, t_m — time of irradiation, pause, and measurement, respectively.

3. Results and discussions

The obtained experimental results on the isomeric ratios of the yields and cross sections of the reactions (γ, n) and $(n, 2n)$ on the ^{140}Ce nucleus are shown in Fig. 1 and Tables II and III. Figure 1 shows the dependence of the isomeric ratios of the yields $d\,(E_\gamma)_{\max} = Y_{\rm m}/Y_{\rm g}$ of the reaction $^{140}{\rm Ce}(\gamma,n)^{139m,g}{\rm Ce}$ on the maximum bremsstrahlung energy. The errors in the experimental values of $d\,(E_\gamma)_{\max}$ for each maximum energy of bremsstrahlung $(E_\gamma)_{\max}$ are due to the statistics of counts in photopeaks and errors in determining the efficiency of the detector. Taking into account the significant increase in statistical errors, measurements of the reaction yield in the immediate vicinity of the threshold of photonuclear reactions were not carried out.

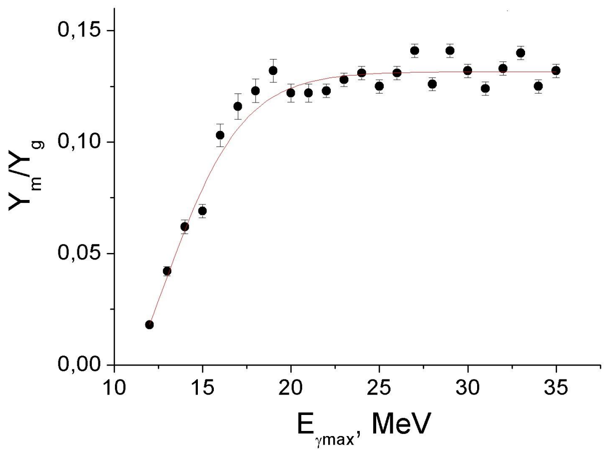

Fig. 1. Energy dependences of isomeric ratios of the yields of the reaction $^{140}{\rm Ce}(\gamma,n)^{139m,g}{\rm Ce}$.

To approximate the experimental data on the isomeric output ratios, we used the sigmoidal (“stepwise”) Boltzmann functions (solid curve in Fig. 1)

$$y = A_2 + \frac{(A_1 - A_2)}{1 + \exp[(E - E_0)/\Delta E]}\,, \tag{4}$$

where A_1, A_2, E_0 and δE are adjustable parameters determined by the least-squares method from a set of experimental values. As a result of fitting, the following values were obtained: $A_1 = -0.00347 \pm 0.02238, A_2 = 0.13072 \pm 0.00169, E_0 = 14.235 \pm 0.626$, and $\delta E = 1.490 \pm 0.317$. As can be seen from Fig. 1, the isomeric ratios of the yields increase from the reaction threshold to ~ 18 MeV. At energies above ~ 18 MeV, a saturation of the $Y_{\rm m}/Y_{\rm g}$ curve occurred. Our results for the photonuclear reaction $^{140}{\rm Ce}(\gamma,n)^{139m,g}{\rm Ce}$ in the energy range of 18–30 MeV agree within the measurement error with the data of [5, 6] (see Table II). In [6], the isomeric yield ratio was determined in the energy range of 11–18 MeV. This table shows only the values close to the saturation region of the $Y_{\mathrm{m}}/Y_{\mathrm{g}}$ curve, which are convenient for comparison. In the energy range of 12–35 MeV, the energy dependences were obtained for the first time.

TABLE II

Isomeric ratios of the yields of the reaction of the (γ, n) type on the ^{140}Ce nucleus.

$(E_\gamma)_{\mathrm{max}}$ [MeV]	$Y_{\mathrm{m}}/Y_{\mathrm{g}}$	Ref.
16.0	0.096 ± 0.0039	[6]
16.5	0.106 ± 0.0043	[6]
17.0	0.116 ± 0.0047	[6]
17.5	0.1085 ± 0.0044	[6]
18.0	0.122 ± 0.0049	[6]
25	0.130 ± 0.008	[5]
20	0.122 ± 0.0037	this work
25	0.125 ± 0.0025	this work
30	0.132 ± 0.0026	this work
35	0.132 ± 0.0026	this work

Based on the data obtained on the isomeric ratios of the yields of the $^{140}\mathrm{Ce}(\gamma, n)^{139m,g}\mathrm{Ce}$ reaction, the integral cross section of the reaction at $(E_\gamma)_{\mathrm{max}} = 25$ MeV was determined, which is equal to 216 ±13 MeV mb and, within the measurement error, is consistent with the data of [12]. Data on the total cross section for the photoneutron reaction were obtained from [13]. The integral cross section was determined according to the method described in [12].

The cross sections for the formation of the isomeric and ground states and their isomeric ratios $\sigma_{\mathrm{m}}/\sigma_{\mathrm{g}}$ for the $(n, 2n)$ reaction were determined at a neutron energy $E_n = 14.1$ MeV. To obtain the absolute values of the cross sections of the ground and isomeric states, we used the methods of comparing the yields of the investigated and monitor reactions. As a monitor reaction, we used $^{27}\mathrm{Al}(n, \alpha)^{24}\mathrm{Na}$ ($T_{1/2} = 15$ h, $E_\gamma = 1368$ keV), the cross section of which is $\sigma_{\mathrm{m}} = 121.57 \pm 0.57$ mb at $E_n = 14.1$ MeV [10]. When determining the cross sections, we took into account the statistical error of counting in the photopeak of the measured γ-line, the error in determining the cross section of the monitor reaction, the efficiency of registration of γ-radiation and self-absorption of gamma rays. The isomeric ratios of the cross sections $\sigma_{\mathrm{m}}/\sigma_{\mathrm{g}}$ were calculated using formula (1). Table III shows the results obtained for the $(n, 2n)$ reaction on the ^{140}Ce nucleus.

TABLE III

Cross section of the reaction ^{140}Ce $(n,2n)$ ^{139}Ce.

E_n [MeV]	$\sigma_{\rm m}$ [mb]	$\sigma_{\rm g}$ [mb]	$\sigma_{\rm m}/\sigma_{\rm g}$	Ref.
13.5	794 ± 44	879 ± 74	0.9 ± 0.1	[14]
14.8	1080 ± 70	775 ± 99	1.4 ± 0.2	[14]
14.1	797 ± 39	906 ± 71	1.1 ± 0.1	this work
14.0*	776	628	1.23	this work
13.73	850 ± 58	—	—	[15]
14.07	951 ± 58	—	—	[15]
14.77	1092 ± 81	—	—	[15]

4. Conclusion

It is seen from Table III that the results on the isomeric ratios of the cross sections $\sigma_{\rm m}/\sigma_{\rm g}$ agree within the measurement errors with the data of other works. In order to calculate the theoretical values of isomeric ratios of yields and reaction cross sections, we have used the TALYS-1.0 software package [10]. The measurement results given in Table III indicate that the relative probability of excitation of isomers in the case of a reaction of the $(n,2n)$ type is several times (~ 7) higher than in the reaction (γ,n). This is probably due to the moment introduced into the nucleus, which are larger in the case of the $(n,2n)$ reaction than in the photonuclear reactions.

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