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ISOMERIC RATIOS ^{109m,g}Pd IN THE (γ, n) AND $(n, 2n)$ REACTIONS

The method of induced activity of the investigated cross-sections of excitation of isomeric states in the $^{110}Pd(\gamma,n)^{109m,g}Pd$ and $^{110}Pd(n,2n)^{109m,g}Pd$ reactions in the energy range 12–35 MeV is studied. The experimental results are compared with those of calculations carried out using the software package TALYS-1.6.

Keywords: isomeric ratios, bremsstrahlung, radioactivity, cross-section, activity, isomer, nucleus, nuclear reaction.

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 the excited states of atomic nuclei. One of the directions of such studies is the measurement of isomeric ratios, i.e. measuring the ratio of the cross-sections for the reactions of the formation of residual nuclei in the isomeric and ground states. These relations 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 the excited states both in the continuous and discrete regions [1–4].

The purpose of this work is to study the isomeric ratios of yields and cross-sections for reactions of the type (γ, n) on a ^{110}Pd nucleus in the energy interval 10–35 MeV. For comparison, the isomeric ratios of the yields of the $(n, 2n)$ reaction on the ^{110}Pd nucleus were determined at the neutron energy $E_n = 14.1$ MeV.

Previously, isomeric ratios in the ^{110}Pd$(\gamma, n)^{109m,g}$Pd reaction were measured in [5–8]. In [5, 6, 8], measurements were carried out at several points of the maximum energy of bremsstrahlung. In [7], isomeric ratios were measured in the energy interval 9–18 MeV. In the energy region above 21 MeV, the energy dependence of the isomeric ratio of the yields was practically not measured. In the case of the reaction $(n, 2n)$, despite numerous experiments at 14 MeV, there is very little data on individual measurements of the cross-sections of the isomeric and ground levels.

2. Experimental Technique

The experiments were conducted by the method of induced activity on the SB-50 betatron of the National University of Uzbekistan and the neutron generator NG-150 of the Institute of Nuclear Physics of the Academy of Sciences of the Republic of Uzbekistan. Measurements of the isomeric ratios in the reaction (γ, n) were carried out on the brake γ-beam of the SB-50 betatron in the energy interval 10–35 MeV with a step of 1 MeV. In order to increase the dose power, the irradiation was performed within the accelerating chamber of the SB-50 high-current betatron at a distance of 12 cm from a tungsten braking target, where the studied sample placed in a special container was transported by a K5-2A pneumatic-

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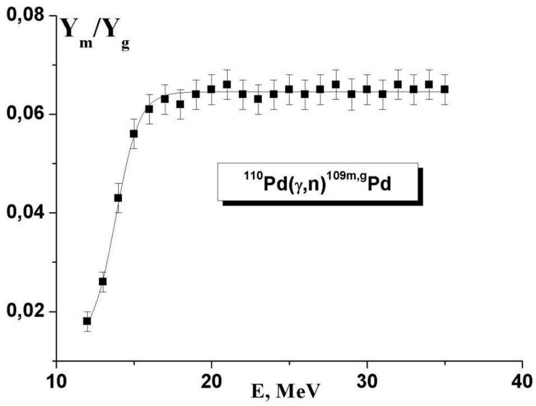

Fig. 1. Energy dependence of the isomeric yield ratios of reactions $^{110}\mathrm{Pd}(\gamma, n)^{109m,g}\mathrm{Pd}$

rabbit facility. The time of the sample transportation to the irradiation locus with the aid of this facility was about 4 s.

The neutron source was the NG-150 neutron generator, which generates fast neutron fluxes with energies of ∼2.4 and 14 MeV from the reactions $D + d \to$ $\to$ $^3\mathrm{He} + n$ or $T + d \to \alpha + n$ using deuterium and tritium targets. In this case, the neutron fluxes are ∼10^8 and 10^{10} neutrons $\cdot$ s^{-1}, respectively. As targets, palladium samples with natural composition 1–2 g in weight in the form of tablets were used. The exposure time is 10–30 min.

The induced gamma activity of the targets was measured with the aid of a Canberra gamma spectrometer consisting of a high-purity (HP) germanium (HPGe) detector having a relative efficiency of 15% and an energy resolution of 1.8 keV for the 1332 keV line of ^{60}Co, a DSA 1000 digital analyzer, and a PC employing the Genie 2000 code package for the accumulation and the processing of gamma spectra. The energy calibration of the gamma spectrometer was performed with the aid of a standard set of RSGR (reference spectrometric gamma-radiation) sources. The measurements were performed for the case of the standard geometry in which the detector was calibrated in efficiency. Measurements of the γ activity were carried out in two series. The first series of measurements was carried out after a pause of $t_p = 1$ min during the course of time $\mathrm{t}_m = 10$ min (for short-lived isotopes). The second series of measurements was carried out in the following mode: $t_p = 30$ min during $t_m = 30$ min.

Table 1. **Spectroscopic characteristics of products of the nuclear reactions (γ, n) and $(n, 2n)$**

Product nucleus	J^π	$T_{1/2}$	E_γ, keV	I_γ, %	p
^{109m}Pd	$11/2^-$	4.69 m	188.9	58	1
^{109g}Pd	$5/2^+$	13.47 h	88.10	5	–

The population of the isomeric and ground levels was identified by $\gamma-$lines. The spectroscopic characteristics of the reaction product nuclei (γ, n) and $(n, 2n)$, necessary for processing the measurement results, are taken from [9] and are given in Table 1, where J^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 the given decay energy, and p is the ramification coefficient of the γ transition.

The ratio of the isomeric yields in the reaction $^{110}\mathrm{Pd}(\gamma, n)^{109m,g}\mathrm{Pd}$ was calculated by the formula [10]

$$d = \frac{Y_m}{Y_g} = \left[\frac{\lambda_g F_m(t)}{\lambda_m F_g(t)}\left(C\frac{N_g I_m \epsilon_m k_m}{N_m I_g \epsilon_g k_g} - U\right) + V\right]^{-1}, \tag{1}$$

where

$$U = p\frac{\lambda_g}{\lambda_g - \lambda_m}, \quad V = p\frac{\lambda_m}{\lambda_m - \lambda_g}, \tag{2}$$

$$F_m(t) = \left[1 - e^{-\lambda_m t_{ir}}\right] e^{-\lambda_m t_p} \left[1 - e^{-\lambda_m t_m}\right], \tag{3}$$

$$F_g(t) = \left[1 - e^{-\lambda_g t_0}\right] e^{-\lambda_g t_n} \left[1 - e^{-\lambda_g t_c}\right]. \tag{4}$$

Here, Y_m and Y_g are the yields of, respectively, the isomeric and ground states; λ_m and λ_g are their decay constants; N_m and N_g are the numbers of detected events of decay of, respectively, the isomeric and ground states; C is a coefficient that accounts for the miscounts of the detecting equipment and pulse positions; ϵ is the spectrometer efficiency; k is the coefficient of self-absorption in the sample; and t_{ir}, t_p, and t_m are the times of irradiation, pause, and measurements, respectively.

3. Results and Discussion

The experimental results on the isomeric ratios of the yields and cross-sections of the (γ, n) and $(n, 2n)$ reactions on the ^{110}Pd nucleus are shown in Figs. 1–3 and in Tables 2–4. Solid lines in Fig. 1 give the results of the approximation of experimental dependences of isomeric relations on the energy by Boltzmann curves.

The absolute error of the isomeric yields is determined by the statistical error of the counts in the photopeak of the measured γ-line and the efficiency of recording the γ-radiation. In the case of the ^{110}Pd (γ, n) ^{109m,g}Pd reaction, the results of measurements showed that the value of the isomeric yield ratios Y_m/Y_g increases from the reaction threshold to $\sim$16 MeV. Perhaps, this happens, because the number of cascade γ-transitions that remove the excitation of the nucleus increases wityh the energy. At an energy above $\sim$16 MeV, the saturation of the Y_m/Y_g curve occurred, since a further increase in the level density probably does not significantly change the probability of the formation of cascades leading to metastable states.

In the region of excitation energies above the giant dipole resonance, i.e. in the 21–35 MeV interval, the energy dependence of the isomeric ratios of the yields of the reaction ^{110}Pd$(\gamma, n)^{109m,g}$Pd was determined for the first time. The values of the isomeric yields obtained in [8] are slightly higher than those of other studies. It is possible that, at high energies, the isomeric ratio increases.

The excitation functions of the (γ, n)-reactions were obtained from the experimental isomer ratios d and the total cross-sections of the photoneutron reaction σ_n [11]. The spectrum of brake photons was calculated using the GEANT4 program [12]. The cross-section was calculated by the Penfold–Liss method with a step of 1 MeV [2, 7, 13].

The experimental dependence of the cross-sections of the reaction ^{110}Pd$(\gamma, n)^{109m,g}$Pd on the boundary energy of bremsstrahlung quanta was approximated by the Lorentz function whose parameters (the position of the maximum of the cross-section E_m, the value of the cross-section at the maximum σ_m, and the width of the distribution at half its height Γ) were determined by the method of least squares from the set of experimental values. The approximation parameters and the integral reaction cross- sections are given in Table 3 (σ_{int} is the integral cross-section for the reaction, and E_h is the upper limit of integration). The errors are estimated from the statistics of the registered reports. The isomer ratio of the reaction cross-sections is $r = \sigma_m/\sigma_n = 0.057 \pm 0.006$ or $r = \sigma_m/\sigma_g = 0.063 \pm 0.006$. In Fig. 2, we show the energy dependence of the ^{110}Pd$(\gamma, n)^{109m}$Pd reaction cross-section.

To evaluate and compare the experimental results, we calculated the reaction cross-sections using the TALYS-1.6 software package [15]. The results of the theoretical calculations are also given in Table 3. As can be seen in Table 3, the value of the cross-section at the maximum σ_m and the width of the distribution at half its height Γ agree with each other within the error of the measurement. The energy position

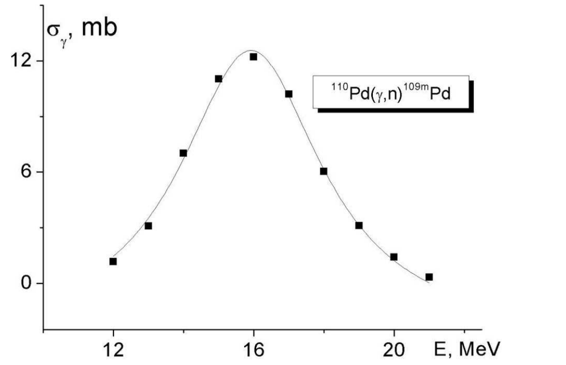

Fig. 2. The cross-section of the reaction ^{110}Pd$(\gamma, n)^{109m}$Pd

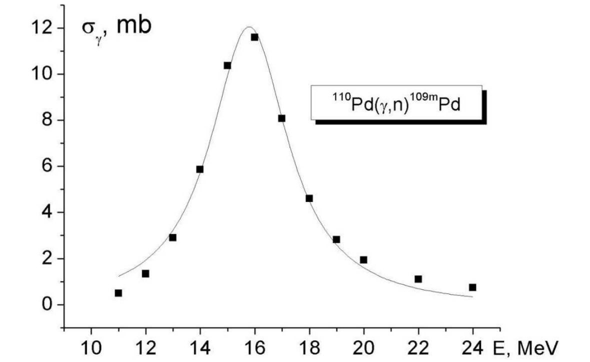

Fig. 3. The cross-section of the reaction ^{110}Pd$(\gamma, n)^{109m}$Pd (TALYS-1.6)

Table 2. **Isomeric yield ratios of (γ, n)-type reactions on nuclei of ^{110}Pd**

$E_{\gamma\max}$, MeV	Y_m/Y_g	Reference
18.5	0.068 ± 0.005	[5]
20.5	0.072 ± 0.006	[5]
25	0.060 ± 0.007	[6]
18.0	0.065 ± 0.0039	[7]
18.5	0.0665 ± 0.0039	[7]
25	0.065 ± 0.003	This work
30	0.063 ± 0.003	” ”
50	0.1061 ± 0.0080	[8]
60	0.1160 ± 0.0084	[8]
70	0.1191 ± 0.0082	[8]

Table 3. **cross-section of the reaction ^{110}Pd(γ, n)^{109m,g}Pd**

Reaction	$E_{\rm m}$, MeV	Γ, MeV	σ_m, mb	$\sigma_{\rm int}$, MeV · mb	E_h, MeV	Reference
^{110}Pd$(\gamma, xn)^{109\rm tot}$Pd	17.8	8	219	1651	21.3	[14]
^{110}Pd$(\gamma, n)^{109}$Pd	15.9	5	201	1111	21.3	[14]
^{110}Pd$(\gamma, n)^{109m}$Pd	15.8 ± 0.1	6.0 ± 0.5	16 ± 3	–	–	[7]
^{110}Pd$(\gamma, n)^{109m}$Pd *	15.8 ± 0.1	3.5 ± 0.3	12.1	70 ± 5	21	This work
^{110}Pd$(\gamma, n)^{109m}$Pd	15.9 ± 0.1	4.9 ± 0.3	13 ± 2	120 ± 11	21	” ”

*Calculations were executed by the TALYS-1.6 program.

Table 4. **Cross-section of the reaction ^{110}Pd(n,2n)^{109m,g}Pd**

E_n, MeV	σ_m, mb	σ_g, mb	Reference
14.0 *	490	1067	This work
14.5 *	510	1068	” ”
14.1	576 ± 50	1402 ± 70	” ”
14.1	415 ± 25	1267 ± 65	[17]
14.2	–	1650 ± 105	[18]
14.8	551 ± 12	–	[19]
14.6	510 ± 35	–	[20]

*Calculation of sections was carried out according to the TALYS-1.6 program.

of the maximum of the cross-section of the reaction ^{110}Pd$(\gamma, n)^{109m,g}$Pd within the margin of error coincides with the energy of the giant dipole resonance ^{110}Pd determined from the empiric ratio which is 15.7 MeV. In Fig. 3, we present the energy dependence of the ^{110}Pd$(\gamma, n)^{109m}$Pd reaction cross-section obtained with the TALYS-1.6 software package. In [8], experimental results were obtained in the energy interval 10–18 MeV. The region of the giant dipole resonance is not completely covered. So, it is difficult to estimate the resonance parameters.

In the case of the reaction $(n, 2n)$, the cross-sections for the formation of the isomeric and ground states and their isomeric ratios σ_m/σ_g were determined. To obtain the absolute values of the cross-sections of the ground and isomeric states, spme methods were used to compare the yields of the test and monitor reactions. As a monitor reaction, we used ^{27}Al (n, α) ^{24}Na ($T_{1/2} = 15$ h, $E_\gamma = 1368$ keV), whose cross- section is $\sigma_m = 121.57\pm0.57$ mb at $E_n = 14.1$ MeV [16]. When determining the cross-sections, the statistical error of the counts in the photopeak of the measured γ-line, the error in determining the cross-section of the monitor reaction, the efficiency of recording γ-radiation and the absorption of gamma rays were taken into account. The isomeric ratios of the cross-sections σ_m/σ_g were calculated according to formula (1).

In Table 4, we give the results obtained for the $(n, 2n)$ reaction on the ^{110}Pd nucleus. As can be seen from this table, our results agree with the data of other studies within the limits of measurement errors. The results of the measurements given in Table. 2 indicate that the relative probability of the isomer excitation in the case of a $(n, 2n)$-type reaction is several times higher than in the reaction (γ, n). This is probably due to the moment introduced in the nucleus, which is larger in the case of the $(n, 2n)$ reaction than in photonuclear reactions. The isomer ratio of the reaction cross-sections is $r = \sigma_m/\sigma_g = 0.41\pm0.03$.

From the analysis of data given in Tables 2 and 3, it follows that experimental studies of the excitation of isomeric states in photonuclear reactions of the type (γ, n) were performed mainly in the energy range 10–25 MeV, i.e. in the region of the giant dipole resonance. We note that, in the energy region above the giant resonance, the energy dependence of isomeric ratios has been little studied. Thus, the present work allows one to obtain information on the density of nuclear levels and the contribution of direct processes to the mechanism of photonuclear reactions in the given energy region.

4. Conclusions

In conclusion, we would like to say that the isomeric ratios obtained in this work for the photonuclear reaction ^{110}Pd$(\gamma, n)^{109m,g}$Pd in the energy interval 21–35 MeV are new results. These results supplement the previously obtained data [7] and form a single picture of the energy dependence of the isomeric ratios of the reaction yields in the energy interval 9–35 MeV.

The obtained energy dependence of the isomeric ratio of the yields and cross-sections of the reactions ^{110}Pd$(\gamma, n)^{109m,g}$Pd and ^{110}Pd$(n, 2n)^{109m,g}$Pd can be used to study the mechanism of nuclear reactions and to develop methods for gamma and neutron activation analysis.

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ІЗОМЕРИЧНІ ВІДНОШЕННЯ
^{109m,g}Pd В РЕАКЦІЯХ (γ, n) ТА $(n, 2n)$

Розглядається метод індукованої активності досліджуваних поперечних перерізів збудження ізомерних станів в реакціях ^{110}Pd$(\gamma, n)^{109m,g}$Pd і ^{110}Pd $(n, 2n)^{109m,g}$Pd в енергетичному діапазоні 12–35 МеВ. Результати експерименту порівнюються з розрахунками, проведеними за допомогою програмного пакета TALYS-1.6.

Ключові слова: ізомерні відношення, гальмівне випромінювання, радіоактивність, переріз, активність, ізомер, ядро, ядерна реакція.