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Excitation of Isomeric States in Reactions (γ,n) and (n,2n) on ^{110}Pd Nucleus

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

***Index Terms*— nuclear reactions, isomeric ratios, bremsstrahlung, radioactivity, cross section, activity, isomer, nucleus, nuclear reaction.**

I. Introduction

The study of isomeric ratios, i.e. relative probabilities of excitation of isomeric and ground states of a finite nucleus in nuclear reactions makes it possible to clarify the nature of the spin dependence of the density of nuclear levels and to better understand the mechanism of the reactions [1]. In addition, these data are necessary for applications of the physics of photonuclear reactions [2].

In this paper, the energy dependence of the isomeric ratio of the yields of reactions of the type (γ,n) on the ^{110}Pd nucleus in the energy range 12-35 MeV in steps of 1 MeV was studied by the induced-activity method. The cross sections for the formation of isomeric $^{109m,\ g}$Pd states in reactions of the type (γ,n) and (n, 2n) on the ^{110}Pd nucleus are determined.

Relative probabilities of excitation, i.e. the isomeric ratios of the yields and reaction cross sections of ^{110}Pd(γ,n)^{109m,g}Pd are studied mainly in the giant dipole resonance region. In the energy region above 24 MeV such studies were not carried out in practice. In the case of the (n, 2n) reaction, in spite of numerous experiments at 14 MeV, very little data is available on individual measurements of the cross sections of the isomeric and ground levels.

II. Experimental procedure

Experiments on the reaction (γ, n) were carried out on a bremsstrahlung γ-beam of the betatron SB-50 in the energy range 10-35 MeV in steps of 1 MeV. Temporary modes, i.e. the time of irradiation, pauses and measurements were chosen in accordance with the half-life of the radionuclides formed. Palladium is used as a target in a natural mixture of isotopes. To increase the dose rate, irradiation was carried out inside the accelerator chamber of the high-current betatron SB-50 at a distance of 12 cm from the tungsten-braking target, where the sample in a special container was delivered with a pneumatic conveying system of the K5-2A type. The time of delivery of the sample to the site of irradiation with a pneumotransport unit is ~ 4 s.

For a source of neutrons, use was made of the NG-150 neutron generator producing fluxes of fast neutrons with energies of about 2.4 and 14 MeV from the reactions D + d →3 He + n or T + d → α + n on deuterium and tritium targets. The resulting neutron fluxes are, respectively, about 10^8 and 10^{10} neutron/s [3]. The samples used were palladium samples of natural composition with a mass of 1-2 g in the form of tablets. Irradiation time 30-60 min. The monitoring of the neutron flux was accomplished with the aid of plates from aluminum of natural isotopic composition that were irradiated together with targets.

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 a Genie 2000 code package for the accumulation and treatment of gamma spectra. The energy calibration of the gamma spectrometer was performed with the aid of standard set of RSGR (reference spectrometric gamma-radiation) sources. The measurements were performed for the case of standard geometry in which the detector was calibrated in efficiency. The measurement time of the induced γ-activity of the targets is 30-60 minutes.

The population of the isomeric and ground levels was identified by γ-lines. The spectroscopic characteristics of the reaction product nuclei (γ, n) and (n, 2n), necessary for processing the measurement results, are taken from [4] and are given in Table. 1, where Iπ is the spin and parity of the level, $T_{1/2}$ is the half-life of the nucleus, I_γ is the intensity of the γ quanta of the given energy for decay, and p is the ramification coefficient of the γ transition. The isomeric ratios of the yields were calculated using the formula [5].

Table 1. Spectroscopic characteristics of nuclear reaction products (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	-

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III. Results and Discussion

The experimental results on the isomeric ratios of the yields of the (γ,n) and (n, 2n) reactions on the ^{110}Pd nucleus are shown in Fig. 1-3 and in Table. 2-4.

The absolute error of the isomeric yields is determined by the statistical error of the counts in the photopic 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 the measurements showed that the value of the isomeric yield ratios Y_m / Y_g increases from the reaction threshold to ~ 16 MeV. Perhaps this is because as the energy increases, the number of cascade γ-transitions that remove the excitation of the nucleus increases, as well as the increase in the moments carried away by quasi-direct neutrons. At an energy above ~ 16 MeV, the saturation of the Y_m/Y_g curve occurred, since a further increase in the level density probably did 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 range, the energy dependence of the isomeric ratios of the yields of the reaction ^{110}Pd(γ,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. One of the possible mechanisms leading to an increase in the values of the isomeric ratios for the nuclei under study is the contribution of direct processes whose fraction in the region above the giant resonance increases.

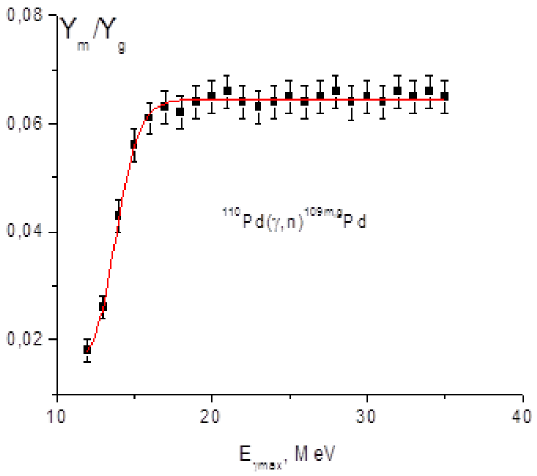

Fig. 1. Energy dependence of the isomeric yield ratios of reactions ^{110}Pd(γ,n)$^{109\,m,\,g}$Pd

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

$E_{\gamma max}$, MeV	Y_m/Y_g	Reference
18,0	0,065±0,0039	[6]
18,5	0,0665±0,0039	[6]
25	0,060±0,007	[7]
25	0,065±0,003	This work
30	0,063±0,003	This work
50	0.1061±0.0080	[8]
60	0.1160±0.0084	[8]
70	0.1191±0.0082	[8]

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 [9]. The spectrum of brake photons was calculated using the GEANT4 program [10]. The cross section was calculated by the Penfold-Liss method with a step of 1 MeV [11].

The experimental dependence of the reaction cross sections ^{110}Pd(γ,n)^{109m,g}Pd on the boundary energy of the 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 in the set experimental values. The approximation parameters and the integral reaction cross sections are given in Table 3. The errors are estimated from the statistics of the registered reports. The isomer ratio of the reaction cross sections is $r=\sigma_m/\sigma_n=0{,}057\pm0{,}006$ or $\sigma_m/\sigma_g=0{,}063\pm0{,}006$. In Fig. 2 shows the energy dependence of the ^{110}Pd(γ,n)^{109m}Pd reaction cross section.

Table 3. Cross section of the reaction ^{110}Pd (γ, n) $^{109m,\,g}$Pd

Reaction	E_m, MeV	Γ, MeV	σ_m, mb	σ_{int}, MeV·mb	E_h, MeV	Reference
^{110}Pd(γ,xn)^{109tot}Pd	17,8	8	219	1651	21,3	[12]
^{110}Pd(γ,n)^{109}Pd	15,9	5	201	1111	21,3	[12]
^{110}Pd(γ,n)^{109m}Pd	15,8±0,1	6,0±0,5	16±3	-	-	[6]
^{110}Pd(γ,n)^{109m}Pd*	15,8±0,1	3,5±0,3	12,1	69±5	24	This work
^{110}Pd(γ,n)^{109m}Pd	15,9±0,1	4,9±0,3	13±2	120±11	21	This work

Note. * Calculation of sections was carried out according to the TALYS-1.6 program. σ_{int} is the integral cross section for the reaction, and E_h is the upper limit of integration.

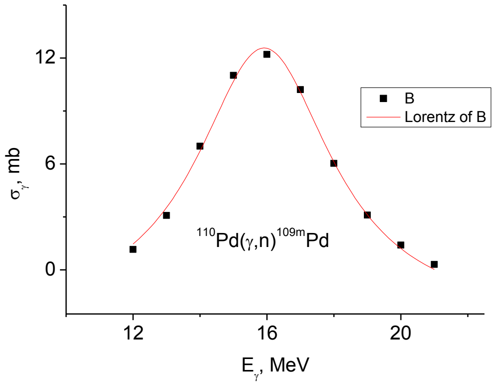

Fig.2. The reaction cross section is $^{110}Pd\ (\gamma,\ n)\ ^{109m,\ g}Pd$

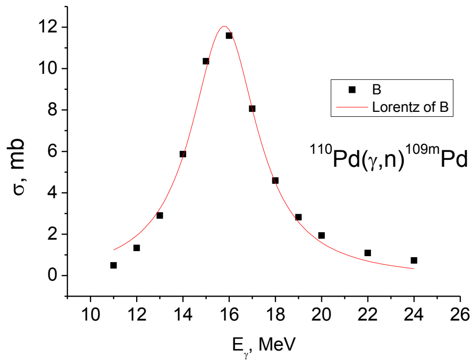

Fig.3. The reaction cross section is $^{110}Pd(\gamma,n)^{109m,g}Pd$ (TALYS-1.6).

To evaluate and compare the experimental results, we calculated the reaction cross-section using the TALYS-1.6 software package [13]. 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 σm and the width of the distribution at half its height Γ agree with each other within the error of the measurement. The energy position of the maximum of the reaction cross section $^{110}Pd(\gamma,n)^{109m,g}Pd$ within the margin of error coincides with the energy of the giant dipole resonance ^{110}Pd, determined from the empirical ratio, which is 15.7 MeV. In Fig. 3 shows the energy dependence of the $^{110}Pd(\gamma,n)^{109m,g}Pd$ reaction cross section obtained with the TALYS-1.6 software package. In [6], experimental results were obtained in the energy range 10-18 MeV. Completely does not cover the region of giant dipole resonance, so it is difficult to estimate the resonance parameters.

The isomeric cross-section ratios σ_m/σ_g were determined in the case of the reaction (n,2n). In order to obtain the absolute values of the cross sections for the ground state and for the isomeric state, use was made of methods based comparing the yields of the reaction under study and the monitoring reaction. The reaction $^{27}Al(n,\alpha)^{24}Na$ ($T_{1/2}$ =15h, E_γ = 1368 keV), whose cross section σ_m was 114 ± 6 mb at E_n =14.6 ±0.3 MeV [14], was taken for a monitoring reaction.
In 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 and the detection efficiency of the γ radiation were taken into account. Calculations of isomeric ratios of cross sections were carried out according to the formula [5].

In Table. 4 shows 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. 4 indicate that the relative probability of 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 are larger in the case of the (n, 2n) reaction than in photonuclear reactions. The isomer ratio of the reaction cross sections is $r=\sigma_m/\sigma_n=0{,}41\pm0{,}03$.

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

Reaction	E_n, MeV	σ_m, mb	σ_g, mb	Reference
$^{110}Pd(\gamma,n)^{109m,g}Pd$	14,0*	490	1067	This work
	14,5*	510	1068	This work
	14,1	576±50	1405±70	This work
	14,2	-	1650±105	[15]
	14,6	-	2510±110	[16]
	14,8	551±12	-	[17]
	14,6	510±35	-	[18]

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

From the data analysis, given in Table. 2 and 3 it follows that experimental studies of the excitation of isomeric states in photonuclear reactions of the type (γ,n) were carried out in the main in the energy range 10-25 MeV, i.e. in the region of giant dipole resonance. In the energy region above the giant resonance, the energy dependence of isomeric ratios has been little studied. Thanks to these studies it is possible to obtain information on the density of nuclear levels and the contribution of direct processes to the mechanism of photonuclear reactions in a given energy region.

The obtained energy dependence of the isomeric ratio of the yields of the $^{110}Pd(\gamma,n)^{109m,g}Pd$ and $^{110}Pd(\gamma,n)^{109m,g}Pd$ reactions can be used to study the mechanism of photonuclear reactions and the development of gamma and neutron activation analysis techniques.

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