EXCITATION CROSS-SECTIONS OF THE 11/2$^-$ ISOMERIC STATES OF THE ^{109}Pd AND ^{111}Cd NUCLEI FOR (γ, n) REACTIONS IN THE GAMMA-QUANTUM ENERGY RANGE OF 8–18 MeV

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The excitation cross-sections of isomeric states for the ^{110}Pd(γ,n)^{109m,g}Pd and ^{112}Cd(γ,n)^{111m}Cd reactions have been studied within the gamma-quantum energy range of 8–18 MeV. The isomeric ratio values obtained experimentally are compared with the results of calculations made in the framework of the cascade-evaporation model.

Nuclear reactions stimulated by low- and medium-energy gamma-quanta are an important source of information concerning both the structure of atomic nuclei and the mechanisms of nuclear reactions. One of the directions in studying photonuclear reactions involves the measurements of the probability of the formation of daughter nuclei in the selected quantum states. This direction includes the research of the isomeric state excitation in photoneutron reactions as well.

This work aimed at finding the cross-sections of the ^{110}Pd(γ,n)^{109m,g}Pd and ^{112}Cd(γ,n)^{111m}Cd reactions and the corresponding isomeric ratios, i.e. the ratios between the cross-sections of reactions with the formation of a daughter nucleus in the isomeric or ground state, at excitation energies lying in the range of giant dipole resonance (GDR). For both nuclei under consideration, the isomeric state is a single-quasiparticle one with $J^\pi = 11/2^-$ and is determined by the $1h_{11/2}$ shell, while the ground states are characterized by the $3s_{1/2}$ and $2d_{5/2}$ shells. Regular studies concerning the excitation of isomeric states of the ^{109}Pd and ^{111}Cd nuclei and its dependence on the gamma-quantum energy have not been carried out till now [1]. Only the isomeric ratios at a few points from the high-energy interval have been determined [2, 3].

The researches were carried out using a beam of bremsstrahlung gamma-quanta from an M-30 microtron at the Institute of Electron Physics of the National Academy of Sciences of Ukraine. A beam of accelerated electrons extracted from the accelerator fell onto a braking tantalic target 1 mm in thickness. The bremsstrahlung beam of gamma-quanta formed by a collimator passed through a thin-walled ionization chamber and hit the specimen under investigation. A secondary emission monitor was used to control the beam of accelerated electrons. The amplitude of the magnetic field in the microtron and, correspondingly, the energy of accelerated electrons were checked by nuclear magnetic resonance methods. The targets to be studied were metal disks 20 mm in diameter and 1.5 g in weight, made up of either enriched (98%) cadmium-112 or palladium with the natural isotope content. The occupation of isomeric levels was identified by the 245-keV gamma line for cadmium and the 188-keV one for palladium. The spectroscopic characteristics of the investigated targets – the spin parity J^π in the ground and isomeric states, the half-life periods $T_{1/2}$ of those states, the energy of the registered gamma-transition E, the number of gamma-quanta per one decay I, and the (γ,n)-reaction threshold B_n for the parent nucleus – were taken from works [4, 5] (see Table).

The induced activity was measured with the help of a gamma-spectrometer based on a DGDK-100 semiconductor detector with a resolution of 3.5 keV for the 1.173-MeV gamma-line of cobalt-60. A section of the experimental gamma-spectrum given by a palladium target irradiated for 10 min at the energy of gamma-quanta $E_{\gamma\,\max} = 12$ MeV is exhibited in Fig. 1. In the figure, n is the number of an analyzer channel, and N is the number of pulses in this channel. The measurements were carried out in the energy interval $8 \div 18$ MeV with the step $\Delta E = 0.5$ MeV. The cross-sections for the reactions ^{110}Pd$(\gamma, n)^{109m,g}$Pd and ^{112}Cd(γ,n)^{111m}Cd were determined in two independent experiments.

Spectroscopic characteristics of nuclei

Nucleus	J^π	$T_{1/2}$	E_γ , MeV	I%	B_n, MeV
^{109m}Pd	$11/2^-$	4.69 min	0.188	56	
^{109g}Pd	$5/2^+$	13.70 h	0.088	3.7	8.8
^{111m}Cd	$11/2^-$	48.54 min	0.245	94	9.4

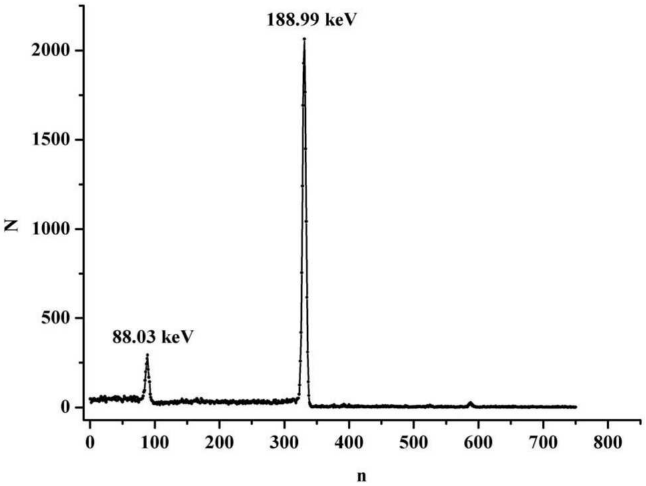

Fig. 1. A part of the experimental gamma-spectrum emitted by the irradiated palladium target

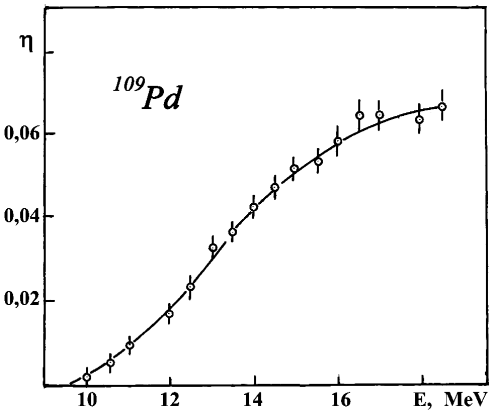

Fig. 2. Experimental isomeric ratios for a ^{109}Pd nucleus obtained in the (γ,n) reaction

Since the ground state of a ^{109}Pd nucleus is unstable, it was the isomeric yield ratio $d = Y_m/Y_g$ [6] that was measured directly in the experiment for the reaction ^{110}Pd(γ,n)^{109m,g}Pd. Here, Y_m and Y_g are the excitation yields of the isomeric and ground states, respectively. But, since the half-life period of the isomeric state is two orders of magnitude shorter than that of the ground state, we split the measurement routine for the induced activity of palladium specimens into two stages in order to obtain higher accuracy in the determination of the isomeric ratio. First, after the target having been irradiated, a short-term (for $T = 10$ min) measurement of the activity was made (the decay of the ^{109m}Pd isomeric state was mainly measured). Then, after the target having been cooled for 40–60 min, a long-term (for 1–2 h) measurement procedure for the ground state decay was carried out. The isomeric state decays almost completely into the ground one within the cooling time interval; therefore, we actually measured the total yield of the (γ,n) reaction, $Y_n = Y_m + Y_g$. The isomeric ratio was calculated by the formula

$$\eta = \frac{Y_m}{Y_n} = \frac{Y_m}{Y_m + Y_n} = \frac{1}{1 + 1/d} = C\frac{N_m}{N_g}\frac{\lambda_m \varphi_g f_g}{\lambda_g \varphi_m f_m}, \qquad (1)$$

where $\varphi_{m,g} = \varsigma_{m,g}\kappa_{m,g}\alpha_{m,g}$; $\varsigma_{m,g}$ are the detection photoefficiencies for the gamma-lines corresponding to the isomeric- and ground-state decays; $\kappa_{m,g}$ – the target's self-absorption coefficients of the lines; $\alpha_{m,g}$ – the line intensities; $N_{m,g}$ – the numbers of pulses in the photopeaks of the isomeric and ground states;

$$f_{m,g} = [1 - \exp(-\lambda_{m,g}t_{\rm irr})]\exp(-\lambda_{m,g}t_{\rm cool})\times [1 - \exp(-\lambda_{m,g}t_{\rm meas})]$$

are the time functions; $\lambda_{m,g}$ – the decay constants; $t_{\rm irr}$, $t_{\rm cool}$, and $t_{\rm meas}$ are the irradiation, cooling, and measurement times, respectively; $c = c_1c_2$ is the coefficient which makes allowance for the possible missing of pulses and their overlapping. The experimental isomeric yield ratios η obtained in such a way for the ^{110}Pd(γ,n)^{109m,g}Pd reaction are plotted in Fig. 2.

The solid curve in Fig. 2 demonstrates the result of the approximation of our experimental data by the Boltzmann curve

$$y = A + (B - A)/[1 + \exp(\frac{E - E_0}{\Delta E_1})].$$

Here, A, B, E_0, and ΔE_1 are fitting parameters. The approximation was carried out by the least squares method. The best agreement was reached for the following parameter values: $A = 0.06869 \pm 0.00137$, $B = 0.00698 \pm 0.00337$, $E_0 = (13.012 \pm 0.146)$ MeV, and $\Delta E_1 = (1.534 \pm 0.137)$ MeV.

The experimental value for the effective threshold of the reaction ^{110}Pd(γ,n)^{109m}Pd turned out equal to (9.6 ± 0.15) MeV, which is by 0.8 MeV higher than the threshold value for the (γ,n) reaction. For palladium-109, the dependence of the isomeric ratio η on the energy $E_{\gamma\,\rm max}$ rises quickly above the reaction threshold and saturates above 18 MeV.

While analyzing the schemes of low-lying levels of a ^{109}Pd nucleus [4], it becomes evident that the first state, which could have been an activation level for the metastable state with $J^\pi = 11/2^-$, is a level with the energy $E = 287.2$ keV and the spin parity $J^\pi = 9/2^-$,

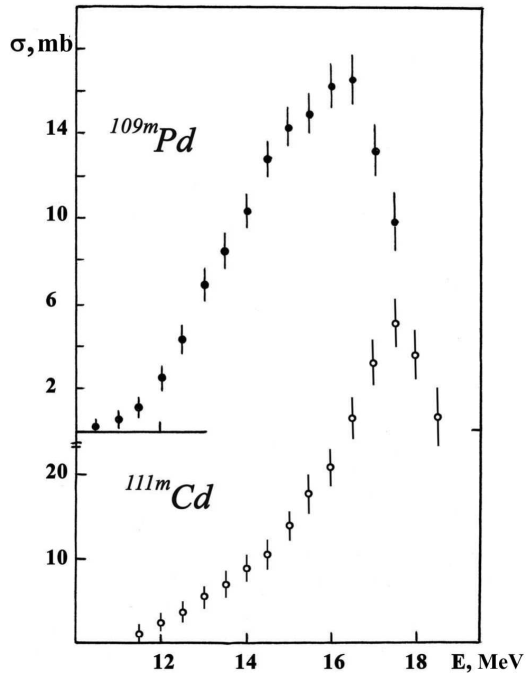

Fig. 3. Excitation cross-sections of the metastable state of ^{109}Pd and ^{111}Cd nuclei

the deexcitations of which occupy the isomer with probability 1. However, this phenomenon does not occur at such low energies, because, for this level to be occupied, neutrons must take away the moment $l = 3$; but such neutrons, according to the optical model [7], can comprise only 1–2% of their total amount, provided that their energy is about 0.7 MeV.

Most likely, the states with $E = 604.5$ keV, $J^\pi = 5/2^-$ and $E = 941.4$ keV, $J^\pi = 3/2^-$ can serve as activation ones. The former state occupies the levels with $E = 287.2$ keV and $J^\pi = 9/2^-$ through $E2$-transitions, with a probability of 2.6% with respect to the basic transition; the latter one occupies the levels with $E = 604.5$ keV through $(M1 + E2)$-transition with a high probability.

Concerning the ^{112}Cd(γ,n)^{111m}Cd reaction, the first activation level could have been a state with $E = 680.4$ keV and $J^\pi = 9/2^-$ [8], but, according to the aforementioned reasons, it cannot. Somewhat higher, a level with $E = 704.9$ keV and $J^\pi = 7/2^+$, which occupies the activation level with $J^\pi = 9/2^-$, and a level with $E = 831.2$ keV and $J^\pi = 7/2^-$, which occupies the isomeric state with $E = 396.2$ keV and $J^\pi = 11/2^-$ with probability 1, are located. In the energy range $E = 1151 \div 1326$ keV, a group of levels with relatively low spins $J^\pi = 5/2^- \div 7/2^+$, which can be occupied at the emission of low-energy neutrons with momenta $l = 1 \div 2$, is located. Those levels decay with a high probability (of about 100%) into the isomeric state through the intermediate levels at 680 and 831 keV. Probably, it is the presence of those levels that determines the effective excitation threshold for the isomeric $11/2^-$-state of ^{111}Cd. Thus, it is evident that the activation levels for a ^{111m}Cd nucleus are located several hundred kiloelectronvolts higher than those for a ^{109m}Pd one, which probably results in the increase of the $(\gamma,\text{n})^m$-reaction threshold for cadmium. The effective experimental threshold for the ^{112}Cd(γ,n)^{111m}Cd reaction is (10.8 ± 0.25) MeV, i.e. it exceeds the threshold of the (γ,n) reactions for a ^{112}Cd nucleus by 1.4 MeV.

The ground state of a ^{111}Cd nucleus is stable, so that relation (1) cannot be used for the determination of isomeric ratios in the reaction ^{112}Cd(γ,n)^{111m}Cd. Therefore, in order to determine the cross-sections of this reaction, we first measured the curves of the excitation yield for the isomeric state Y_m:

$$Y_m = k \int_{E_{\text{th}}}^{E_{\gamma\max}} \sigma_m(E)\Phi(E, E_{\gamma\max})dE, \qquad (2)$$

where $\Phi(E, E_{\gamma\max})$ is the bremsstrahlung spectrum of gamma-quanta, σ_m is the cross-section of the $(\gamma,\text{n})^m$ reaction, E_{th} the threshold energy of the (γ,n) reaction, $E_{\gamma\max}$ the maximum energy of the gamma-spectrum, and k the normalizing factor that depends on the monitor type. The flux of gamma-quanta was measured making use of a thick-walled aluminum absolute chamber [9]. To calculate the cross-section σ_m from the yield Y_m curves, we used the Penfold–Leiss method [10]. The calculations were carried out with the step $\Delta E = 1$ MeV. The experimental values of the isomeric ratio η measured by us (solid curve in Fig. 2) and the values for the total cross-section of the (γ,n) reactions with palladium [5] were applied to calculate the cross-section of the reaction ^{110}Pd(γ,n)^{109m}Pd as well.

The experimentally obtained values for the cross-sections of palladium and cadmium are depicted in Fig. 3. Dark and light points correspond to the cross-sections of the ^{110}Pd(γ,n)^{109m}Pd and ^{112}Cd(γ,n)^{111m}Cd reactions, respectively. These curves have a single maximum of (16.6 ± 1.2) or (38 ± 2) mb located at an energy of 16.5 or 17.5 MeV, respectively. A comparison of the obtained cross-sections with the total cross-section of the (γ,n) reaction shows that their maxima are shifted toward higher energies. The fact that the cross-section maxima of the reactions ^{110}Pd(γ,n)^{109m}Pd and

^{112}Cd(γ,n)^{111m}Cd are shifted with respect to each other can be explained by different threshold values for $(\gamma, 2\text{n})$ reactions: 15 MeV for ^{110}Pd and 16.4 MeV for ^{112}Cd.

The values obtained for the cross-sections σ_m of the $(\gamma,\text{n})^m$ reactions and the values of the total cross-sections σ_n of the (γ,n) reaction allowed us to estimate the experimental isomeric ratio $r = \sigma_m/\sigma_n$ between them. We determined the quantity r in the vicinity of the maxima of the curves $\sigma_n(E)$, i.e. where the relative determination error for r is minimal and amounts to 15%. The obtained values for the isomeric ratio σ_m/σ_n at energies of 15.5, 16, and 16.5 MeV are 0.08, 0.097, and 0.135, respectively, for cadmium-111; and 0.075, 0.081, and 0.09, respectively, for palladium-109.

We calculated the isomeric ratios in the framework of the cascade-evaporation model [12,13]. In so doing, we supposed that a dipole gamma-quantum is absorbed, and the states of a giant dipole resonance, which afterwards decay and emit a neutron, are excited. In their turn, the excited states of the daughter nucleus with the spin parity (J_f, π_f) also decay into a cascade of dipole gamma-quanta.

The probability of the formation of a compound nucleus with the spin parity (J_c, π_c) was considered proportional to the density of levels with the corresponding characteristics. The density of levels was evaluated by the Bethe–Bloch formula [14,15]

$$\rho(U,J) = \frac{2J+1}{24\sqrt{2}a^{1/4}U^{5/4}\sigma^3}\exp\left(2\sqrt{aU} - \frac{(J+1/2)^2}{2\sigma^2}\right),$$

where σ is the spin cut-off parameter, A the mass number, α the level density parameter, and U the excitation energy; we adopted the effective energy to play the role of the latter [15].

The reduced probability P for a compound nucleus to emit a neutron with the momentum l and the energy n, followed by the transition of the former into the daughter nucleus state (J_f, π_f), was calculated by the formula

$$P(J_c,\pi_c;J_f,\pi_f) = \beta\rho(J_f)\sum_{S=|J_f-s|}^{J_f+s}\sum_{l=|J_c-S|}^{J_c+S} T_l(\epsilon)\omega_l(\pi_c,\pi_f),$$

where β is a constant, s the spin of the emitted neutron, $T_l(\epsilon)$ the barrier penetrance [7], $\omega_l(\pi_c,\pi_f) = [1 + (-1)^l\pi_c\pi_f]/2$ is the factor that takes the parity of states into account, and ϵ is the neutron energy.

The procedure of calculations was described in work [13] in more details. The corresponding calculations give the overestimated values for the isomeric ratios. An agreement was attained by fixing the spin cut-off parameter σ at a level of $2.5 \div 3$. For cadmium-111, the presence of an intermediate level with $J^\pi = 5/2^+$ between the isomeric level with $J^\pi = 11/2^-$ and the ground one with $J^\pi = 1/2^+$ was taken into account. This circumstance makes ^{111}Cd and ^{109}Pd nuclei to be practically identical with respect to the calculation of their isomeric ratios.

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ПЕРЕРІЗИ ЗБУДЖЕННЯ ІЗОМЕРНОГО СТАНУ 11/2$^-$ ЯДЕР ^{109}Pd ТА ^{111}Cd В РЕАКЦІЯХ (γ, n) У ДІАПАЗОНІ ЕНЕРГІЙ γ-КВАНТІВ 8–18 MeB

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Резюме

У діапазоні енергій гамма-квантів 8–18 МеВ досліджено перерізи збудження ізомерних станів в реакціях ^{110}Pd(γ,n)^{109m,g}Pd і ^{112}Cd(γ,n)^{111m}Cd. Одержані експериментальні ізомерні відношення порівнюються з розрахунками в рамках каскадно-випарювальної моделі.