CROSS SECTION OF THE $(\gamma, n)^m$ REACTION FOR ^{116}Cd NUCLEUS IN THE REGION OF GIANT E1-RESONANCE

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The isomeric yield ratios and the cross section of the reaction ^{116}Cd$(\gamma, n)^{115m,g}$Cd have been studied as functions of the energy of gamma quanta. The obtained experimental results have been compared with calculations performed with the use of the TALYS-1.0 software.

The principal peculiarity in the cross sections of gamma quanta absorption by nuclei is the giant dipole resonance (GDR). In the case of medium and heavy nuclei, it manifests itself as a pronounced maximum 4–8 MeV in width lying at energies of 14–20 MeV. Experimental investigations of various properties of the GDR, including the processes of its decay, have played a crucial role in the formation of modern ideas of collective excitations in nuclei. Investigations of the giant dipole resonance for the case of cadmium isotopes are till now incomplete. Among them, there are the studies of the cross sections of total gamma absorption performed by summing partial reactions at targets of the natural isotopic composition [1] and the researches of the cross section of the reaction ^{112}Cd$(\gamma, n)^{111m}$Cd [2].

Systematic investigations of partial channels of the GDR decay for ^{116}Cd nucleus are also absent. There exist several works dealing with the study of the isomeric yield ratios $d = Y_m/Y_g$ for the reaction ^{116}Cd$(\gamma, n)^{115m,g}$Cd at separate energy points above the GDR maximum [3, 4] (here, Y_m and Y_g stand for the excitation yields of the isomeric and ground states, respectively).

This work deals with the investigation of the isomeric ratios and the cross section of the reaction ^{116}Cd$(\gamma, n)^{115m,g}$Cd depending on the energy of gamma quanta. The ground and low-lying excited states of the daughter nucleus ^{115}Cd are formed by the $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, and $1h_{11/2}$ subshells. Moreover, the $1h_{11/2}$ subshell forms the isomeric state. The experiments were carried out at the Institute of Electron Physics of the National Academy of Sciences of Ukraine with a beam of bremsstrahlung gamma quanta from an electron accelerator (M-30 microtron) in the energy range 8–20 MeV with the step $\Delta E = 0.5$ MeV. An electron beam extracted from the microtron fell at a bremsstrahlung tantalum target 0.5 mm in thickness. The beam current was controlled with the help of a secondary emission monitor calibrated by a Faraday cup. The energy of accelerated electrons was determined by the magnitude of the guiding magnetic field controlled with the use of the nuclear magnetic resonance method. The investigated cadmium targets with the natural isotopic composition were metal plates 30 mm in diameter and 1.5 g in weight. The spectroscopic characteristics of the studied nuclei, namely the spin parity of the ground and isomeric states J^π, their half-lives $T_{1/2}$, the energy of the registered gamma transition E_γ, the number of gamma quanta per one decay event I, and the threshold of the (γ, n) reaction for the mother nucleus B_n were taken from [5, 6] and are listed in Table. The population of the isomeric state of ^{115m}Cd was identified using the 935-keV line.

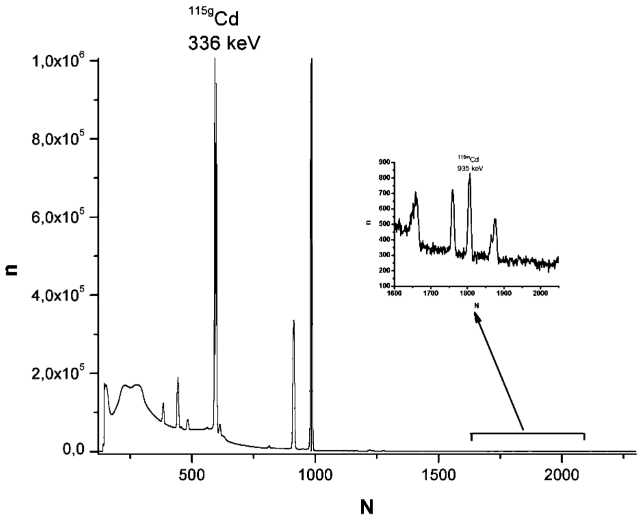

Fig. 1. Section of the experimental gamma spectrum from the irradiated Cd target

The ^{116}Cd$(\gamma,n)^{115m,g}$Cd reaction was studied using the activation technique. The gamma activity induced after the irradiation of a target was measured with the help of a spectrometer based on a Ge(Li) detector with a volume of 100 cm^3 and a resolution of ≈ 3.0 keV for the 1.173-MeV line of cobalt-60. A section of the experimental gamma spectrum from the cadmium target irradiated at $E_{\gamma_{\max}} = 17$ MeV is shown in Fig. 1 (the irradiation time amounted to 2 h, the cooling and measurement times were equal to 24 h). Here, N stands for the number of an analyzer channel, and n is the number of pulses in it.

A special attention was paid to studying the natural background spectra. The applied methods of passive protection did not allow us to completely suppress the 934.8-keV line in the background spectrum emitted by the ^{214}Bi isotope present in the ^{238}U radioactive series. Therefore, this fact should be taken into account in days-long measurements of the decay spectra of ^{115m}Cd.

The ground state of ^{115g}Cd is unstable. That is why the isomeric yield ratio $d = Y_m/Y_g$ for the reaction ^{116}Cd$(\gamma,n)^{115m,g}$Cd can be directly determined by experiment. The isomeric ratio was calculated using the formula [7]

$$d(E_{\gamma_{\max}}) = \frac{Y_m}{Y_n} = \frac{Y_m}{Y_m+Y_n} = \frac{1}{1+1/d} =$$

$$= C\frac{N_m}{N_g}\frac{\lambda_m\varphi_g f_g}{\lambda_g\varphi_m f_m}, \qquad (1)$$

where $\lambda_{m,g}$ are the decay constants for the isomeric and ground states, $N_{m,g}$ are the numbers of registered pulses of the corresponding states, C stands for the coefficient that takes the missing and the overlapping of pulses into account, $\varphi_{m,g} = \varsigma_{m,g}\kappa_{m,g}\alpha_{m,g}$, $\varsigma_{m,g}$ are the photoefficiencies of detection of gamma lines of the isomeric- and ground-state decays, $\kappa_{m,g}$ are the self-absorption coefficients of the target lines, $\alpha_{m,g}$ are the line intensities, p is the branching factor, $t_{\rm irr}$, $t_{\rm cool}$, and $t_{\rm meas}$ are the times of irradiation, cooling, and measurement, respectively, and $f_{m,g}$ is the time function: $f_{m,g} = [1-\exp(-\lambda_{m,g}t_{\rm irr})]\exp(-\lambda_{m,g}t_{\rm cool})$. The standard time of measuring one value of the isomeric ratio amounted to 24 h. The isomeric yield ratios d obtained in such a way are plotted by points in Fig. 2. The marked errors are mean square. One can see from the figure that, above the threshold of the $(\gamma,n)^m$ reaction, the isomeric ratio d for ^{115}Cd quickly grows as a function of the energy $E_{\gamma_{\max}}$ and reaches the saturation in the region of 20 MeV. The solid curve in Fig. 2 shows the result of approximating the experimental data by the Boltzmann curve,

$$y = A + (B-A)/[1+\exp((E-E_0)/\Delta E)], \qquad (2)$$

where A, B, E_0, and ΔE are some parameters. The approximation was carried out within the least square method. The optimal fitting was reached at the following values of the parameters: $A = 0.16555 \pm 0.01183$, $B = -0.03714 \pm 0.02003$, $E_0 = 13.80461 \pm 0.399$, and $\Delta E = 2.43724 \pm 0.47554$.

As follows from the analysis of spectroscopic data [6], the states that could serve as the first activation levels for the isomeric state of ^{115}Cd with $J^\pi = 11/2^-$ are that with $E = 393.9$ keV and $J^\pi = 7/2^-$ and that with $E = 417.2$ keV and $J^\pi = 9/2^-$. After the decay, these levels populate the isomeric state with probability 100%. However, in the near-threshold region of the photo-neutron reaction, the level with $J^\pi = 9/2^-$ will not be populated most probably, because, in this case, outgoing neutrons must take away the moment not less than $l = 4$. According to the results of calculations [8], the escape of such neutrons numbering 1–2% is possible only under the condition that their energy is equal to 1.5 MeV. To populate the level with $J^\pi = 7/2^-$, neutrons must take away the moment $l = 2$. To provide

Spectroscopic characteristics of ^{115}Cd nucleus

Nucleus	J^π	$T_{1/2}$	E_γ (MeV)	I (%)	B_n (MeV)
^{115g}Cd	$1/2^+$	53.46 h	0.336	47	8.7
^{116m}Cd	$11/2^-$	44.6 days	0.935	1.95	–

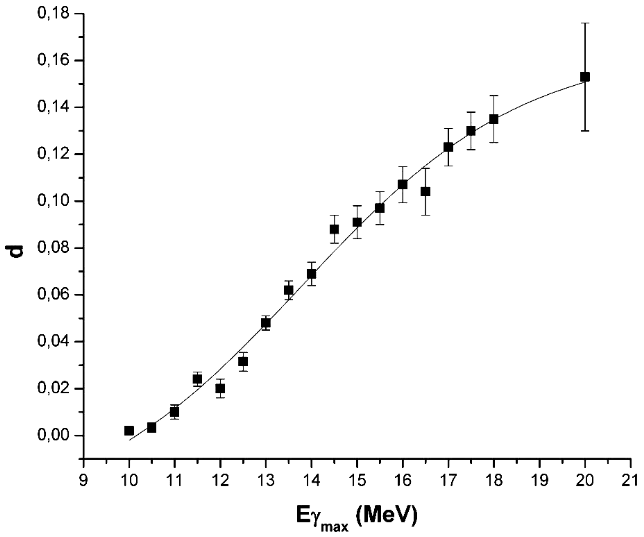

Fig. 2. Experimental isomeric ratio for the reaction $^{116}\mathrm{Cd}(\gamma, n)^{115m,g}\mathrm{Cd}$

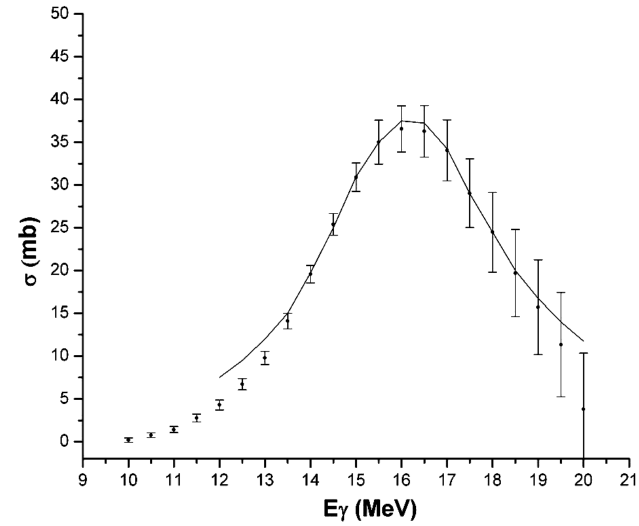

Fig. 3. Cross section of excitation of the isomeric state in the reaction $^{116}\mathrm{Cd}(\gamma, n)^{115m}\mathrm{Cd}$

the appearance of such neutrons, it is sufficient that their energy be equal to only 250–300 keV [8], which agrees with the experimental values obtained for d in the near-threshold region within error limits. Another activation state can be the level with $E = 719.9$ keV and $J^\pi = 5/2^-$, that populates the isomeric state through the levels with $E = 393.9$ keV and $E = 417.2$ keV with an almost 100% probability. Using the obtained experimental isomeric ratios d for the process $^{116}\mathrm{Cd}(\gamma, n)^{115m,g}\mathrm{Cd}$ (Fig. 2) and knowing the total cross section of the (γ, n) reaction on cadmium isotopes [1], we calculated the cross section of the reaction $^{116}\mathrm{Cd}(\gamma, n)^{115m,g}\mathrm{Cd}$ with the help of the inverse matrix method [9]. The obtained experimental cross section is plotted by points in Fig. 3. As one can see from the figure, it is a one-hump curve with a maximum at the energy $E_0 = 16.1$ MeV. The comparison of the obtained results with the total cross section of the (γ, n) reaction [1] demonstrates that the cross section of the $(\gamma, n)^m$ process is somewhat shifted toward larger energies, which is due to the form of the function $d = f(E_{\gamma_{\max}})$. The solid curve in Fig. 3 corresponds to the result of approximating the experimental cross section by the Lorentzian curve of the form

$$\sigma(E) = \sigma_0(\Gamma_0^2 E^2)/[(E^2 - E_0^2)^2 + \Gamma_0^2 E^2]. \quad (3)$$

Here, σ_0, E_0, and Γ_0 are fitting parameters. The approximation was carried out within the least square method. As a result, the following values of the parameters were obtained: $\sigma_0 = (37.85 \pm 0.93)$ mb, $E_0 = (16.13 \pm 0.041)$ MeV, and $\Gamma_0 = (4.6 \pm 0.16)$ MeV. The experimental cross section of the reaction $^{116}\mathrm{Cd}(\gamma, n)^{115m}\mathrm{Cd}$ depicted in Fig. 3 allows one to estimate the isomeric ratios of the cross sections $r = \sigma_m/\sigma_{tot}$ using the total cross section of the (γ, n) reaction. The value of r was determined in a vicinity of the cross section maximum, i.e. in the region where the relative error is minimal and approximates 16%. The isomeric ratios for ^{115}Cd obtained in such a way at energies of 15.5, 16.0, and 16.5 MeV are equal to 0.156, 0.171, and 0.184, respectively.

In order to compare the experimental data with the theoretical results, we calculated the cross section of the reaction $^{116}\mathrm{Cd}(\gamma, n)^{115m}\mathrm{Cd}$ with the use of the TALYS-1.0 software [10]. It unites the majority of up-to-date models that describe all stages of nuclear reactions, which provides a sufficiently complete and accurate description of these processes.

The calculation was performed according to the following scheme: an incident gamma quantum with energy E_γ fell at a target nucleus with the parameters (Z_i, N_i) and the spin parity (J_i, π_i), which resulted in the formation of a compound nucleus with the excitation energy E_x $(E_x = E_\gamma)$ and the spectrum of possible spins and parities (J_c, π_c). The total photoabsorption cross section σ_{tot} was calculated. The excited nucleus decayed either according to the mechanism of semidirect processes (whose portion amounts to 1–14% depending on the nature of a nucleus and the excitation energy) or according to the statistical Hauser–Feshbach mechanism [11]. The neutron emission was calculated for specific levels (bands) of a daughter nucleus with regard for the transmission coefficients T_l determined in the framework of the optical model. Moreover, at excitation energies of

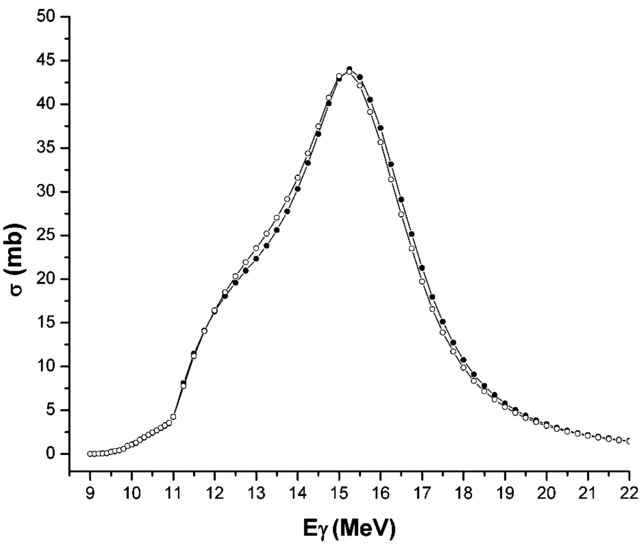

Fig. 4. Calculated cross section of excitation of the isomeric state in the reaction $^{116}\mathrm{Cd}(\gamma,n)^{115m}\mathrm{Cd}$

the daughter nucleus below 3 MeV, we used the information about spectroscopic and decay characteristics of discrete nuclear levels from the RIPL–3 database. At higher excitation energies, the spectrum was described by the model level density $\rho(E_x, J, \pi)$ and was divided into a certain number of energy bands. The decay of an excited level into a band in the continuous spectrum was calculated with the use of the effective transmission coefficients.

In our calculations, the level density of the continuous spectrum ρ was described in two ways. In the first one, we applied the energy-shifted Fermi gas model [12], while, in the second one, the nuclear level densities calculated in the framework of the combinatoric microscopic model were used [13]. The calculation results are demonstrated in Fig. 4. The data obtained using the level densities from the Fermi gas model are plotted by black circles, whereas white circles mark the results obtained with the help of the combinatoric model. The both calculations are in good agreement. From the comparison of the computation results with the experiment, it follows that the theory satisfactorily describes the experimental cross section of excitation of the isomeric state $11/2^-$ in the reaction $^{116}\mathrm{Cd}(\gamma,n)^{115m}\mathrm{Cd}$ and the position and magnitude of its maximum. An insignificant peculiarity existing in the calculated cross section in a vicinity of 12 MeV can be related to the insufficiently accurate allowance for the branching factors when considering the decay of discrete levels or to the inconsistent algorithm of matching the results obtained for the discrete and continuous spectra.

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ПЕРЕРІЗ РЕАКЦІЇ $(\gamma,n)^m$ ДЛЯ ЯДРА ^{116}Cd
В ОБЛАСТІ ГІГАНТСЬКОГО E1-РЕЗОНАНСУ

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Р е з ю м е

В області енергій гігантського дипольного резонансу досліджено залежність ізомерних відношень виходів та перерізу від енергії гамма-квантів в реакції $^{116}\mathrm{Cd}(\gamma,n)^{115m,g}\mathrm{Cd}$. Одержані експериментальні результати порівняно з розрахунками, проведеними за допомогою програмного пакета TALYS-1,0.