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Research Article

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Cross Section of Excitation of Isomer States $^{81m,g}Se$ in the Reaction (γ,n) and (n,2n)

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Abstract The method of induced activity of the investigated cross-sections of excitation of isomeric states in the reactions of $^{82}Se(\gamma,n)^{81m,g}Se$ and $^{82}Se(n,2n)^{81m,g}Se$ in the energy range 11-35 MeV. The experimental results are compared with calculations carried out using the software package TALYS-1.0.

Keywords photonuclear reactions, isomeric ratios, bremsstrahlung, selenium isotopes, radioactivity, cross section, spin, neutron, activity, isomer, nucleus, nuclear reaction

1. Introduction

An investigation of the relative probabilities of excitation of isomeric and ground states of a final nucleus in nuclear reactions has fundamental and applied values. The importance of the study of the formation of isomeric States of nuclei in nuclear reactions with different bombarding particles, which allows to obtain data on mechanisms of nuclear reactions and properties of excited States of atomic nuclei [1]. Especially interesting is the study of nuclear reactions of type (n,2n) and (γ,n) resulting in the same kernel.

In this paper, we examine the cross section of excitation of isomers $^{81m,g}Se$ the reactions (γ,n) and (n,2n) - ^{82}Se in the energy region 13-35 MeV.

2. Experimental Procedure

The relative probability of excitation, i.e. the isomeric relations of the yields and cross sections of the reaction $^{82}Se(\gamma,n)^{81m,g}Se$ was studied mainly in the region of the giant dipole resonance at energies above 24 MeV. It should be noted that such practical work was carried out. In the case of the reaction (n,2n), despite the numerous experiments with 14 MeV, very little data on individual measurements of isomeric cross sections and primary levels.

Our studies were conducted using the SB-50 high current betatron at the Research Institute of Applied Physics, National University of Uzbekistan, and using the NG-150 neutron generator at the Institute of Nuclear Physics, Republic of Uzbekistan Academy of Sciences.

The (γ,n) reaction experiments were conducted on the braked γ beam of the SB-50 betatron in the energy range 10–35 MeV with a step of 1 MeV. The time regimes (i.e., the time of irradiation, pauses, and measurements) were chosen in accordance with the half-life of the formed radioactive nuclides. Samples of selenium weighing 2-3 g were used as targets, in the form of tablets with a diameter of 15 mm. The irradiation time 20-40 minutes.To increase the dose power, we performed the irradiation inside the acceleration chamber of the SB-2 high-current betatron at a distance of 12 cm from the tungsten braking target where the sample inside the special container was delivered with the help of a type K5-2A pneumatic transport setup. It took the transport setup ~4 s [4] to deliver the sample to the irradiation site.

The neutron source was an NG-150 neutron generator that generated fluxes of fast neutrons with energies of ~2.4 and 14 MeV from reactions of $D+d \longrightarrow {}^3He+n$ or $T+d \longrightarrow \alpha+n$ using deuterium and tritium targets. The neutron fluxes were about ~10^8 and 10^{10} neutron·s^{-1}, respectively [5]. The time of irradiation by the neutron flux at an energy of 14 MeV was 30 min.

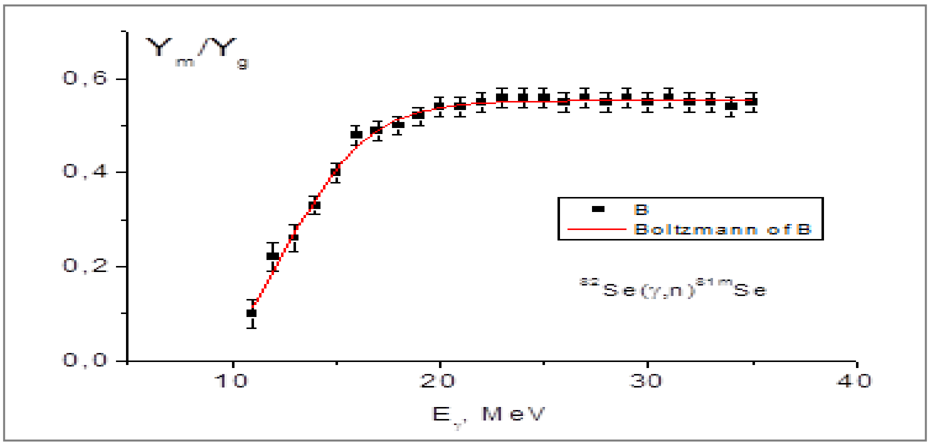

Figure 1: Energy dependences of the isomeric ratios of the yields of the ^{82}Se (γ, n) $^{81m,\,g}Se$ reaction

The induced activity of targets was measured using a Canberra γ spectrometer consisting of an HPGe germanium detector with a relative efficiency of 15% and a resolution for the 1332-keV Co line of 1.8 keV, a DSA 1000 digital analyzer, and a personal computer with the Genie 2000 software package for the acquisition and processing of γ spectra. The gamma spectrometer was energy calibrated using the OSGI standard set of sources. Measurements were made in the standard geometry in which the detector was calibrated with respect to efficiency. Measurements of the gamma spectra of targets began after a pause of 0.5–40 min and proceeded for 3–120 min.

The filling of the isomeric and ground levels was identified according to their γ lines. The spectroscopic characteristics of the product nuclei of the (γ,n) and (n,2n) reactions, required for processing the measurement results, are taken from [6] and given in Table 1, where J^{π} is the spin and parity of the level, $T_{1/2}$ is the nucleus half-life, I_{γ} is the intensity of γ quanta of the fixed decay energy, and p is the branching coefficient of the γ transition.

Table 1: Spectroscopic characteristics of the product nuclei of (γ,n) and (n ,2n) reactions

Product nucleus	J^{π}	$T_{1/2}$	E_{γ}, keV	I_{γ} , %	p
^{81m}Se	$7/2^+$	57.3 m	103.0	8.7	0.99
^{81g}Se	$1/2^-$	18.5 m	289.9	0.288	

Isomeric yield ratios were calculated according to the formula [7]

$$d=\frac{Y_m}{Y_g}=\left[\frac{\lambda_g F_m(t)}{\lambda_m F_g(t)}\left(C\frac{N_g I_m \varepsilon_m}{N_m I_g \varepsilon_g}-p\frac{\lambda_g}{\lambda_g-\lambda_m}\right)+p\frac{\lambda_m}{\lambda_g-\lambda_m}\right]^{-1}, \qquad (1)$$

where

$$F_m(t)=\left[1-\exp(-\lambda_m t_i)\right]\exp(-\lambda_m t_c)\left[1-\exp(-\lambda_m t_m)\right], \qquad (2)$$

$$F_g(t)=\left[1-\exp(-\lambda_g t_i)\right]\exp(-\lambda_g t_c)\left[1-\exp(-\lambda_g t_m)\right], \qquad (3)$$

λ_m and λ_g are the decay constants of the isomeric and ground states, respectively; C is a coefficient that allows for miscounts of the recording apparatus and the positions of pulses; N_m and N_g are the numbers of decay events for the isomeric and ground states respectively; I is the intensity of γ quanta with the given decay energy; ε is the spectrometer efficiency; p is the branching coefficient of the γ transition; and t_i, t_c, t_m are the irradiation, cooling and measurement times, respectively.

3. Results and Discussion

The obtained experimental results on the isomeric ratios of the yields of the (γ, n) and (n, 2n) reactions on the ^{82}Se nucleus are shown in Fig. 1 and in Table 1, 2 and 3. The absolute error of 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. To approximate the experimental data on the isomeric ratios of the yields used sigmoidal ("step shaped") Boltzmann function (solid curve in Figure 3)

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

where A_1, A_2, and E_0 is ΔE - fitting parameters, which were determined by the least squares method on a set of experimental values. The fitting of the following values: A_1 = -0.0957 ± 0.0931; A_2 = 0.5539 ± 0.0029; E_0 = 12.516 ± 0.626 and ΔE = 2.037 ± 0.209.

In the ^{82}Se (γ, n) ^{81m,g}Se 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 ~ 20 MeV. Perhaps this is due to the fact that as the energy increases, the number of cascade γ--transitions that remove the excitation of the nucleus increases, as well as an increase in the moments carried away by quasi-direct neutrons. At energies above ~ 20 MeV ($E_{\gamma max} \geq E_m + \Gamma$, E_m are the positions of the maximum, Γ is the half-width of the GDR) 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 cascades leading to metastable states.

In Table 2 and 3 show the experimental results of the measurements, and also the previously obtained data for comparison. As can be seen from Table. 2, the results of ^{82}Se (γ, n) ^{81m,g}Se obtained by us for the reactions within the error limits agree with the data of [1]. In the energy range E> 25 MeV, the isomeric yield ratios were obtained for the first time.

Table 2: Isomeric yields ratios for ^{82}Se (γ, n) ^{81m,g}Se

Reaction	$E_{\gamma max}$, MeV	Y_m/Y_g	References
^{82}Se(γ,n)^{81m,g}Se	22	0.54±0.03	[1]
	25	0.57±0.03	This work
	30	0.56±0.02	This work

The excitation functions of the (γ,n)-reactions were obtained from the experimental isomer ratios and from the total cross sections of the photoneutron reaction σ_{tot} [4]. The brake photon spectrum was calculated using the GEANT4 program [5]. The cross section was calculated by the Penfold-Liss method with a step of 1 MeV [6]. The energy dependences of the reaction cross sections are approximated by the Lorentz curves. The cross sections have a single-rod shape from the position of the maximum E_m = 16.1 MeV. At E_γ = 16 MeV, we obtained an isomeric cross-section ratio: $r=\sigma_m/\sigma_g$=0,52±to 0.09.

The experimental dependence of the cross sections for the reactions ^{82}Se(γ,n)^{81m,g}Se on the boundary energy of braking photons approximated by the Lorentz function whose parameters (position of the maximum cross-section E_m, the value of the maximum cross section σm and the width of the distribution at half of its height Γ) was determined using the least squares method on a set of experimental values. The experimental value of the cross sections were compared with theoretical calculations performed using the code TALYS 1.0 [7].

Table 3: The reaction cross-section ^{82}Se(γ,n)^{81}Se

Reaction	E_m, MeV	Γ, MeV	σ_m, mb	σ_{int}, MeV·mb	E_h, MeV	References
^{82}Se(γ,n)^{81}Se	15.89	4	142.7	727	26.5	[8]
^{82}Se(γ,n)^{81m}Se	16.00±0.11	4.76±0.24	51.1±2.2	-	-	[9]
^{82}Se(γ,n)^{81g}Se*	15.65±0.09	3.73±0.37	93.24	552±58	30	This work
^{82}Se(γ,n)^{81m}Se*	16.01±0.05	3.78±0.19	47.19	286±13	30	This work
^{82}Se(γ,n)^{81m}Se	16.01±0.06	4.07±0.36	48	302±33	21	This work

*The calculation of the cross sections was carried out according to the program TALYS-1.0.

**σ_{int} – integral reaction cross section, upper limit integration - 25 MeV.

E_h - верхний предел интегрирования.

The obtained experimental isomeric yield ratios are compared with the results of calculations of the Fermi gas carried out by us in the framework of the statistical theory [1]. The density of nuclear levels was calculated by the Bethe-Bloch formula, the spin part of which has the form

$$\rho(J) = (2J+1)\exp\left[-(J+1/2)^2/2\sigma^2\right], \qquad (5)$$

where σ is the spin or spin cutoff parameter, which can be written as

$$\sigma^2 = 0{,}0889\sqrt{aU}\cdot A^{2/3}, \qquad (6)$$

where A is the mass number, a is the level density parameter, and U is the excitation energy, by which is meant the effective energy. The parameter of the spin constraint in the Fermi-gas theory is related linearly to the solid state of inertia of the nucleus.

To improve the quantitative agreement between calculations and experiment, we succeeded in fixing the spin constraint parameter σ. At the same time, a satisfactory agreement is reached for σ = 2.

In the case of reaction (n, 2n), the cross sections for the formation of the isomeric and ground states and their isomeric ratios σ_m/σ_g are determined. To obtain absolute values of the cross sections of the ground and isomeric states, methods were used to compare the yields of the study and the monitor response. ^{27}Al (n, α) ^{24}Na ($T_{1/2}$ = 15 h, E_γ = 1368 keV) were used as a monitor reaction, the cross section of which is equal to σ_m = 114±6 mb for E_n = 14.6±0.3 MeV [10]. 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 [3].

In Table 3 shows the results obtained for the (n, 2n) reaction on the 82Se 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 3 indicate that the relative probability of excitation of isomers 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. According to the data given in Table 3, it is possible to determine the values σ_m/σ_{tot} which is equal to: 0.72 ± 0.03.

Table 4: Cross section of the reaction ^{82}Se (n, 2n) ^{81mg}Se

Reaction	E_n, MeV	σ_m, mb	σ_g, mb	σ_m/σ_g	References
^{82}Se(n,2n)^{81m,g}Se	14.1	896±49	-	-	[11]
	14.6	1002±50	392±20	2.56±0.18	[11]
	14.1	1078±42	441±26	2.40±0.20	[12]
	14.6	1114±44	431±28	2.60±0.20	[12]
	13.9	1692±227	-	2.17±0.33	[13]
	14.5	1587±218	-	2.70±0.22	[13]
	14.8	850±50	310±25	2.74±0.27	[14]
	14.1	975±53	388±22	2.51±0.09	This work
	14.0*	885	352	2.51	This work
	14.5*	908	349	2.60	This work

Note. * Calculation of cross sections was carried out according to the program TALYS-1.0.

4. Conclusion

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 relative probability of excitation, i.e. the isomeric relations of the yields and cross sections of the reaction ^{82}Se(γ,n)^{81m,g}Se was studied mainly in the region of the giant dipole resonance at energies above 24 MeV. It should be noted that such practical work was carried out. In the case of the reaction (n,2n), despite the numerous experiments with 14 MeV, very little data on individual measurements of isomeric cross sections and primary levels.

The obtained energy dependence of the isomer ratio of the yields of the $^{82}Se\ (\gamma,n)^{81m,g}Se$ and $^{82}Se\ (n,2n)\ ^{81m,g}Se$ reactions can be used in studying the mechanism of photonuclear reactions and the development of gamma and neutron activation analysis techniques.

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