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Investigation of isomer ratios in the reactions (γ, *n*) and (*n*, 2*n*) on nuclei ^{76}Ge and ^{82}Se

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INVESTIGATION OF ISOMER RATIOS IN THE REACTIONS (γ, n) AND $(n, 2n)$ ON NUCLEI ^{76}Ge AND ^{82}Se

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Abstract

The method of the induced activity measured the isomeric yield ratios and cross-sections ratios of reactions (γ, n) and $(n, 2n)$ on nuclei ^{76}Ge and ^{82}Se. Samples of natural have been irradiated in the bremsstrahlung beam of the betatron SB-50 of National University of Uzbekistan in the energy range of 10-35 MeV with energy step of 1 MeV. For 14 MeV neutron irradiation, we used the NG-150 neutron generator of Institute of Nuclear Physics. The gamma spectra reactions products were measured with a spectroscopic system consisting of HPGe detector CANBERRA with energy resolution of 1.8 keV at 1332 keV gamma ray of ^{60}Co, amplifier 2022 and multichannel analyzer 8192 connected to computer for data processing. The filling of the isomeric and ground levels was identified according to their γ lines. Values $\eta = \mathrm{Y}_m/(\mathrm{Y}_m + \mathrm{Y}_g)$ at $\mathrm{E}_{\gamma\,\max} = 30$ MeV for the reaction (γ, n) on nuclei ^{76}Ge and ^{82}Se are respectively: 0.55±0.02 and 0.36±0.01 ($\mathrm{Y}_m/\mathrm{Y}_g$ = 0.56±0.02). In the range 26-35 MeV the isomeric yield ratios η of the reaction (γ, n) on ^{76}Ge and ^{82}Se are obtained at first. The isomeric cross-section ratios σ_m/σ_g was 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, α) ^{24}Na ($\mathrm{T}_{1/2}$ = 15 h, E_γ = 1368 keV), whose cross section σm was 121.57±0.57 mb at E_n= 14.1 MeV, was taken for a monitoring reaction.

Keywords: isomeric yield ratio, activity, isomeric, nuclear of atom, nuclear reaction, photonuclear reaction, isotopes, radioactivity, cross section, spin, neutron.

Physics and Astronomy Classification Scheme: 25.20.-x

1 Introduction

The study of the relative probabilities of excitation of isomeric and ground states of the final nucleus in nuclear reactions has fundamental and applied values. The relative probability of excitation of the isomeric and ground states of the final nucleus is defined as the isomeric ratio of the yields ($\mathrm{Y}_m/\mathrm{Y}_g$) or cross sections ($\sigma_m/\sigma_g$) of nuclear reactions. A comparison of the experimental data on the isomeric ratio with the results of calculating the main one using statistical theory allows obtaining information on the spin dependence of the density of nuclear levels [1]. Of great importance is the study of the formation of isomeric states of nuclei in nuclear reactions with various bombarding particles, which allows one to obtain information on the mechanisms of nuclear reactions and on the properties of excited states of atomic nuclei [2]. Also, data on the isomeric ratios of the yields of photonuclear reactions are necessary for assessing the potential of the gamma-activation method and for developing an optimum experimental procedure [3]. Of particular interest is the study of nuclear reactions of the type (n,2n) and (γ,n) resulting in the formation of the same nucleus [4].

In this work, the energy dependence of the isomeric ratios of the yields of photonuclear reactions of the (γ,n) type on ^{76}Ge and ^{82}Se nuclei in the energy range 11-35 MeV with a step of 1 MeV is experimentally investigated. The isomeric ratios of reaction cross sections of the (n,2n) type on ^{76}Ge and ^{82}Se nuclei at a neutron energy $E_n = 14.1$ MeV were also determined.

The isomeric ratios of the yields and cross sections of the ^{82}Se(γ,n)^{81m,g}Se reaction were studied mainly in the energy range from the reaction threshold to 24 MeV. In the energy region above 24 MeV, such work has not been carried out in practice. In the case of the reaction (n,2n), despite numerous experiments at 14.1 MeV, there is very little data on individual measurements of the cross sections of the isomeric and ground levels.

In the case of the reaction ^{76}Ge(γ,n)^{75m,g}Ge, the isomeric ratios are very poorly studied. There are several works [3, 5, 6] in which isomeric ratios are determined at fixed energies. No experiments were carried out to measure the energy dependence of the isomeric yield ratios in a wide energy range.

2 Experimental procedure

The experiments were carried out on the SB-50 high-current betatron of the National University of Uzbekistan and the NG-150 neutron generator of the Institute of Nuclear Physics of the Academy of Sciences of the Republic of Uzbekistan.

The experiments on the reaction (γ, n) were carried out on the brake γ-beam of the SB-50 betatron in the energy range 10–35 MeV with a step of 1 MeV. Temporary modes, i.e. exposure time, pause and measurement were selected in accordance with the half-life of the resulting radionuclides. Selenium and germanium (GeO_2) were used as targets in a natural mixture of isotopes. 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 tungsten braking target, where the sample under study placed in special container was transported by a K5-2A pneumatic-rabbit facility. The time of sample transportation to the irradiation locuswith the aid of this facility was about 4 s [7].

To study nuclear reactions of the (n,2n) type, the NG-150 neutron generator was used, which implements fast neutron fluxes with energies of $\sim$ 2.4 and 14 MeV from the reactions D + d $\rightarrow^3$He + n or T + d$\rightarrow$ α + n when using deuterium and tritium targets. In this case, the neutron fluxes are $\sim$ 108 and 1010 n/s, respectively. Samples of selenium and germanium oxide (GeO_2) weighing 2–3 g in the form of tablets with a diameter of 15 mm prepared by compression were used as targets. To exclude the influence of background neutrons (thermal neutrons), the samples were packed into

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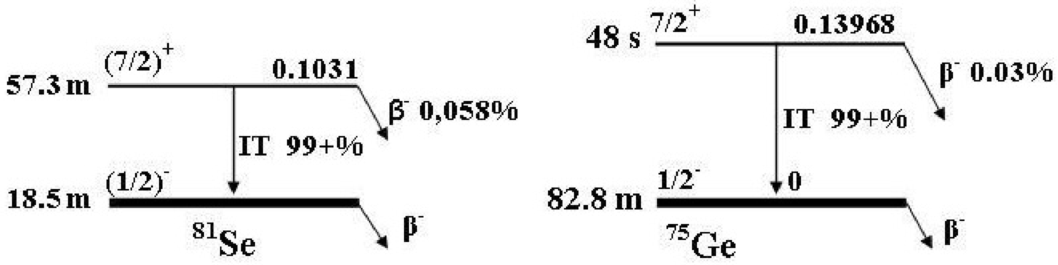

Figure 1: Scheme of decay of isomers ^{81m}Se and ^{75m}Ge.

cadmium screens 1 mm thick. In addition, in the quality of the monitor, aluminum foil was attached to the samples in front and behind. Irradiation time 20–40 min.

The induced γ activity of the targets was measured on a Canberra gamma spectrometer, consisting of an HPGe germanium detector (with a relative efficiency of 15%, resolution for the ^{60}Co line 1332 keV - 1.8 keV), a digital analyzer DSA 1000 and a personal computer with the Genie software package 2000 for the collection and processing of gamma spectra. Energy gamma spectrometer calibrated using a standard set of gamma sources. The measurements were performed in standard geometry, in which the detector was graduated by efficiency. The population of the isomeric and basic levels was identified by γ-lines. The spectroscopic characteristics of the reaction product nuclei (n,2n) necessary for processing the measurement results are taken from [8, 9] and are given in Table 1, where I^{π} is the spin and level parity, $T_{1/2}$ is the half-life of the nucleus, I_{γ} - intensity of γ - quanta of a given energy into decay, p - branching coefficient of the γ – transition.The decay scheme of ^{81m}Se and ^{75m}Ge is shown in Fig. 1.

Table 1. Nuclear-physical characteristics of the reaction product nuclei (γ,n) and (n,2n) on nuclei

Nuclide	Spin states J^{π}	Half-life $T_{1/2}$	E_{γ}, keV	I_{γ} , %	p
$^{75\ m}$Ge	$7/2^{+}$	48 s	139,80	40	0,99
^{75g}Ge	$1/2^{-}$	82,8 min	264,8	12	-
^{81m}Se	$7/2^{+}$	57,3 min	103	8	0,99
^{81g}Se	$1/2^{-}$	18,5 min	275,94 290,08	0,5 0,44	-

The ratio of the isomeric yields in the reaction (γ,n) was calculated by the formula [10].

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

where

$$F_m(t) = \left[1 - \exp(-\lambda_m t_o)\right] \exp(-\lambda_m t_n) \left[1 - \exp(-\lambda_m t_c)\right],$$

$$F_g(t) = \left[1 - \exp(-\lambda_g t_o)\right] \exp(-\lambda_g t_n) \left[1 - \exp(-\lambda_g t_c)\right],$$

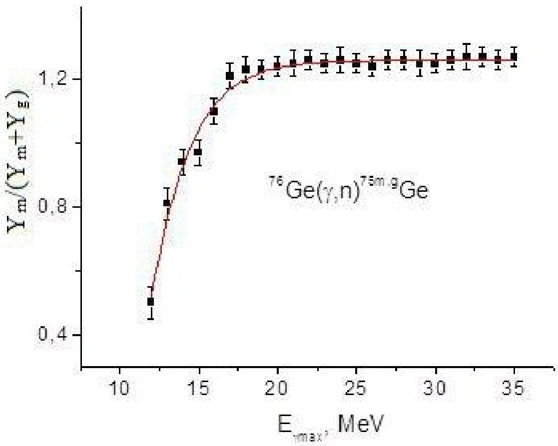

Figure 2: Energy dependences of the isomeric ratios of the yields of photonuclear reactions ^{76}Ge (γ,n) ^{75m,g}Ge

Here, Y_m and Y_g are the yields of, respectively, the isomeric and the ground state; $\lambda_{\ m}$ and $\lambda_{\ g}$ are their decay constants; N_m and N_g are the numbers of detected events of decay of, respectively, the isomeric and the ground state; C is a coefficient that takes into account 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_{meas} are the times of irradiation, pause, and measurements, respectively.

3 Results and discussion

The experimental results obtained on the isomeric ratios of the yields and cross sections of the reactions (γ,n) and (n,2n) on the ^{82}Se nucleus are shown in Figures 2 and 3 and in Tables 2 and 3. The absolute error of the isomeric ratios of the outputs is determined by the statistical error of the counts in the photopic the measured γ-line and the efficiency of registration of γ-radiation.

The energy dependences of the isomeric ratios of the yields of the photonuclear reactions ^{76}Ge(γ,n)^{75m,g}Ge and ^{82}Se(γ,n)^{81m,g}Se are shown in Figs. 1. To approximate the experimental data on the isomeric ratios of the yields, we used the sigmoidal ("step-shaped") function Boltzmann (solid curve in Figs. 2 and 3):

$$y = A_2 + \frac{(A_1 - A_2)}{(1 + exp[(E - E_0)/\Delta E])}, \tag{2}$$

where A_1, A2, and E_0 is ΔE - fitting parameters, which were determined by the least squares method on a set of experimental values.

The isomeric yield ratios η = $Y_m/(Y_m + Y_g)$ of the ^{76}Ge (γ,n)^{75m,g}Ge reaction increases from the reaction threshold to $\sim$ 17 MeV, which correspond to the value of the position of the maximum cross section of the giant dipole resonance. Above these energies, the η ($E_{\gamma max}$) curve saturates. It should be noted that in the saturation

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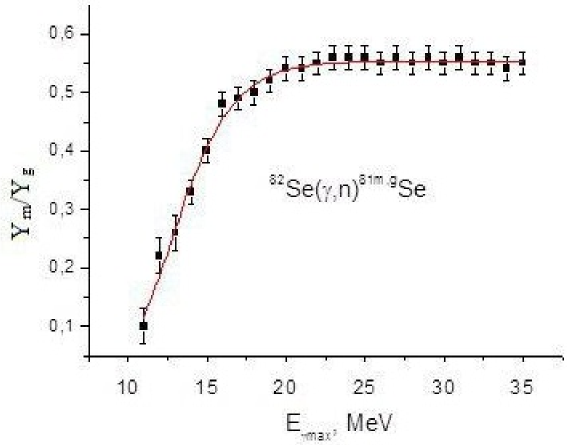

Figure 3: Energy dependences of the isomeric ratios of the yields of photonuclear reactions ^{82}Se (γ,n) ^{81m,g}Se

region $< \eta > = 0.56 \pm 0.08$. In the energy range 26–35 MeV, we obtained the values of the isomeric ratios of the reaction yields for the first time. In the case of the ^{82}Se (γ,n)^{81m,g}Se reaction, a similar picture is also observed, i.e. the value of the isomeric ratio of the yields d $=$ Y$_m$/ Y$_g$ increases from the reaction threshold to $\sim$ 19 MeV, then the curve d (E$_{\gamma max}$) saturates. Perhaps this is due to the fact that with an increase in energy, the number of cascade γ transitions that remove the excitation of the nucleus, as well as an increase in the moments carried away by quasidirect neutrons, increase. At energies above $\sim$ 20 MeV, the Y$_m$/Y$_g$ curve saturates, since a further increase in the level density probably did not noticeably change the probability of the formation of cascades leading to metastable states. It should be noted that in the saturation region the value $<$d$>$ $= 0.55 \pm 0.09$.

In the table. 2 and 3 show the experimental results of measurements and, for comparison, the previously obtained data are also given. As can be seen from the table. 2, the results obtained by us for the ^{82}Se(γ,n)^{81m,g}Se reactions within the error range are consistent with data from other works [5, 6, 11, 12, 13, 14]. In the energy range E>25 MeV, the energy dependence of the isomeric yield ratios was obtained by us for the first time.

Table 2. Isomeric ratio of yields reactions ^{76}Ge (γ, n)^{75m,g}Ge

E$_{max}$, MeV	η=Y$_m$/(Y$_m$ +Y$_g$)	References
22	0,56±0,02	[3]
25	0,57±0,06	[5]
25	0,56±0,03	[6]
30	0,56±0,02	[6]
20	0,55±0,02	This work
25	0,56±0,02	This work
30	0,56±0,01	This work
35	0,56±0,01	This work

Table 3. Isomeric ratio i outputs reactions ^{82}Se(γ,n)$^{81m,\ g}$Se

E_{max}, MeV	Y_m/Y_g	References
19	0,42±0,04	[11]
20	0,497±0,054	[12]
21	0,515±0,056	[12]
22	0,536±0,055	[12]
22	0,54±0,03	[13]
21	0.521±0,048	[14]
22	0.558±0,050	[14]
23	0.550±0,050	[14]
25	0.52±0,06	[5]
25	0,57±0,03	[6]
30	0,56±0,02	[6]
20	0,54±0,02	This work
25	0,56±0,02	This work
30	0,55±0,02	This work
35	0,55±0,02	This work

The excitation functions of the ^{82}Se(γ,n)$^{81m,\ g}$Se reactions were obtained from the experimental isomer ratios and from the total cross sections of the photoneutron reaction $\sigma_{\ tot}$ [15]. The brake photon spectrum was calculated using the GEANT4 program [16]. The cross section was calculated by the Penfold-Liss method with a step of 1 MeV [17]. The energy dependences of the reaction cross sections are approximated by the Lorentz curves. Experimental dependence of reaction cross sections ^{82}Se(γ,n)^{81m,g}Se of the boundary energy of bremsstrahlung quanta was approximated by the Lorentz function:

$$\sigma(E_y) = \sigma_m \frac{E_\gamma^2 \mathit{\Gamma}^2}{\left(E_\gamma^2 - E_m^2\right)^2 + E_\gamma^2 \mathit{\Gamma}^2}, \tag{3}$$

where E_m is the position of the resonance maximum; σ_m is the cross section at the resonance maximum; $\mathit{\Gamma}$ is the resonance width at half the maximum height. The parameters (E_m, σ_m and $\mathit{\Gamma}$) of the Lorentz function were determined by the least squares method using a set of experimental values. Data on the approximation parameters and integral reaction cross sections are given in table. 2. The cross sections have a single-rod shape from the position of the maximum E_m = 16.1 MeV. At Eγ = 16 MeV, we obtained an isomeric cross-section ratio: r=$\sigma_{\ m}/\sigma_{\ g}$=0,52±0.09. The experimental value of the cross-sections were compared with theoretical calculations performed using software package TALYS 1.6 [18].This package includes the majority of modern models applied for the description of nuclear reactions.

Table 4. 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
$^{82}Se(\gamma,n)^{81}Se$	15,89	4	142,7	727	26	[19]
$^{82}Se(\gamma,n)^{81m}Se$	16.00±0,11	4,76±0,24	51,1±2,2	-	-	[12]
$^{82}Se(\gamma,n)^{81g}Se$*	15,65±0,09	3,76±0,24	93,24	552±58	30	This work
$^{82}Se(\gamma,n)^{81m}Se$*	16,01±0,05	3,78±0,19	47,19	289±13	30	This work
$^{82}Se(\gamma,n)^{81m}Se$	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 is the upper limit of integration.

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, 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_γ = 1368 keV), whose cross section is σ_m = 121,57±0.57 mb at E_n = 14.1 MeV [20]. 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 self-absorption of gamma rays were taken into account. The isomeric ratios of the cross sections σ_m/σ_g were calculated according to the formula (1).

In the table.5 shows the results obtained for the reaction (n,2n) on the ^{82}Se nucleus. As can be seen from this table, our results on the isomeric ratios of the cross sections σ_m/σ_g within the limits of measurement errors are consistent with data from other works. The measurement results are given in table. 3 indicate that the relative probability of excitation of isomers in the case of a reaction of the type (n,2n) is several times higher than in the reaction (γ,n). This is probably due to the moment introduced into the nucleus, which in the case of the (n,2n) reaction is larger than in the photonuclear reactions. According to the data given in Table 3, it is possible to determine the value of σ_m/σ_{tot} which is equal to: 0.72 ± 0.03.

Table 5. Reaction cross section ^{82}Se (n,2n) ^{81}Se

E_n, MeV	σ_m, mb	σ_g, mb	σ_m/σ_g	References
14,1	896±49	-	-	[21]
14,6	1002±50	392±20	2,56±0,18	[21]
14,1	1078±42	441±26	2,40±0,20	[22]
14,6	1114±44	431±28	2,60±0,20	[22]
13,9	1692±227	-	2,17±0,33	[23]
14,5	1587±218	-	2,70±0,22	[23]
14,8	850±50	310±25	2,74±0,27	[24]
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. * Cross sections were calculated using the TALYS-1.0 program.

Table 5 shows the values of the cross sections for the formation of isomeric states ^{75m,g}Ge obtained in this and other works. The values of the cross section for the formation of σm isomeric states within the measurement error are consistent between the subwoofers. At E_n = 14.1 MeV of energy, our results on isomeric ratios of cross sections are in good agreement with the data of [10] and the calculated data that were carried out using the TALYS-1.6 program.

Table 6. The reaction cross-section ^{76}Ge(n,2n)^{75}Ge

E_n, MeV	σ_m, mb	σ_g, mb	σ_m/σ_g	References
13.73	713±70	478±57	-	[25]
14.42	778±63	513±61	-	[25]
14.77	842±63	535±64	-	[25]
11.720	-	-	0,73±0,05*	[26]
14.680			0,80±0,04*	[26]
14,1	770±80	600±50	-	[27]
13.87	696.85±42.09	329,82±24,46	2.11±0.21	[28]
14.36	740.11±43.67	330.10±25.46	2.24±0.22	[28]
14.80	754.56±46.86	335.70±26.80	2.25±0.23	[28]
14.7	-	-	1,3±0,15	[10]
14,1	735±45	373±26	1,97±0,14	This work
14,0	725	397	1,83	TALYS-1.0.
14,5	752	399	1,88	TALYS-1.0.

Note. * The value of σ_m/σ_{tot} is given

4 Conclusion

From the analysis of the data given in table. 2 and 3, it follows that experimental studies of the excitation of isomeric states in photonuclear reactions of the ^{82}Se(γ,n)^{81m,g}Se were carried out mainly in the energy range 10–25 MeV, i.e. in the field of giant dipole resonance. In the energy region above 25 MeV, the energy dependence of isomeric ratios has not been studied much. In the case of the photonuclear reaction ^{76}Ge(γ,n)^{75m,g}Ge, the isomeric ratios are practically not studied. For this reaction, it is necessary to carefully measure the isomeric ratios of the yields and cross sections in the energy region from the reaction threshold of 25 MeV with a small step of energy change. Thanks to these studies, information on the density of nuclear levels and the contribution of direct processes to the mechanism of photonuclear reactions in this energy region can be obtained.

The obtained energy dependence of the isomeric ratio of the yields and cross sections of the reactions (γ,n) and (n,2n) on ^{76}Ge and ^{82}Se nuclei can be used to study the mechanism of photonuclear reactions and develop methods for gamma and neutron activation analysis.

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