***https://doi.org/10.46813/2022-141-007***

UDC 539.172.2

# STUDY OF THE EXCITATION OF THE ISOMERIC STATE 7/2$^+$ $^{81}$Se NUCLEAR IN THE REACTION (γ,n) BY THE METHOD OF ISOMERIC RELATIONSHIPS

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Selenium is known for the transitional nature of the region from light to medium-heavy nuclei and their insufficient study. The $^{82}$Se(γ, n)$^{81m}$Se reaction yield was measured, and its cross-section in the range of gamma-ray energies 9…19 MeV was calculated. A comparison of the experimental results with theoretical calculations performed using the TALYS-1.9 software complex. The dominance of the statistical mechanism for this (γ, n) reaction was found.

## INTRODUCTION

Nuclear reactions are an important means of studying the characteristics and properties of the atomic nucleus. Using the high particles of a different sort as probes makes it possible to determine the number of properties of nuclei and the parameters of their individual levels. Research on gamma-ray beams has many advantages:

1. The interaction of photons with nuclei occurs with the help of electromagnetic forces, the properties of which are studied and well known.
2. Photons bring relatively minor changes to the nucleus (compared to highly interacting particles); therefore, they are adequate tools for studying the structures of nuclei.
3. In these reactions, a certain angular momentum is introduced into the nucleus in the studied energy region, and the moments' variance after the particle's radiation was 2h–3h.

All this simplifies the analysis of experimental results.

The main feature in the cross-sections of the interaction of gamma quanta with nuclei is the giant resonance (GR). Therefore, the study of its main characteristics can be carried out as a method of summation of partial cross-sections of reactions (γ, n) (γ, 2n) (γ, 3n), etc. [1], or direct measurement of the total cross-section $s_{tot}$ by the absorption method [2, 3].

Photonuclear reactions with the fixation of the formation of the final nucleus in certain identified states have recently become one of the main sources of new information about the giant dipole resonance (GDR) properties.

In the presence of isomeric states in the nucleus, the relative population of the isomeric and ground state of the nucleus will be determined by the distribution on the spins of higher levels.

The energy dependencies of the $Y_m/(Y_m+Y_g)$ (or cross-sections) isomeric ratio obtained by investigating the population of isomeric $Y_m$ and the ground $Y_g$ states of the nucleus provide information about the mechanisms of the reaction under study, the level density parameters, the spin constraint parameters of the statistical model, etc.

This work aims to study the cross-section of the $^{82}$Se(γ, n)$^{81m}$Se reaction in the region of giant E1 resonance energies by isomeric relations. The choice of the target is due to the transitional nature of the selenium region from light to medium-heavy nuclei and their insufficient study.

## EXPERIMENTAL METHODS

Irradiation of the experimental samples was performed on a beam of gamma quanta of the M-30 microtron Department of Photonuclear Processes of the Institute of Electronic Physics of the National Academy of Sciences of Ukraine in the field of energies 9…19 MeV. The main characteristics of the microtron are given in [4]. The accelerated electron current was kept at 5 μA during the experiment. The accuracy of determining the maximum energy of the braking spectrum $E_{\gamma max}$ was determined by measuring the magnetic induction of the conductor's magnetic field. These measurements were performed by the nuclear magnetic resonance method, the error of which did not exceed 0.1%. The energy scatter of the electron beam is due to phase oscillations, is practically independent of the orbit number, and in our case, is ~ 30 keV. The change in the energy of accelerated electrons took place in two ways: within wide limits by changing the number of orbits, i.e., by changing wave inserts, and within one number of orbits by changing the resonator electric field strength and correspondingly changing the value of the conductive magnetic field of microtron.

The electron beam, after leaving the microtron was falling on a 0.5 mm thick brake tantalum target. A secondary emission monitor was used for the beam current control, the current of which was recorded every 1.2 s.

The investigated targets were high-purity powdered metallic selenium disks pressed into caprolon cassettes. The target weighed 2 g and had a diameter of 30 mm.

The activation technique was used to study the $^{82}$Se(γ, n)$^{81m}$Se reaction. After irradiation of the target, the induced gamma activity was measured in good background conditions with a high-resolution spectrometer based on an HP Ge-detector with a volume of 175 cm$^3$ and 8192 channel analyzer CANBERRA, which is connected to a computer for data collection. The detector's resolution was ~ 2 keV for the 1332 keV line of cobalt-60. Spectroscopic characteristics of the decay of the ground and isomeric state of the $^{81}$Se isotope are given in Table [5]:

| Nuclide | $J^\pi$ | $T_{1/2}$, min | α, % | P | $E_\gamma$, MeV |
|---|---|---|---|---|---|
| $^{81m}$Se | $7/2^+$ | 57.3 | 8.7 | 0.995 | 0.1030 |
| $^{81g}$Se | $1/2^-$ | 18.5 | 0.288 | – | 0.2899 |

The following symbols are given in the table: $J^\pi$ is the spin-parity of the ground and isomeric states, $T_{1/2}$ is the half-life, α is the number of gamma quanta per decay, and p is the branching factor, and $E_\gamma$ is the energy of the analytical line.

Directly from the experimental data, the isomeric ratios of the yields $d = {}^{Y_m}\!/_{Y_g}$ were determined by the formula [6]:

$$d = \left[ \frac{\lambda_g}{\lambda_m} \frac{F_m(t)}{F_g(t)} \left( C \cdot \frac{N_g}{N_m} \cdot \frac{\phi_m}{\phi_g} \cdot - p \frac{\lambda_g}{\lambda_g - \lambda_m} \right) + p \frac{\lambda_g}{\lambda_g - \lambda_m} \right]^{-1}. \quad (1)$$

In formula (1) $\lambda_{m,g}$ are the corresponding decay steels of the isomeric and ground states, and $F_{m,g}$ is the time function:

$$F_{m,g} = (1 - e^{-\lambda_{m,g} \cdot t_{irr}}) \cdot e^{-\lambda_{m,g} \cdot t_{cool}} \cdot (1 - e^{-\lambda_{m,g} \cdot t_{meas}}), \quad (2)$$

where ($t_{irr}$, $t_{cool}$, $t_{meas}$ – times of irradiation, cooling, and measurement); $C$ – coefficient that takes into account the possibility of miscalculations and the imposition of impulses; $N_m$ *and* $N_g$ – the number of registered pulses from the decay of the isomeric and ground states; $\varphi_{m,g} = \alpha_{m,g} \cdot \xi_{m,g} \cdot k_{m,g}$, here $\alpha_{m,g}$ is the intensity of gamma transitions that accompany the decay of the isomeric and ground states; $\xi_{m,g}$ is the efficiency of registration of the corresponding gamma lines; $k_{m,g}$ is self-absorption coefficients of gamma quanta in the target, $p$ – branching coefficient.

Fig.1 shows the squares of the isomeric ratio of yields $\eta = \frac{Y_m}{Y_n} = \frac{Y_m}{Y_m + Y_g}$, where $Y_n$ is the total yield of the photoneutron reaction, which is related to formula (1) by the $\eta = \frac{1}{(1 + {}^1\!/_d)}$ ratio.

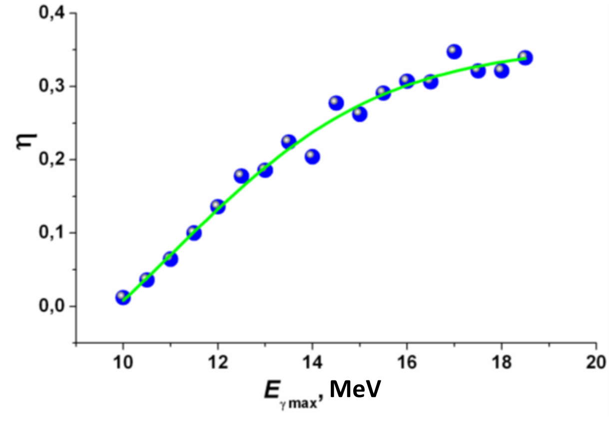

*Fig. 1. Dependence of the ratio of yields η in the reaction $^{82}Se(\gamma, n)^{81m}Se$ on the maximum energy of the braking gamma spectrum*

The standard error *h* is not more than 1% and does not exceed the size of the square. The solid line in Fig. 1 shows the result of fitting by the method of least squares of experimental data the Boltzmann curve

$$\eta = \frac{A + (B - A)}{\left\{ 1 + \exp\left[ {}^{(E - E_0)}\!/_{\Delta E} \right] \right\}},$$

where $A$, $B$, $E_0$, $\Delta E$ are the fitting parameters. As a result of fitting, the following values of parameters were obtained: $A = 0.3575$, $B = -0.2059$, $E_0 = 11.0894$ MeV, $\Delta E = 2.2274$ MeV.

The isomeric ratio η has a sigmoid shape and, starting from the effective threshold $E_{thr} = (9.9 \pm 0.1)$ MeV, increases rapidly and reaches saturation in the region of ~ 18 MeV.

The measured experimental dependences of isomeric relations on the maximum energy of the braking spectrum $\eta = f(E_{\gamma max})$ allow, by using the available total cross-sections of $^{82}$Se(γ, n)$^{81}$Se reactions, to calculate partial cross-sections of isomeric states in $^{82}$Se(γ, n)$^{81m}$Se. The calculation of the cross-section $\sigma_m$ was performed by the inverse matrix method [7] with a step ΔE = 0.5 MeV. In calculating the cross-section $\sigma_m(E)$, the curve $\eta(E_{\gamma max})$ was taken, which was obtained as a result of fitting the experimental data with the Boltzmann curve. As a result, the squares in Fig. 2 give the cross-section of the excitation of metastable states in the reaction (γ, n) on the $^{82}$Se nucleus.

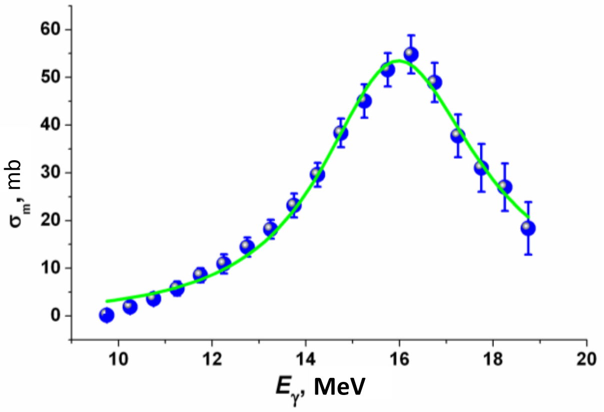

*Fig. 2. Cross-section of excitation of metastable states in the reaction (γ, n) on the $^{82}$Se nucleus*

In Fig. 2 shows that the section $\sigma_m(E)$ has a single hump shape with a maximum at an energy of ~ 16.25 MeV. The solid curve in Fig. 2 shows the result of fitting the cross-section $\sigma_m(E)$ by the Lorentz curve:

$$\sigma_m = \sigma_0 \cdot \frac{\Gamma_0^2 E^2}{(E^2 - E_0^2) - \Gamma_0^2 E^2}.$$

The curve was approximated by the method of least squares. Here $\sigma_0$, $E_0$, and $\Gamma_0$ are parameters. As a result, the following values of parameters were obtained: $\sigma_0 = (53.52 \pm 0.98)$, $E_0 = (15.98 \pm 0.04)$, $\Gamma_0 = (4.07 \pm 0.13)$.

Theoretical calculation of $^{82}$Se(γ, n)$^{81m}$Se reaction cross-sections is important, followed by comparing theoretical data with experimental results. Theoretical estimates were performed using the TALYS-1.9 software package [8], a set of modern models describing the process of nuclear reactions collected in one code.

The following procedure was used in such calculations: a gamma quantum with energy $E_\gamma$ ($E_\gamma$=$E_c$) and a spectrum ($J_c$, $\pi_c$) of possible values for spin and parity falls on the target nucleus with parameters ($Z_i$, $N_i$). Next, the full cross-section of the photo absorption $\sigma_{tot}$ is calculated, for which the experimentally obtained parameters of giant resonances are used [1]. Finally, it is assumed that the decay of the excited nucleus occurs due to two processes: a semi-direct mechanism [8], the share of which is 1.694% at $E_\gamma$ = 12 MeV, 9.0% at $E_\gamma$ = 16 MeV, and 18.2% at $E_\gamma$ = 20 MeV, and statistical Hausber-Feschbach process [9].

Neutron emission is calculated at specific levels (zones) of the daughter nucleus, considering the permeability coefficients $T_l$, calculated by the optical model [10]. In this case, up to the E = 3 MeV [11] of excitation energy of the daughter nucleus, the known discrete energy levels from the RIPL-3 database were taken [11].

At higher excitation energies of the daughter nucleus, the spectrum of excited states was considered continuous. It was divided into 50 energy zones and was described by the density of levels ρ (*E*, J, π). During the decay of the studied nucleus from a certain energy zone of the continuous spectrum, the average effective permeability coefficient $T_l$ was used. The density of levels ρ was calculated using the Fermi gas model with energy displacement [12].

A comparison of theoretical and experimental cross sections is shown in Fig. 3.

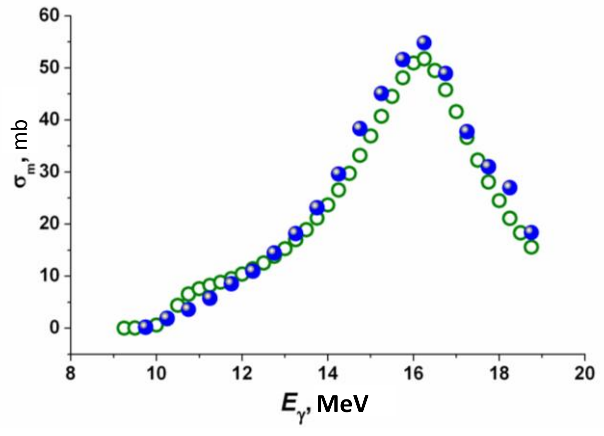

*Fig. 3. Comparison of experimental cross sections of $^{82}$Se(γ, n)$^{81m}$Se reaction with the theoretical calculation*

Black squares show the result of the experiment, and circles are the result of theoretical calculation. A comparison of the results shows that the theory satisfactorily describes the experimental cross-sections of the excitation of isomeric states in the $^{82}$Se(γ, n)$^{81m}$Se reaction. This agreement indicates the main contribution of the statistical mechanism in the cross-section of the studied (γ, n)$^{m}$ reaction.

## CONCLUSIONS

Experimental studies of the $^{82}$Se(γ, n)$^{81m}$Se reaction were performed on the brake beam of gamma quanta of the M-30 microtron in the region of gamma quanta energies of 9…19 MeV.

As a result of measurements, the ratio of $Y_m$ yields of the isomeric state to the total yield of the $^{82}$Se(γ, n)$^{81m}$Se reaction was determined, which made it possible to calculate both the absolute yield and the cross-section of the $^{82}$Se(γ, n)$^{81m}$Se reaction using the full (γ, n) cross-section [1]

Using the software package TALYS-1.9 [8], theoretical calculations of the cross-section of the (γ, n) reaction were performed, which agree satisfactorily with the experiment, which indicates the dominance of the statistical mechanism in the studied reaction (γ, n)$^{m}$.

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*Article received 28.09.2022*

# ВИВЧЕННЯ ПЕРЕРІЗУ ЗБУДЖЕННЯ ІЗОМЕРНОГО СТАНУ $7/2^+$ ЯДРА $^{81}$Se В РЕАКЦІЇ (γ,n) МЕТОДОМ ІЗОМЕРНИХ ВІДНОШЕНЬ ВИХОДІВ

***В.М. Мазур, З.М. Біган, П.С. Деречкей, О.М. Поп***

Селен відомий перехідним характером області від легких до середньоважких ядер і їх недостатньою вивченістю. Виміряно вихід реакції $^{82}$Se(γ, n)$^{81m}$Se та розраховано її переріз у діапазоні енергій гамма-випромінювання 9…19 МеВ. Проведено порівняння результатів експерименту з теоретичними розрахунками, виконаними за допомогою програмного комплексу TALYS-1.9. Було виявлено домінування статистичного механізму для цієї (γ, n)-реакції.