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Activation Level and Probabilities of Electromagnetic γ-transitions in the Reaction $^{77}Se(\gamma,\gamma')^{77m}Se$

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Abstract

The dependence of the absolute yield from energies for reaction $(\gamma,\gamma')^m$ on the nucleus ^{77}Se was approximated by fit dependences (lines). Due to the visually detected fracture of the reaction yield, the energy interval 5.75-8.0 MeV is conventionally divided into two parts. For the transition step as one experimental point, the left part was approximated to 6.6 MeV, and the right part - from 6.26 MeV. There approximations were eight for both intervals. Given the features of the calculation and the minimum values for χ^2, the "best" two fits are approximation dependences in the neighborhood of the intersection point x_0 for the left and right arrays of energies. The energy for the activation level (the intersection point for these functions) is $E_a \approx 6.35$ MeV. The scheme of electromagnetic γ-transitions for nucleus ^{77}Se are constructed and analyzed. Possible transitions to the isomeric level from higher levels are indicated. Weiskopf model was used to estimate the values of the reduced probabilities of electric *EJ*- and magnetic *MJ*- transitions, the probabilities of transitions per unit time and half-life. The theoretical values of the half-lives $T_{1/2}$ are compared with the experimental data. Prospects for further use of the obtained results for topical problems of nuclear physics are discussed.

Keywords:

Activation Level;
Reaction Yield;
Fracture;
Probabilities of γ-transitions;
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1- Introduction

The main purpose of most papers on the study of reaction (γ,γ') with isomer formation was to obtain an energy dependence of the effective cross-section of the reaction in a relatively wide energy range at 8-25 MeV with a relatively large step of 0.5-1.0 MeV [1, 2]. Studies have shown that near the threshold of photonuclear reactions (γ,n) and (γ,p), the cross-section reaches a maximum, and in the region of the giant resonance it first decreases and then increases again. The second area of research is the measurement of yields for reactions (γ,γ') in the small energy range at 1.5-6.0 MeV, but in steps of 0.1-0.2 MeV. The points of deviation of the energy dependence of the yield from the monotonically increasing curve make it possible to determine the values of the individual activation levels or groups of levels, through which the isomers of the nucleus are populated.

In Bohinyuk et al. (2015), Zhaba and Holovchak (2017), Bohinyuk et al. (2015), Zhaba and Gohman (2018) and Gohman and Zhaba (2019) studies, the dependences of the absolute yield from energies for reaction $(\gamma,\gamma')^m$ on the nuclei ^{77}Se, ^{79}Br, ^{89}Y, ^{103}Rh, ^{111}Cd, ^{137}Ba, ^{179}Hf, ^{197}Au and ^{199}Hg were analyzed for the presence of such fractures [2-6]. The number of found activation levels in each of these $(\gamma,\gamma')^m$- reactions was ranges from one to three values.

Selenium is widely used. Example, it is necessary for agronomic biofortification of leafy vegetables grown with isotopically labelled selenium ^{77}Se [7], for selenium isotope fractionation during adsorption by Fe, Mn and Al oxides [8], for selenium-isotopic signature toward mass-spectrometric identification and for enzyme activity assay [9], for search of ratios of cross sections of isomeric and ground states in $^{77,79,81,83}Se$ [10], for research of solid-state ^{77}Se

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nuclear magnetic resonance of organoselenium Compounds through cross polarization magic angle spinning method [11].

In this paper we use approach of the Bohinyuk et al. (2015) research [2] to find activation levels for the selenium nucleus. According to this approach, the reaction yield regions are broken down into pre- and post- fracture parts. They are then approximated by lines.

2- The Energy Dependence of the Yields for Reaction $(\gamma,\gamma')^m$

During the period 1990-2010 years, at the accelerator as microtron M-10 of UzhNU thorough studies of the reaction $A(\gamma,\gamma')A^m$ were carried out on groups of averages and heavy nuclei. The experimental setup, the experimental procedure and the results of data processing have been described in detail in the papers reviews [2, 12-14]. Such studies covered the intermediate energy region at 5-10 MeV.

Data in Bohinyuk et al. (2015) study [2] presents the mean square errors for a series of 5-8 independent absolute measurements for the yield of reaction (γ,γ’) for nuclei ^{77}Se, ^{79}Br, ^{89}Y, ^{103}Rh and ^{111}Cd. As can be seen, the monotonically increasing course of the curves is disturbed at some energy values. Therefore, these energy dependencies of the yields were analyzed for fractures, because the fracture points correspond to the energy of the activation level.

The characteristics for products of ^{77}Se(γ,γ’)^{77m}Se reaction (in particular the ^{77m}Se isomers) are described in detail in Stone (2005), Tuli (2011) and Firestone et al. (1996) researches [15-17].

The flowchart of the scientific study in this paper is presented in Figure 1. The relevant elements of the flowchart will be considered further.

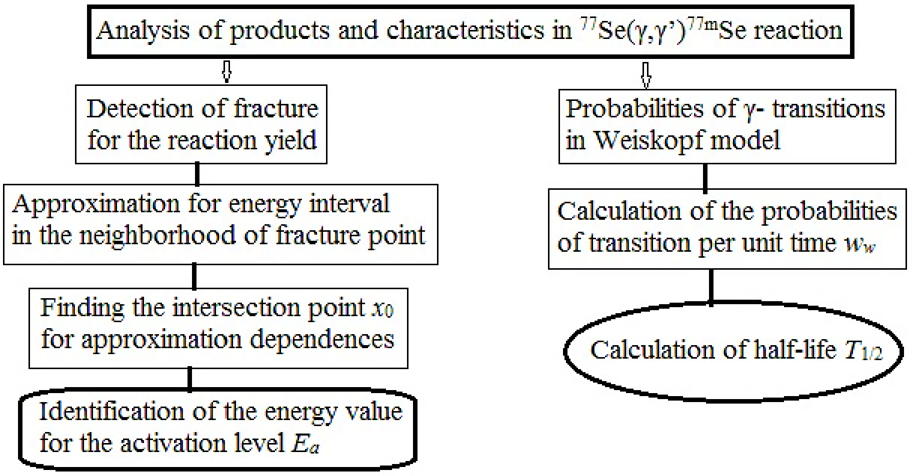

Figure 1. The flowchart of the scientific study.

The experimental data from Bohinyuk et al. (2015) [2] study for ^{77}Se(γ,γ’)^{77m}Se reaction were approximated by a line:

$$y = a + bx \tag{1}$$

Due to the visually detected fracture of the reaction yield, the energy interval is conventionally divided into two parts, where 5.75 and 8.0 MeV are the extreme left and right points, respectively. The left part was approximated to 6.6 MeV, and the right part - from 6.26 MeV. The transition step is one experimental point. There were four steps for the left and right intervals, i.e. by four approximations (fits 1-4 and 5-8, respectively).

In Table 1 is shows the approximation results for a specific interval in the neighborhood of fracture point for the yield of reaction. The parameters *a* and *b* for lines are given. To evaluate the quality of the approximation, the following parameters are calculated:

1) Standard deviation of the fit:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}\left(y_i^{(\exp)} - y_i(a,b)\right)^2}{N-P}}$$

2) χ^2 per degree of freedom of function:

$$\chi^2 = \frac{1}{N-P}\sum_{i=1}^{n}\left(y_i^{(\exp)} - y_i(a,b)\right)^2 \tag{2}$$

3) Correlation coefficient *R*.

The accuracy of the approximation is characterized by (2), where *N* is the number of points for the array y_i of the experimental data; $y_i(a,b)$ is approximating function (1); *a*, *b* is parameters; *P*=2 is the number of parameters for function (1).

In the end, the "best" or "worse" approximation can be estimated by comparing the correlation coefficient *R* (or value χ^2), but the following two circumstances should be considered: 1) when approximating, we have different width of energy interval; 2) in all cases, the approximation is performed by one function (line).

Table 1. Parameters of approximate dependencies.

Marking	Energy interval *E*, MeV	σ	χ^2	*R*	*a*	*b*
fit 1	5.75-6.35	0.18336	**0.03362**	0.92436	-12.0545	2.27559
fit 2	5.75-6.40	0.47372	0.22441	0.82276	-18.2566	3.31179
fit 3	5.75-6.50	0.46065	0.21220	0.86441	-19.4285	3.50653
fit 4	5.75-6.60	0.44754	0.20030	0.89802	-20.3446	3.65810
fit 5	6.26-8.00	1.18620	**1.40707**	0.97481	-54.0927	8.89892
fit 6	6.31-8.00	1.20643	1.45546	0.97306	-54.9060	9.00813
fit 7	6.35-8.00	1.23532	1.52602	0.97043	-55.5909	9.09983
fit 8	6.40-8.00	1.27532	1.62645	0.96555	-55.3941	9.07353

The visual representation of the obtained approximate dependences fits 1-8 is shown in Figure 2. A detailed examination in the neighborhood of the intersection point of these lines is given in Figure 3.

Using the values of the parameters *a* and *b* (Table 1) for the corresponding approximations, it is possible to determine the intersection points of fits 1-4 and 5-8 for the corresponding energy intervals of approximation. To do this, we use the solution of simple linear two equations:

$$a_i + b_i x_0 = a_j + b_j x_0$$

Where the indices *i* and *j* characterize fits 1-4 and 5-8 respectively. Numerical values of the intersection points x_0 are shown in Table 2. As the analysis of the obtained values of x_0 shows, the fracture of the experimental curve of yield is in the range ΔE=6.35-6.48 MeV. This value corresponds to the activation level E_a. In Bohinyuk et al. (2015) [2] study for ^{77m}Se, the corresponding E_a value was 6.32 MeV.

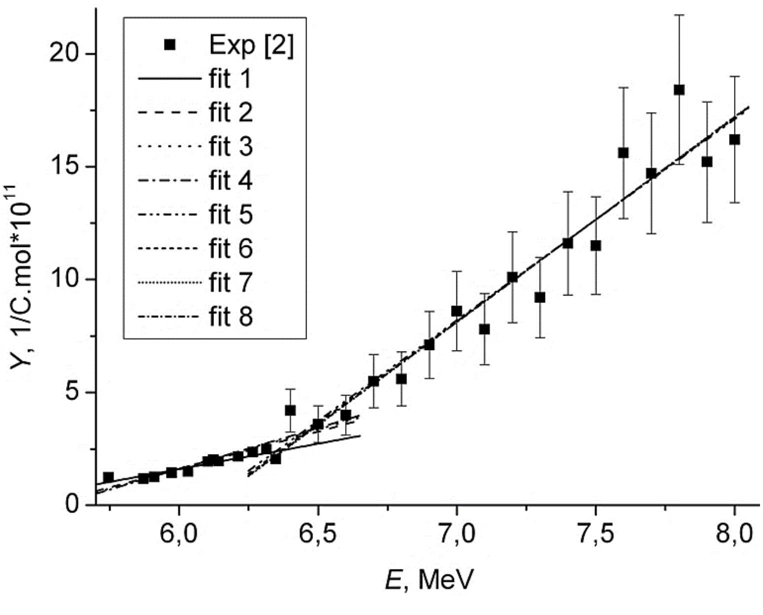

Figure 2. Energy dependence of the absolute yield for the reaction ^{77}Se(γ,γ')^{77m}Se.

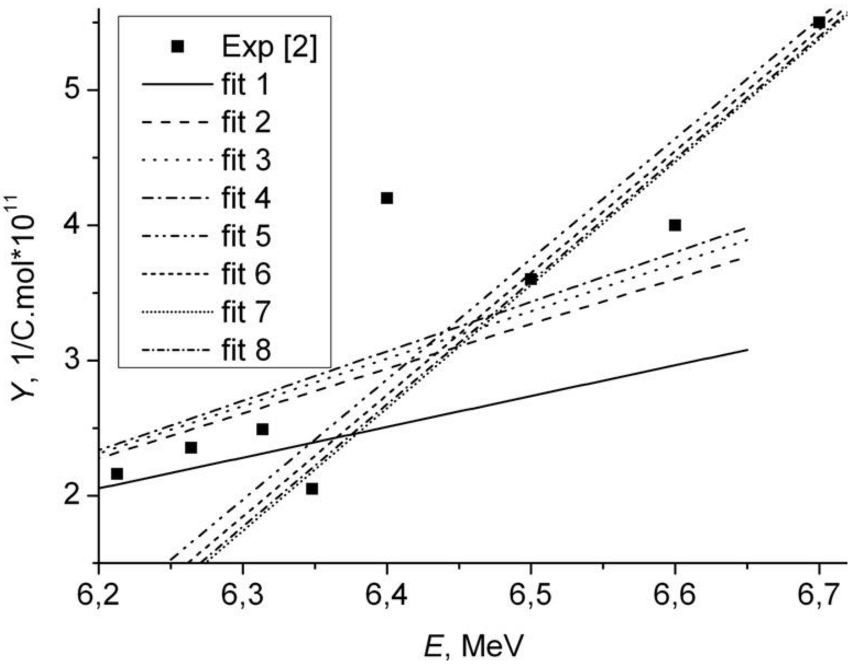

Figure 3. Approximation dependences in the neighborhood of the intersection point.

Given the features of the calculation and the minimum values for χ^2 (Table 1), the "best" approximations are fit 1 and fit 5 for the left and right arrays of energies respectively. Then the intersection point for these functions (Table 2) is placed at energy $E_a \approx 6.35$ MeV. This value is the energy of the activation level.

The values Ea for ^{77m}Se as 6.32 MeV in Bohinyuk et al. (2015) [2] study and 6.35 MeV in this paper differ in magnitude 0.03 MeV. The difference between the obtained values is insignificant, although our value is refined and more precisely defined.

Table 2. Intersection points for approximate dependencies.

	fit 5	fit 6	fit 7	fit 8
fit 1	**6.34699**	6.36484	6.37540	6.37966
fit 2	6.41404	6.43385	6.44554	6.45024
fit 3	6.42835	6.44857	6.46049	6.46529
fit 4	6.43947	6.46004	6.47215	6.47703

3- The Electric and Magnetic γ-transitions

The probabilities of γ-transitions can be estimated approximately by the formulas [18]:

$$W(EJ) \approx \frac{1}{\lambda}\left(\frac{R}{\lambda}\right)^{2J}; \qquad W(MJ) \approx \frac{1}{\lambda}\left(\frac{R}{\lambda}\right)^{2J+2} \tag{3}$$

Where $\lambda = \hbar c / E_\gamma$ is the wavelength for the emitted or absorbed γ- quanta's; J is multipolarity; EJ and MJ is the electric and magnetic γ- radiations with parity $P=(-1)^J$ and $P=(-1)^{J+1}$ respectively; R is the radius of the emitter nucleus.

Electromagnetic transitions from metastable levels to the isomeric level ^{77m}Se are given in Gohman and Zhaba (2019) study [6], where additionally the ratio of the probability for γ- transitions is specified:

$$\alpha = \frac{W(EJ)}{W(MJ)} \tag{4}$$

In addition to the magnitudes of the probabilities of γ- transitions (3), it is possible to calculate the values of the reduced probability of γ- radiation in Weiskopf model. This values for electrical EJ- and magnetic MJ- transitions is written as [19, 20].

$$B_w(EJ) = \frac{1}{4\pi}\left(\frac{3}{3+J}\right)^2 R^{2J} e^2 \tag{5}$$

$$B_w(MJ) = 0.307 A^{-2/3} B_w(EJ) \tag{6}$$

At value $B(EJ)=B_w(EJ)$ the probability of an electric transition per unit time is represented by the form [19, 20]:

$$w_w(EJ) = \frac{4.4(J+1)}{J\left[(2J+1)!!\right]^2}\left(\frac{3}{3+J}\right)^2\left(\frac{E_\gamma}{197}\right)^{2J+1} R^{2J}\cdot 10^{21}\ [s^{-1}], \tag{7}$$

Where the radius of the nucleus $R=r_0 A^{1/3}$ is given in units of fm; A is the atomic mass; energy in units of MeV. The probability of γ- decay w_γ determines the value of the half-life $T_{1/2}$ of nucleus relatively to γ- radiation [19, 20]:

$$T_{1/2} = \frac{\ln 2}{w_\gamma} = \frac{0.693}{w_\gamma} \equiv \frac{4.57\cdot 10^{-16}}{\Gamma_\gamma(eV)}\quad [s^{-1}] \tag{8}$$

Where $\Gamma_\gamma = \hbar w_\gamma$ is the radiation width of the level. The half-life (8) is the time at which half of the initial number of excited nuclei will break up as a result of γ- transitions. In the presence of EJ- type electric transitions only, the half-life is determined by the following approximative expression (with energy in units of MeV):

$$T_{1/2}(EJ) \cong 0.3125\frac{(1+J/3)^2}{1+1/J}\frac{\left[(2J+1)!!\right]^2}{E_\gamma}\frac{1}{(6.1\cdot 10^{-3}A^{1/3}E_\gamma)^{2J}}\cdot 10^{-19}\quad [s] \tag{9}$$

Given expression (6), in the presence of magnetic transitions of type MJ, the half-life is written as:

$$T_{1/2}(MJ) \cong \frac{T_{1/2}(EJ)}{0.307A^{-2/3}}\quad [s] \tag{10}$$

In Figure 4 shows a schematic representation of the electromagnetic transitions [17], that characterize of the nucleus ^{77}Se. Possible transitions to the isomeric level from higher levels and transitions from isomeric levels to the ground state are indicated. In Figure 4 shows the spin and parity values of the state on the left and the energy of level (in keV) on the right.

Given the marking on Figure 4, the values of the probabilities of transition per unit time $w_w = \ln 2/T_{1/2}$ and half-lives (9), (10) of electrical and magnetic transitions respectively have been calculated in the approach of Weiskopf's theory. The results are shown in Table 3, where J_i^P, J_f^P are the full moment of the initial and final states; P is the parity of the state. It is obvious that in most cases the calculated value of the half-life coincides with the experimental one [17].

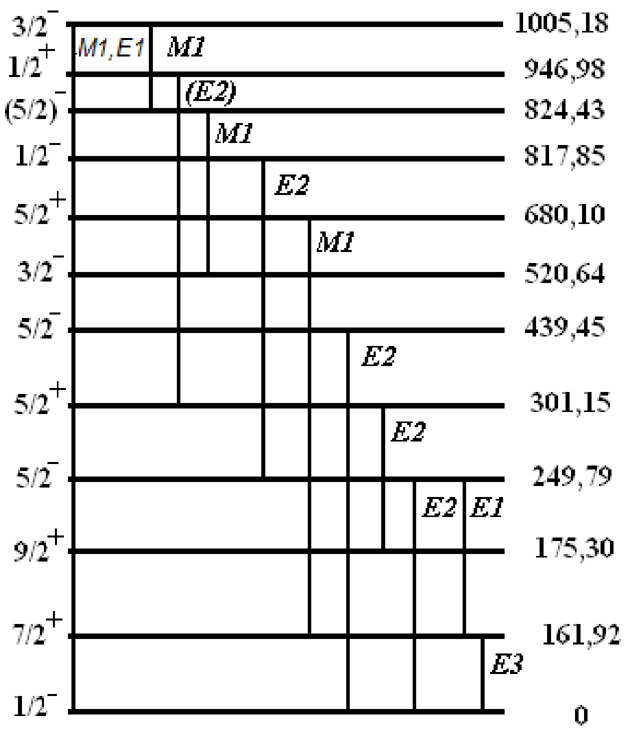

Figure 4. Electromagnetic transitions for ^{77}Se.

Table 3. Characteristics of electromagnetic transitions for ^{77}Se.

J_i^P	J_f^P	*EJ*; *MJ*	E_γ, keV	w_γ, s^{-1}	$T_{1/2}$, s (theory)	$T_{1/2}$, s (exp.)
$7/2^+$	$1/2^-$	*E*3	161.92	0.598	1.16	17.36
$5/2^-$	$7/2^+$	*E*1	87.87	$1.27\cdot10^{12}$	$5.47\cdot10^{-13}$	$9.7\cdot10^{-9}$
$5/2^-$	$1/2^-$	*E*2	249.79	$2.35\cdot10^{7}$	$2.95\cdot10^{-8}$	$0.9\cdot10^{-8}$
$5/2^+$	$9/2^+$	*E*2	125.84	$7.62\cdot10^{5}$	$9.10\cdot10^{-7}$	–
$5/2^-$	$1/2^-$	*E*2	439.45	$3.96\cdot10^{8}$	$1.75\cdot10^{-9}$	$2.3\cdot10^{-11}$
$1/2^-$	$5/2^-$	*E*2	568.07	$1.43\cdot10^{9}$	$4.85\cdot10^{-10}$	–
$1/2^+$	$5/2^+$	(*E*2)	645.83	$2.71\cdot10^{9}$	$2.55\cdot10^{-10}$	–
$3/2^-$	$1/2^-$	*E*1	1005.19	$1.89\cdot10^{15}$	$3.65\cdot10^{-16}$	–
$5/2^+$	$7/2^+$	*M*1	518.18	$4.41\cdot10^{12}$	$1.57\cdot10^{-13}$	–
$(5/2)^-$	$3/2^-$	*M*1	303.79	$8.88\cdot10^{11}$	$0.78\cdot10^{-12}$	$0.52\cdot10^{-12}$
$3/2^-$	$(5/2)^-$	*M*1	180.75	$1.87\cdot10^{11}$	$3.71\cdot10^{-12}$	$3.2\cdot10^{-12}$
$3/2^-$	$1/2^-$	*M*1	1005.19	$3.22\cdot10^{13}$	$2.15\cdot10^{-14}$	–

4- Conclusion

The dependence of the absolute yield from energies for the reaction $(\gamma,\gamma')^m$ on the nucleus ^{77}Se is analyzed. For this purpose, fit dependences were used as straight lines. Only one value for activation levels for this reaction in the energy range of 5.75-8.00 MeV is described. The energy for the activation level is $E_a\approx6.35$ MeV.

The calculated values of the probabilities of transitions per unit time and half-life by Weiskopf model coincide with the experimental data in several orders of magnitude. Similar calculations of the values of the reduced probabilities of electric *EJ*- and magnetic MJ- transitions, the probabilities of transitions per unit time and half-life by Weiskopf model can be made for nuclides ^{89m}Y, ^{103m}Rh, ^{179m}Hf and others. It should be noted that the obtained probability values of electromagnetic γ-transitions can be useful for estimating the cross-sections of *E*1-*E*3 and *M*1-*M*2 excitation of atomic nuclei for low-energy isomeric states in the process of inelastic scattering of nonrelativistic electrons [21] (in the framework of the nonrelativistic plane wave Born approximation - PWBA method).

The obtained results for the activation level of ^{77m}Se will expand our understanding of the mechanisms and laws of excitation of isomeric states of atomic nuclei, as well as can replenish the databases of nuclear data and constants and find practical applications in physics of nucleus, elementary particles and high energy physics. In perspective, the data obtained in this paper can be used to investigate the shell configurations of transitions from the ground state of nuclei to activation levels (as was done for the ^{109}Ag, ^{115}In, ^{111}Cd nuclei in Sokolyuk (1998) [22] study), taking into account nuclear-physical data for isomers [15, 17]. They can also be used to analyze single-particle neutron or two-quasiparticle states and shape isomers [23] and in the development of gamma-ray laser on nuclear transitions [24].

5- Conflict of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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