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ESTIMATION OF GROSS-STRUCTURE PARAMETERS OF GIANT DIPOLE RESONANCE: 2. EXPERIMENTAL TESTING

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Experimental testing of a novel technique for determination of width and maximum of excitation function of a photonuclear reaction with dominant giant dipole resonance is conducted. The method is based on measurement of normalized reaction yield in a thin target, overlapping entirely a flux of X-rays and on processing of data obtained with the use of a developed analytical model. For the checking of method, the nickel and molybdenum foils of natural isotopic composition were activated by bremsstrahlung radiation at four energies of the electron beam in the range 40…95 MeV. The obtained parameters of cross-section of the reference reactions ^{58}Ni(γ,n)^{57}Ni and ^{100}Mo(γ,n)^{99}Mo are in good agreement with those presented in the available databases.

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INTRODUCTION

It was shown in work [1] on the basis of a developed analytical model for description of isotope generation in an X-ray beam of an electron accelerator (the S-model), that one can determine the width (FWHM) and maximum σ_{max} of the excitation function of a reaction with dominating giant dipole resonance (GDR) by the coefficient of photonuclear conversion (CPC) specified at a given energy of the primary electron beam. In current paper, the results of the experimental study of the novel technique on the example of reactions ^{58}Ni(γ,n)^{57}Ni and ^{100}Mo(γ,n)^{99}Mo are presented.

1. METHODS AND MATERIALS

1.1. DETERMINATION OF FWHM AND σ_{max} OF EXCITATION FUNCTION

The experimental value of CPC, $Y_0^{exp}(E_e)$, corresponding to the electron beam energy E_e, can be determined by the activity $A_{PNC}^{exp}(E_e)$ of a thin extended target overlapping completely the photon beam and normal to its axis (such a target is called a photonuclear converter, PNC), using the equation [1]

$$Y_0^{exp}(E_e) = \frac{eA_{PNC}(E_e)}{I\Delta\left[1-\exp(-\lambda t)\right]}, \quad (1)$$

where e is the electron charge; I is the average beam current; Δ is the mass thickness of PNC; t is the activation period, λ is the decay constant of an isotope-product. For a possible FWHM value of the excitation function of a reaction in Lorentz representation, Γ, one can calculate the corresponding maximum cross-section using the expression of the S-model

$$\sigma_{max}(\Gamma) = Y_0^{exp}(E_e)\frac{\overline{A}}{\eta(E_e)N_A\nu S(\Gamma,E_e)}, \quad (2)$$

where $\eta(E_e)$ is the energy conversion coefficient of electron into X-ray radiation; N_A is the Avogadro number; $\overline{A}$ is the average atomic mass of the target material; ν is the relative content of the isotope-target in it; S is the dimensionless factor depending on parameters of the excitation function, in particular, on its width Γ, and also on electron beam energy E_e [1].

For the each beam energy $E_{e,i}$, provided in the experiment, and also for the each variant of excitation function by width Γ of a reaction under study, one can ascertain the pair of parameters $\{\sigma_{max}(E_{e,i},\Gamma);\ \Gamma\}$, which meets the condition (2). In turn for the each such pair, one can calculate the reaction yield in a photonuclear converter by MC simulations, A_{PNC}^{sim}, and compare it with the experimental value $A_{PNC}^{exp}(E_{e,i})$ by the equation

$$dev^2(\Gamma,\sigma_{max,i}) = \left[A_{PNC}^{sim}(\Gamma,\sigma_{max,i}) - A_{PNC}^{exp}(E_{e,i})\right]^2. \quad (3)$$

From the condition $Min[\sum_i dev^2(\Gamma,\sigma_{max,i})]$, one can determine the Γ and σ_{max} values for the given reaction.

1.2. EXPERIMENT

The activation of samples was carried out at a LU-40m Linac of NSC KIPT [2]. The beam spectrum FWHM was not higher than 2%. Transformation of electron radiation into X-rays was carried out by a conversion target comprising the four tantalum plates each 1mm thick separated with the same gaps for cooling. The electron beam and its charge incident on the converter were measured in on-line mode using a magnetic induction probe. The beam size and position were determined with a wire scanner.

The two stacked foils, each by 3×3 cm in size and 0.1mm thick, from natural nickel and molybdenum were applied for testing the proposed method against the reactions ^{58}Ni(γ,n)^{57}Ni and ^{100}Mo(γ,n)^{99}Mo. Their cross-sections are quite different, characterized with dominating GDR and well-studied both theoretically [3] and experimentally [4 - 6]. The advantage of these reactions is also the absence of extra channels of the isotope-product generation. Such channels can arise, in particular, at the increase of photon energy and to distort the yield of a reaction under study.

The stacks of foils were positioned on the electron beam axis and activated for 1hour at each of the four electron energies in the range 40…95 MeV. After cooling, the gamma spectrometry of foils was carried out with the reduction of data obtained by EOB (Fig. 1). The activity of ^{57}Ni was determined by the number of pulses in the photopeak 1377.6 keV (81.7% branching ratio) and ^{99}Mo by line 739.5 keV (12.2%). The relative uncertainty of the activity determination is 8 and 5% for ^{57}Ni and ^{99}Mo, respectively.

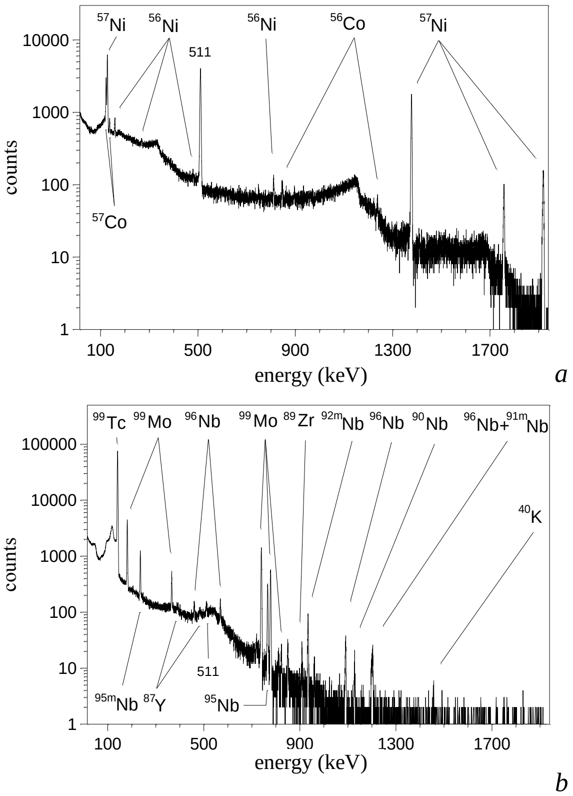

Fig. 1. γ-spectra of activated PNC from natural nickel (a) and molybdenum (b), E_e=40 MeV

1.3. MODELING

The MC simulations of photonuclear isotope generation in PNC was performed on the basis of a modified transport code GEANT4 [7]. A specially developed technique [8] was applied for speeding-up the computation of the reaction yield. Such a method enables to decrease the counting time approximately by four orders of values without diminution of accuracy. To fulfill such an approach, the classes G4UserSteppingAction and G4UserRunAction in GEANT4 were properly modified. It makes it possible, in particular, to use the TALYS-calculated cross-sections in the simulations of the reaction microyield along the photon trajectories in a target by the method [8]. The statistical uncertainty of the simulation results is not higher than 1%.

2. RESULTS AND DISCUSSION

2.1. ^{58}Ni(γ,n)^{57}Ni

In Table 1, the experimental data are given on the ^{57}Ni activity in PNC from natural nickel, reduced to average beam current of 1μA and 1h irradiation run, as well as the value of the product [$S(E_e)\cdot\sigma_{max}$], calculated by the formulae (1), (2). It should be noted, that the measured PNC activity, A^{exp}_{PNC}, overestimates systematically the results of the numerical experiment with the use of TALYS cross-section data but lies nearer to that calculated on the basis of the S-model [1].

Table 1

Characteristics of ^{58}Ni(γ,n)^{57}Ni reaction (experiment)

E_e	A^{exp}_{PNC}, kBq/μA·h	$[S(E_e)\cdot\sigma_{max}]\cdot10^{26}$, cm^2
40	360	1.17
60	527	1.60
80	647	1.93
95	693	2.04

The S-factor of the reactions ^{58}Ni(γ,n)^{57}Ni and ^{100}Mo(γ,n)^{99}Mo at different electron energies is given in work [1]. Hence the range of the possible σ_{max} and Γ values, complying with the condition (2), was specified (with allowance for the uncertainty of Y_0^{exp} (E_e) measurement). The yield of each reaction in PNC, corresponding to every such a pair of parameters, was obtained also by MC simulations (Tables 2-5, the values closest to the experimental data are denoted in bold). The region of σ_{max} and Γ parameters providing the most closeness of the calculated and experimental yield of the reaction was established with the use of equation (3) Fig. 2.

Table 2

Yield of ^{57}Ni in PNC, E_e = 40 MeV (simulations)

σ_{max}, mb	Γ, MeV			
	6	7	8	9
	A^{sim}_{PNC}, kBq/(μA×h)			
21	-	-	306	329
22	-	291	319	346
23	-	305	335	**362**
24	-	319	350	377
25	297	332	**364**	392
26	310	345	379	-
27	321	**359**	-	-
28	333	373	-	-
29	345	386	-	-
30	**356**	-	-	-

Table 3

Yield of ^{57}Ni in PNC, E_e = 60 MeV (simulations)

σ_{max}, mb	Γ, MeV			
	6	**7**	**8**	9
	A^{sim}_{PNC}, kBq/(μA×h)			
21	-	-	451	489
22	-	430	472	512
23	-	449	494	**536**
24	-	470	516	560
25	436	488	**537**	582
26	452	507	558	-
27	470	**528**	-	-
28	487	547	-	-
29	504	566	-	-
30	**524**	-	-	-

Table 4

Yield of ^{57}Ni in PNC, E_e = 80 MeV(simulations)

σ_{max}, mb	Γ, MeV			
	6	7	8	9
	A^{sim}_{PNC}, kBq/(μA×h)			
21	-	-	536	580
22	-	508	561	609
23	-	529	588	**637**
24	-	554	613	664
25	514	578	**638**	692
26	533	601	664	-
27	555	625	-	-
28	573	**648**	-	-
29	596	669	-	-
30	**617**	-	-	-

Table 5

Yield of ^{57}Ni in PNC, E_e = 95 MeV(simulations)

σ_{max}, mb	Γ, MeV			
	6	7	8	9
	A^{sim}_{PNC}, Bq/(μA×h)			
21	-	-	581	631
22	-	552	609	661
23	-	578	635	**691**
24	-	601	663	721
25	557	626	**692**	751
26	579	651	721	-
27	600	677	-	-
28	622	**704**	-	-
29	646	728	-	-
30	**668**	-	-	-

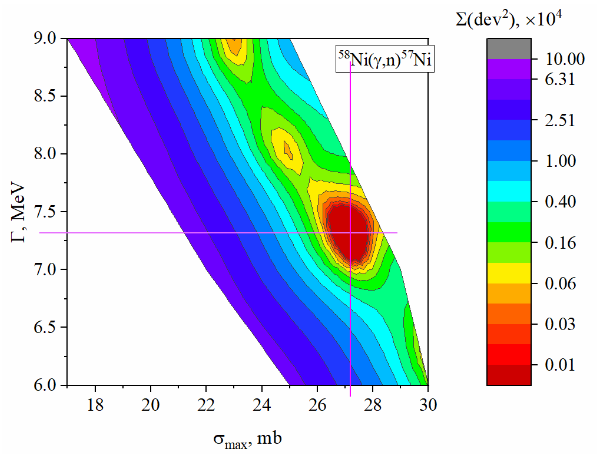

Fig. 2. Distribution of deviation square sums of calculated ^{57}Ni activity from experimental one in PNC from natural nickel

2.2. ^{100}Mo(γ,n)^{99}Mo

In Table 6, the experimental data on the normalized activity of ^{100}Mo in *PNC* from natural molybdenum and the product $[S(E_e)\cdot\sigma_{max}]$ for the reaction ^{100}Mo(γ,n)^{99}Mo are listed. The results of those data processing are presented in Tables 7-10 and in Fig. 3

Table 6

Characteristics of ^{100}Mo(γ,n)^{99}Mo reaction (experiment)

E_e	A^{exp}_{PNC}, kBq/μA·h	$[S(E_e)\cdot\sigma_{max}]\cdot10^{25}$, cm^2
40	124	0.74
60	169	0.94
80	196	1.07
95	204	1.10

Table 7

Yield of ^{99}Mo in PNC, E_e = 40 MeV (simulations)

σ_{max}, mb	Γ, MeV				
	3.5	3.75	4	4.25	4.5
	A^{sim}_{PNC}, kBq/(μA×h)				
130	-	-	-	-	113
135	-	-	-	113	118
140	-	-	111	117	**123**
145	-	108	115	121	127
150	107	113	119	**125**	131
155	110	116	**123**	129	135
160	113	120	127	133	140
165	117	**124**	130	137	144
170	121	128	134	142	-
175	**125**	132	139	-	-

Table 8

Yield of ^{99}Mo в PNC, E_e = 60 MeV (simulations)

σ_{max}, mb	Γ, MeV				
	3.5	3.75	4	4.25	4.5
	A^{sim}_{PNC}, kBq/(μA×h)				
130	-	-	-	-	150
135	-	-	-	148	156
140	-	-	146	154	162
145	-	144	152	159	**168**
150	140	148	158	165	173
155	145	154	162	**171**	179
160	150	159	**168**	176	185
165	154	164	173	182	191
170	159	**169**	178	187	-
175	163	174	184	-	-
180	**169**	179	-	-	-

Table 9

Yield of ^{99}Mo в PNC, E_e = 80 MeV (simulations)

σ_{max}, mb	Γ, MeV				
	3.5	3.75	4	4.25	4.5
	A^{sim}_{PNC}, kBq/(μA×h)				
130	-	-	-	-	170
135	-	-	-	169	177
140	-	-	167	176	184
145	-	163	173	182	191
150	160	170	179	189	**198**
155	165	175	185	**194**	204
160	170	181	191	201	210
165	175	187	**197**	207	217
170	181	192	203	213	-
175	186	**197**	208	-	-

Table 10

Yield of ^{99}Mo in PNC, E_e = 95 MeV (simulations)

σ_{max}, mb	Γ, MeV				
	3.5	3.75	4	4.25	4.5
	A_{PNC}^{sim}, kBq/(μA×h)				
130	-	-	-	-	182
135	-	-	-	181	189
140	-	-	178	187	197
145	-	175	184	194	**204**
150	171	181	191	**201**	211
155	176	187	197	208	218
160	182	193	**204**	215	225
165	187	199	210	221	231
170	193	**205**	216	228	-
175	199	211	223	-	-
180	**204**	217	-	-	-
185	210	-	-	-	-

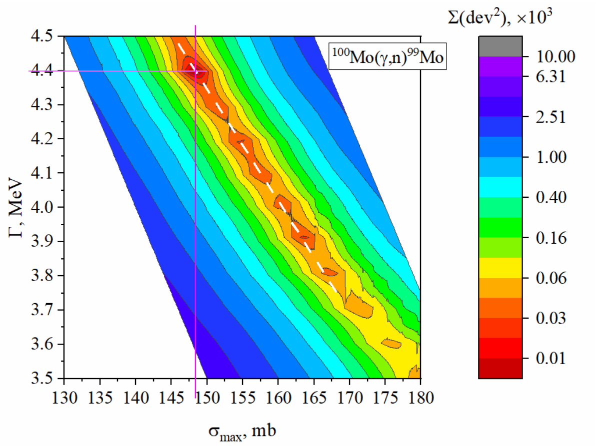

Fig. 3. Distribution of deviation square sums of calculated ^{99}Mo activity from experimental one in PNC from natural molybdenum

CONCLUSIONS

The proposed method enables to estimate the width (FWHM) and maximum of excitation function of a reaction with dominating giant dipole resonance on the basis of the simple experiments on activation of a thin extended target overlapping in full a flux of X-rays with specified end-point energy, and also of the developed analytical model for calculating the reaction yield in such a target. So, in Table 11, the σ_{max} and Γ values for the reactions ^{58}Ni(γ,n)^{57}Ni and ^{100}Mo(γ,n)^{99}Mo obtained by the novel technique, and also, for comparison, the data for those reactions calculated with the use of TALYS package, are given. It is evident, that the both sources provide close results. The two calculated values of Γ for the reaction ^{58}Ni(γ,n)^{57}Ni represent the ambiguous TALYS data. So, one of them is due a theoretically predicted local resonance in the front part of the excitation function (Γ =10.1 MeV, Fig. 4,a red curve) and without it (Γ=7.1 MeV), as it follows from the experiment [4].

It should be noted, that the Lorentz representation of excitation functions of the reference reactions with the Γ and σ_{max} values, obtained in this work (see the blue curves in Fig. 4) have appeared nearer to the experimental data as compared with their presentation obtained with the TALYS code.

Table 11

σ_{max} and Γ of reference reactions

Reaction	^{58}Ni(γ,n)^{57}Ni		^{100}Mo(γ,n)^{99}Mo	
Source	This work	TALYS	This work	TALYS
σ_{max}, mb	27.2	26.0	148.4	148.6
Γ, MeV	7.3	7.1;10.1	4.4.	3.9

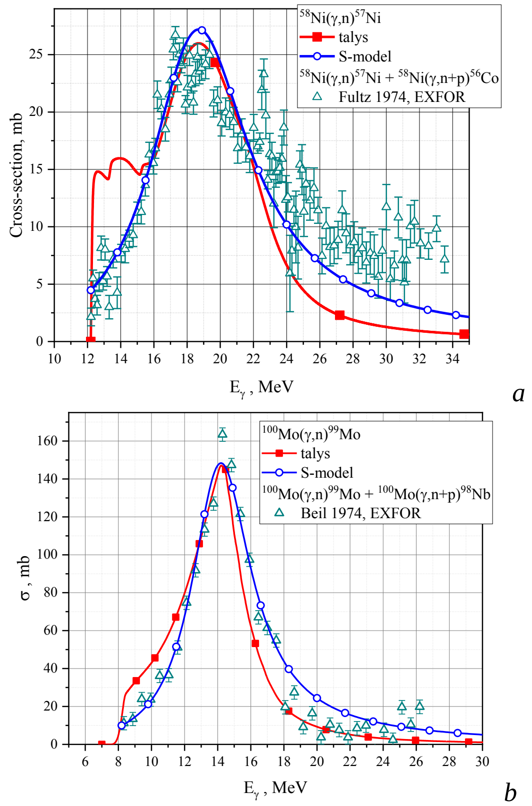

Fig. 4. Cross-section of reference reactions: ^{58}Ni(γ,n)^{57}Ni (a); ^{100}Mo(γ,n)^{99}Mo (b)

REFERENCES

1. V.L. Uvarov, A.A. Zakharchenko. Estimation of Gross-Structure Parameters of Giant Dipole Resonance: 1. A Method //*Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2021, № 3, p. 104-108.
2. M.I. Aizatskyi, V.I. Beloglasov, V.N. Boriskin, et al. State and Prospects of the Linac of Nuclear-Physics Complex with Energy of Electrons up to 100 MeV // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2014, № 3, p. 60-63.
3. The TALYS Code System, ftp://ftp.nrg.eu/pub/www/talys/talys.tar.
4. S.C. Fultz, B.A. Alvarez, B.L. Berman, P. Meyer. Photoneutron cross sections of ^{58}Ni and ^{60}Ni // *Phys. Rev. C.* 1974, v. 10, p. 608-619.
5. H. Beil, R. Bergere, P. Carlos, A. Lepretre, A. DeMiniac, A. Veyssiere. A study of the photoneutron contribution to the giant dipole resonance in doubly even Mo isotopes // *Nucl. Phys. A.* 1974, v. 227, p. 427-449.

6. Experimental Nuclear Reaction Data (EXFOR) https://www-nds.iaea.org/exfar/
7. J. Allison, K. Amako, J. Apostolakis, et al. Recent developments in Geant4 // *NIM.* 2016, A 835, p. 186-225.
8. V.I. Nikiforov, V.L. Uvarov. Development of the technique embedded into a Monte Carlo transport system for calculation of photonuclear isotope yield // *Nukleonika*. 2012, 57(1), p. 75-80 (in Russian.)

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ОЦЕНКА ПАРАМЕТРОВ ГРОСС-СТРУКТУРЫ ГИГАНТСКОГО ДИПОЛЬНОГО РЕЗОНАНСА: 2. ЭКСПЕРИМЕНТАЛЬНАЯ ПРОВЕРКА

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Проведена экспериментальная проверка нового метода определения ширины и максимума функции возбуждения фотоядерной реакции с доминированием гигантского дипольного резонанса. Метод основан на измерении нормированного выхода реакции в тонкой мишени, перекрывающей полностью поток тормозного излучения ускорителя электронов, и обработке полученных данных с использованием разработанной аналитической модели. Для проверки метода фольги из никеля и молибдена природного состава были активированы тормозным излучением при четырех значениях энергии пучка электронов в диапазоне 40…95 МэВ. Полученные параметры сечений референтных реакций ^{58}Ni(γ,n)^{57}Ni и ^{100}Mo(γ,n)^{99}Mo хорошо согласуются с представленными в имеющихся базах данных.

ОЦІНКА ПАРАМЕТРІВ ГРОСС-СТРУКТУРИ ГІГАНТСЬКОГО ДИПОЛЬНОГО РЕЗОНАНСУ: 2. ЕКСПЕРИМЕНТАЛЬНА ПЕРЕВІРКА

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Проведена експериментальна перевірка нового методу визначення ширини і максимуму функції збудження фотоядерної реакції з домінуванням гігантського дипольного резонансу. Метод базується на вимірюванні нормованого виходу реакції у тонкій мішені, що повністю перекриває потік гальмівного випромінювання прискорювача електронів, і обробці одержаних даних з використанням розробленої теоретичної моделі. Для перевірки методу були активовані фольги з нікелю та молібдену природного складу гальмівним випромінюванням при чотирьох значеннях енергії пучку електронів у діапазоні 40…95 МеВ. Одержані параметри перерізів референтних реакцій ^{58}Ni(γ,n)^{57}Ni та ^{100}Mo(γ,n)^{99}Mo добре узгоджуються з такими, що представлені у наявних базах даних.