https://doi.org/10.46813/2022-139-016

AN ESTIMATE OF CROSS-SECTION OF PHOTO-PROTON REACTIONS ON $^{47\text{-}50}$Ti ISOTOPES

N.P. Dikiy, A.A. Zakharchenko, Yu.V. Lyashko, V.L. Uvarov, V.A. Shevchenko, A.Eh. Tenishev
National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine
E-mail: uvarov@kipt.kharkov.ua

Development of technology of isotope production at an electron accelerator, in particular ^{47}Sc by the ^{48}Ti(γ,p)^{47}Sc reaction, requires accurate data on cross-sections of this and other photo-proton reactions on the titanium isotopes, as the available data are characterized by considerable scatter. A simple technique for estimating maximum and width of the excitation function of a reaction with dominating giant dipole resonance was proposed and validated earlier. The method is based on measurement of normalized reaction yield in a thin target, overlapping completely a flux of X-rays, and processing of data obtained with the use of a developed analytical model. The joint activation of foils from natural nickel, molybdenum and titanium by bremsstrahlung radiation with end-point photon energy in the range 40…95 MeV was carried out. The characteristics of the reactions ^{48}Ti(γ,p)^{47}Sc, ^{49}Ti(γ,p)^{48}Sc, ^{50}Ti(γ,np)^{48}Sc, ^{47}Ti(γ,p)^{46}Sc, and ^{48}Ti(γ,np)^{46}Sc are studied by new technique. For verifying results, the well-examined ^{58}Ni(γ,n)^{57}Ni and ^{100}Mo(γ,n)^{99}Mo reactions, taking place in the nickel and molybdenum foils, are used.

PACS: 07.05.Tr, 41.50.+h; 41.75.Fr; 78.70En

INTRODUCTION

One of developed methods for production of promising therapeutical β-emitter ^{47}Sc ($T_{1/2}$ = 80.4 h) is a photonuclear technique based on the reaction ^{48}Ti(γ,p)^{47}Sc [1, 2]. In addition to this nuclide, the most active scandium isotopes ^{48}Sc ($T_{1/2}$ = 43.7 h) and ^{46}Sc ($T_{1/2}$ = 83.8 d) can be generated. The accurate data on the cross-sections of those isotope generation are required for estimation of capacity of the technology as well as isotopic purity of the end-product. At the same time, the reaction parameters presented in the available databases are characterized by the considerable spread, that amounts to hundred percent and even higher [3 - 6]. As an example, some data on the ^{48}Ti(γ,p)^{47}Sc reaction are demonstrated in Fig. 1.

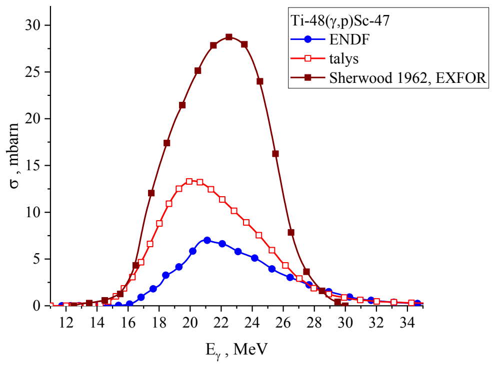

Fig. 1. Cross-section of reaction ^{48}Ti(γ,p)^{47}Sc

In general, excitation function of a photonuclear reaction can to have rather complicate form. Conversely, for estimating the yield of a reaction with dominant giant dipole resonance (GDR), it is enough to know the key parameters of its gross-structure, namely:

- the energy threshold, E_{th};
- the photon energy corresponding to maximum cross-section, E_{max};
- FWHM of the excitation function, Γ;
- the maximum cross-section, σ_{max}.

The two last characteristics reveal the most uncertainty. In current work, the σ_{max} and Γ parameters of the excitation functions of the photo-proton reactions on the $^{47\text{-}50}$Ti isotopes are determined with the use of a novel technique [7].

1. METODS AND MATERIALS

1.1. DETERMINATION OF σ_{max} AND Γ

1.1.1. In work [8], a model for the analytical description of isotope yield in a flux of bremsstrahlung radiation of an electron accelerator was proposed. It was shown, that the activity of a target is directly proportional to a quantity called the coefficient of photonuclear conversion (CPC), Y_0. It represents the yield of isotope-product in a thin target, overlapping completely the photon flux (such a target is called the photonuclear converter, PNC), normalized to the one electron with energy E_e of the primary electron beam and to the mass thickness of PNC

$$Y_0 = \frac{N_A}{\bar{A}} \nu \int_{E_{th}}^{E_e} n_\gamma(E_e, E)\sigma(E)dE\,, \tag{1}$$

where N_A – is the Avogadro number; $\bar{A}$ is the average atomic mass of the target material; ν – is the relative concentration of the isotope-target nuclei; $n_\gamma(E)$ – is the spectral density of bremsstrahlung photons normalized to the one beam electron; $\sigma(E)$ – is the reaction cross-section.

If $\sigma(E)$ is known, one can calculate CPC by MC simulations. It can be also determined experimentally ($Y_0^{\exp}$) from the measured activity of PNC, $A_{PNC}^{\exp}(E_e)$, using the expression

$$Y_0^{\exp}(E_e) = \frac{eA_{PNC}(E_e)}{I\Delta\left[1-\exp(-\lambda t)\right]}\,, \tag{2}$$

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 the isotope-product.

It should be noted, that $Y_0^{\exp}$ can be determined with minimal uncertainty [7]. Thus, it is suitable for checking the accuracy of data on the reaction cross-section obtained from the different sources.

1.1.2. The excitation function of a reaction with dominating GDR can be represented in the Lorentzian form, as follows,

$$\sigma(E) = \sigma_{\max} \frac{(E\Gamma)^2}{(E^2 - E_{\max}^2)^2 + (E\Gamma)^2} . \quad (3)$$

It was shown in work [8], that an estimate of CPC in such a case can be obtained on the basis of an analytical model (called the S-model) by the equation

$$Y_0^S(E_e) = \eta(E_e) \frac{N_A}{\bar{A}} \nu \sigma_{\max} S(E_e) , \quad (4)$$

where $\eta(E_e)$ – is the coefficient of energy conversion of electron radiation into X-rays; S – is the dimensionless factor depending on the E_{th}; E_{max} and Γ parameters of the excitation function, and also on the energy of the primary electron beam E_e. It has been established on the basis of the S-model, that if E_{th} and E_{max} being specified, one can determine the possible range of Γ and $\sigma_{\max}$ parameters by the CPC values corresponding to a number of electron energies $E_{e,i}$ [7]. So, the experimentally measured PNC activity, $A_{PNC}^{\exp}(E_{e,i})$, enables to calculate $Y_0^{\exp}(E_e)$ using the formula (2), and also to determine the product $[\sigma_{\max} \cdot S(E_e)]$ by the formula (4). For the Γ values in the supposed range, one can calculate the corresponding $S(\Gamma, E_{e,i})$ and $\sigma_{\max}(\Gamma, E_{e,i})$ characteristics. Hence for the every variant of excitation function with parameters Γ and $\sigma_{\max}(\Gamma, E_{e,i})$, obtained in such a way, it is possible to determine by MC simulations the yield of the reaction in PNC, A_{PNC}^{sim}, and to compare it with the experimental value using the equation

$$dev^2(\Gamma, \sigma_{max,i}) = \left[A_{PNC}^{sim}(\Gamma, \sigma_{max,i}) - A_{PNC}^{\exp}(E_{e,i}) \right]^2 . \quad (5)$$

From the condition $Min[\sum_i dev^2(\Gamma, \sigma_{\max,i})]$, one can to establish the actual range of Γ and $\sigma_{\max}$ for the given reaction.

The experimental checking of the method on the well-studied ^{58}Ni(γ,n)^{57}Ni and ^{100}Mo(γ,n)^{99}Mo reactions has demonstrated good agreement with the available data [9]. These reactions were used also for verifying results obtained on the titanium isotopes.

1.1.3. Modeling.

Simulations of processes of electron radiation conversion into X-rays, as well as of photonuclear isotope generation were conducted on the basis of a modified transport code GEANT4 [10]. For the high-speed calculation of reaction yield, a specially developed technique, providing the decrease of counting time by four orders of values without loss of accuracy, was used [11]. To make possible the usage of various data on the photonuclear cross-sections, including those taken from the TALYS package, the classes G4UserSteppingAction and G4UserRunAction in the GEANT4 code were properly modified. The statistical uncertainty of simulations was not higher than 1%.

1.2. EXPERIMENT

1.2.1. Activation of samples was conducted at a LU40m Linac of NSC KIPT [12]. The four beam energies in the range 40…95 MeV were used. FWHM of the beam spectrum was not higher than 2%. In each run, a stack of 3 foils by 3×3 cm in size was irradiated. The two foils from natural nickel and molybdenum each by 0.1 mm in thickness were applied to check the activation regime against the yield of the ^{58}Ni(γ,n)^{57}Ni and ^{100}Mo(γ,n)^{99}Mo reactions. The third foil 0.05 mm thick from titanium of natural isotopic composition was used for the measurement of cross-section of the reactions on the isotopes $^{47-50}$Ti. The isotopic characteristics of the materials are listed in Table 1.

Table 1

Isotopic composition of targets

Material	$\bar{A}$	Isotope-target	ν, rel.un.
Ti	47.90	^{47}Ti	0.073
		^{48}Ti	0.738
		^{49}Ti	0.055
		^{50}Ti	0.054
Ni	58.71	^{58}Ni	0.683
Mo	95.94	^{100}Mo	0.0963

1.2.2. After activation of each stack at a given electron beam energy $E_{e,i}$ and cooling for 24 h, the measurement of γ-activity of the foils was carried out with a HPGe-spectrometer. The ^{47}Sc activity was determined at the line 159.4 keV (68% branching ratio). The most long-lived by-product ^{46}Sc was measured by averaging the counting rate in the photopeaks 889.2 keV (100%) and 1121 keV (100%). The activity of ^{48}Sc was determined at the lines 983.5 keV (100%), 1037 keV (97.5%), and also 1312 keV (100%). The total uncertainty of measurement of the scandium isotope activity was 9, 5 and 4% for ^{47}Sc, ^{46}Sc, and ^{48}Sc, respectively.

2. RESULTS AND DISCUSSION

2.1. MAIN REACTIONS

2.1.1. In Table 2, the main reactions contributing to photogeneration of isotopes $^{46-48}$Sc in natural titanium, as well as the key parameters of their cross-sections, taken from the TALYS package, are listed.

Table 2

Parameters of main photo-proton reactions of $^{46-48}$Sc production in natural titanium (TALYS)

Isotope-product	Reaction	E_{th}, MeV	E_{max}, MeV	Γ, MeV	σ_{max}, mb
^{46}Sc	^{47}Ti(γ,p)	10.5	20.3	6.4	9.8
	^{48}Ti(γ,np)	19.9	30.5	11.7	3.8
	^{49}Ti(γ,2np)	25.6	43.4	18,4	1.9
^{47}Sc	^{48}Ti(γ,p)	11.4	20.2	7.5	13.4
	^{49}Ti(γ,np)	19.6	28.2	14.5	3.6
	^{50}Ti(γ,2np)	26.7	46.8	28.8	1.4
^{48}Sc	^{49}Ti(γ,p)	11.3	21.2	6.0	5.0
	^{50}Ti(γ,np)	20.1	34.8	16.5	1.1

In Tables 3-5, the data are presented on the yield of scandium isotopes in PNC 0.05 mm thick from natural titanium, obtained by MC simulations with the use of the TALYS data and for all those channels of isotope generation. It is evident, that the (γ,p) and (γ,np) reactions provide the dominating contribution to the total activity of an isotope-product.

Table 3

Reduced activity of ^{47}Sc in PNC, kBq/μA·h (simulations)

E_e, MeV	^{48}Ti(γ,p)^{47}Sc	^{49}Ti(γ,np)^{47}Sc	Total
40	19.8	0.23	20.1
60	30.1	0.56	30.7
80	35.8	0.77	36.6
95	38.9	0.89	39.8

Table 4

Reduced activity of ^{46}Sc in PNC, kBq/μA·h (simulations)

E_e, MeV	^{47}Ti(γ,p)^{46}Sc	^{48}Ti(γ,np)^{46}Sc	Total
40	0.061	0.090	0.152
60	0.090	0.244	0.339
80	0.107	0.339	0.455
95	0.116	0.392	0.519

Table 5

Reduced activity of ^{48}Sc in PNC, kBq/μA·h (simulations)

E_e, MeV	^{49}Ti(γ,p)^{48}Sc	^{50}Ti(γ,np)^{48}Sc	Total
40	0.88	0.06	0.94
60	1.35	0.22	1.57
80	1.62	0.35	1.97
95	1.76	0.42	2.18

2.1.2. In Fig. 2, the spectra of the activated titanium foils are presented. The observed traces of ^{44m}Sc ($T_{1/2}$ = 58.6 h) can be explained by the ^{46}Ti(γ,np)^{44m}Sc reaction. Its yield in PNC is about 30 Bq/μA·h at 40 MeV and up to 540 Bq/μA·h at 95 MeV. The lines of ^{42,43}K at 95 MeV are caused by the reactions ^{47,48}Ti(γ,pα), respectively, ^{40}K is the background.

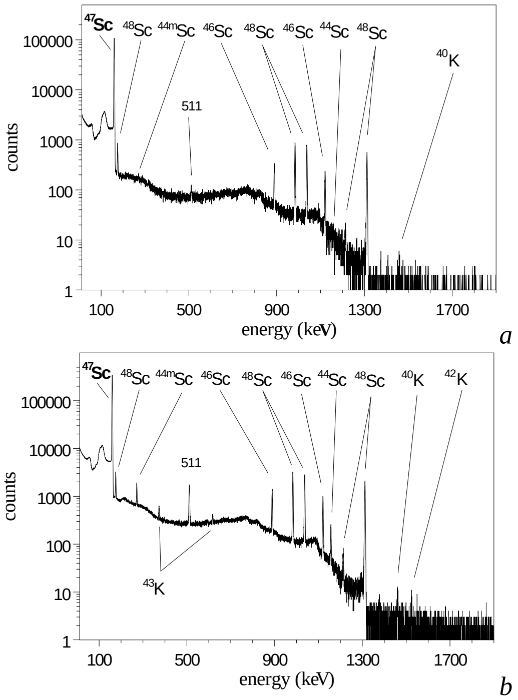

Fig. 2. γ-spectra of irradiated foils from natural titanium: E_e= 40 MeV (a); E_e = 95 MeV (b)

The measured yield of the scandium isotopes is listed in Table 6. It is evident, that the experimental data are considerably higher than the calculated values.

For determination of the σ_{max} and Γ parameters of the reactions under study, the procedure described in the subsection 1.1.2 was applied. The E_{max} value was taken from the TALYS code. In a case when an isotope-product is generated in the several reactions simultaneously, it was assumed, that the contribution of each channel is proportional to the corresponding simulation result (see Tables 3-5).

Table 6

Reduced activity of scandium isotopes in PNC from natural titanium, kBq/μA·h (experiment)

E_e, MeV	^{46}Sc	^{47}Sc	^{48}Sc
40	0.30	34.7	3.23
60	0.60	54.6	5.40
80	0.79	66.8	6.83
95	0.94	74.1	7.64

2.2. ^{48}Ti(γ,p)^{47}Sc

This reaction determines the yield of ^{47}Sc in natural titanium, as the content of ^{48}Ti is by one order of magnitude higher than that of other titanium isotopes (see Table 1). Using the experimental data on the ^{47}Sc activity in PNC, the conduct $[\sigma_{max} \cdot S(E_e)]$ was calculated by the formulae (2), (4) for each electron beam energy. In Fig. 3, the family of variants of the excitation function for the ^{48}Ti(γ,p)^{47}Sc reaction, normalized to maximum cross-section, and corresponding to a set of the possible Γ values, is shown. The data on the parameters of the reaction, used in the calculations, are listed in the Tables 7 and 8. The reaction yield was determined by MC technique for every variant of its excitation function. The obtained data were processed using the equation (5) followed by establishment of actual range of Γ and σ_{max} (Fig. 4).

Table 7

S-factor of ^{48}Ti(γ,p)^{47}Sc reaction used in simulations

E_e, MeV	Γ, MeV			
	11	12	12.5	13
	S-factor			
40	0.581	0.613	0.628	0.643
60	0.813	0.862	0.884	0.907
80	0.937	0.995	1.023	1.049
95	0.998	1.060	1.090	1.119

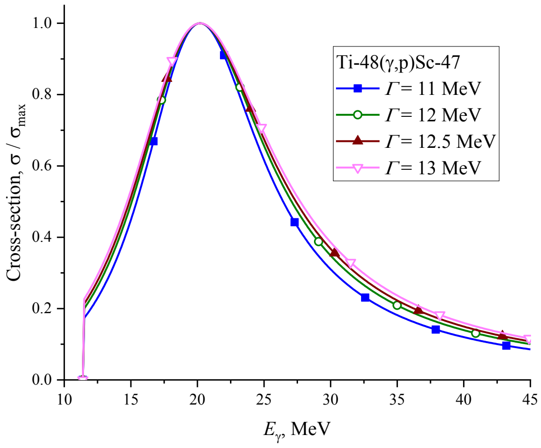

Fig. 3. Variants of normalized excitation function of ^{48}Ti(γ,p)^{47}Sc reaction

Table 8

Parameters of cross-section of $^{48}Ti(\gamma,p)^{47}Sc$ reaction used in simulations

E_e, MeV	Γ, MeV			
	11	12	12.5	13
	σ_{max}, mb			
40	12.7	12.1	11.8	11.5
60	13.4	12.7	12.3	12.0
80	13.9	13.1	12.8	12.4
95	14.4	13.5	13.2	12.8

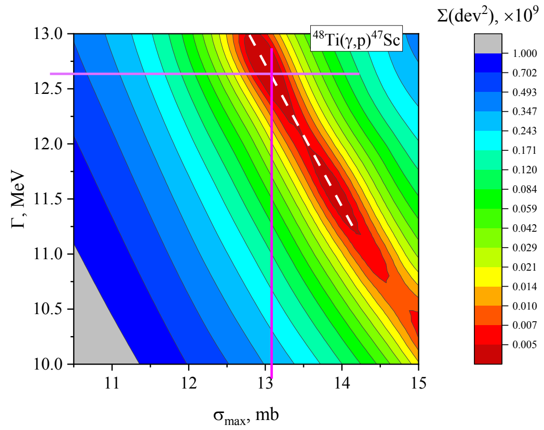

Fig. 4. Distribution of deviation square sums of calculated ^{47}Sc activity from one measured

Hence for the ^{48}Ti(γ,p)^{47}Sc reaction, σ_{max} and FWHM lie in the range 12.5…14 mb and 11.5…13 MeV at the most probable values of 13.1 mb and 12.6 MeV, respectively.

2.3. ^{47}Ti(γ,p)^{46}Sc and ^{48}Ti(γ,np)^{46}Sc

2.3.1. As it is follows from the data of Table 4, these the two channels provide above 99% of the ^{46}Sc total yield. The relative contribution of each reaction into the measured ^{46}Sc activity was assumed proportional to the values given in this Table. The experimental data on the yield of the ^{47}Ti(γ,p)^{46}Sc reaction in PNC, reduced in such a way, as well as the corresponding values of the product $\left[\sigma_{max}\cdot S(E_e)\right]$ are listed in Table 9. The range of the possible reaction parameters, used in the simulations, is presented in Tables 10, 11.

Table 9

Reduced yield of $^{47}Ti(\gamma,p)^{46}Sc$ reaction in PNC

E_e	A_{PNC}, Bq/μA·h	$[S(E_e)\cdot\sigma_{max}]\cdot10^{28}$, cm^2
40	121	0.656
60	159	0.808
80	186	0.924
95	210	1.032

Table 10

S-factor of $^{47}Ti(\gamma,p)^{46}Sc$ reaction

E_e, MeV	Γ, MeV				
	6	7	8	9	10
	S-factor				
40	0.189	0.214	0.237	0.259	0.279
60	0.259	0.295	0.328	0.359	0.388
80	0.296	0.337	0.375	0.411	0.446
95	0.314	0.357	0.398	0.437	0.474

Table 11

Parameters of cross-section of $^{47}Ti(\gamma,p)^{46}Sc$ reaction used in simulations

E_e, MeV	Γ, MeV				
	6	7	8	9	10
	σ_{max}, mb				
40	17.3	15.3	13.8	12.7	11.8
60	15.6	13.7	12.3	11.3	10.4
80	15.6	13.7	12.3	11.2	10.4
95	16.5	14.5	13.0	11.8	10.9

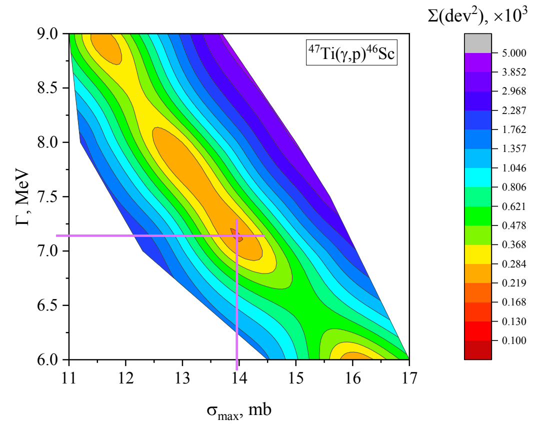

Fig. 5. Distribution of deviation square sums of calculated ^{46}Sc activity, produced by $^{47}Ti(\gamma,p)^{46}Sc$ reaction, from experimental data

The results of calculations of $\sum_i dev^2$ for the given reaction are shown in Fig. 5. It is seen, that the pair (14 mb; 7.2 MeV) provides the most closest calculated yield of ^{46}Sc to that obtained experimentally for the given reaction.

2.3.2. The initial data and results of calculations of characteristics of the ^{48}Ti(γ,np)^{46}Sc reaction are presented in Tables 12-14 and in Fig. 6.

Table 12

Reduced yield of $^{48}Ti(\gamma,np)^{46}Sc$ reaction in PNC

E_e	A_{PNC}, Bq/μA·h	$[S(E_e)\cdot\sigma_{max}]\cdot10^{27}$, cm^2
40	179	0.96
60	441	2.22
80	604	3.04
95	730	3.56

Table 13

S-factor of $^{48}Ti(\gamma,np)^{46}Sc$ reaction

E_e, MeV	Γ, MeV			
	10	11	12	13
	S-factor			
40	0.181	0.194	0.205	0.216
60	0.384	0.412	0.437	0.461
80	0.497	0.533	0.568	0.600
95	0.552	0.593	0.632	0.669

Table 14

Parameters of cross-section of $^{48}Ti(\gamma,np)^{46}Sc$ reaction used in simulations

E_e, MeV	Γ, MeV			
	10	11	12	13
	σ_{max}, mb			
40	5.3	5.0	4.7	4.5
60	5.8	5.4	5.1	4.8
80	6.1	5.7	5.4	5.1
95	6.4	6.0	5.6	5.3

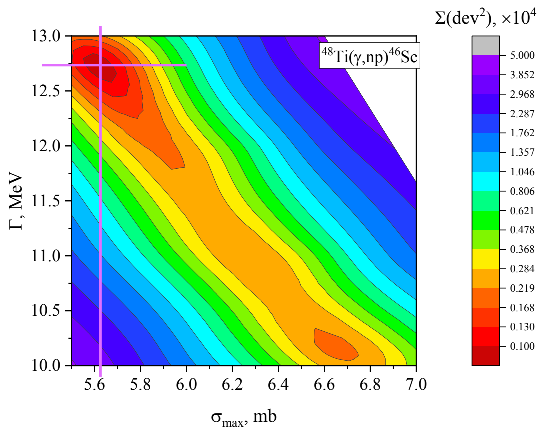

Fig. 6. Distribution of deviations square sums of calculated ^{46}Sc activity, produced by reaction ^{48}Ti(γ,np)^{46}Sc, from experimental data

It is evident, that the best result is located in the neighborhood of the pair (5.6 mb; 12.7 MeV).

2.4. ^{49}Ti(γ,p)^{48}Sc and ^{50}Ti(γ,np)^{48}Sc

2.4.1. The reduced experimental data for the reaction ^{49}Ti(γ,p)^{48}Sc and the results of their processing are given in Tables 15-17, and also in Fig. 7. The best result is located nearby (10.6 mb, 9.5 MeV). It should be noted, that the yield of this reaction at each electron beam energy obtained by the MC simulations with the use of these parameters does not differ by more than 1% from the experimental data.

Table 15

Reduced yield of ^{49}Ti(γ,p)^{48}Sc reaction in PNC

E_e	A_{PNC}, kBq/μA·h	$[S(E_e)\cdot\sigma_{max}]\cdot10^{27}$, cm^2
40	3.02	4.78
60	4.63	6.86
80	5.62	8.16
95	6.17	8.86

Table 16

S-factor of ^{49}Ti(γ,p)^{48}Sc reaction

E_e, MeV	*Γ*, MeV			
	8	9	9.5	10
	S-factor			
40	0.433	0.472	0.491	0.509
60	0.613	0.671	0.699	0.726
80	0.708	0.776	0.809	0.841
95	0.753	0.827	0.862	0.897

Table 17

Parameters of cross-section of ^{49}Ti(γ,p)^{48}Sc reaction used in simulations

E_e, MeV	*Γ*, MeV			
	8	9	9.5	10
	σ_{max}, *mb*			
40	11.0	10.1	9.7	9.4
60	11.2	10.2	9.8	9.5
80	11.5	10.5	10.1	9.7
95	11.8	10.7	10.3	9.9

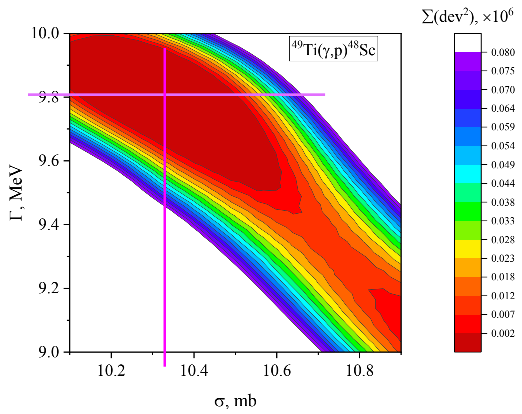

Fig. 7. Distribution of deviations square sums of calculated ^{48}Sc activity, generated by ^{49}Ti(γ,p)^{48}Sc reaction, from experimental data

2.4.2. The reduced experimental data on the yield of the ^{50}Ti((γ,np)^{48}Sc reaction and the results of their processing are presented in Tables 18-20, and also in Fig. 8.

Table 18

Reduced yield of ^{50}Ti(γ,np)^{48}Sc reaction in PNC

E_e, MeV	A_{PNC}, kBq/μA·h	$[S(E_e)\cdot\sigma_{max}]\cdot10^{27}$, cm^2
40	0.21	0.34
60	0.77	1.17
80	1.21	1.79
95	1.47	2.16

Table 19

S-factor of ^{50}Ti(γ,np)^{48}Sc reaction

E_e, MeV	*Γ*, MeV			
	12	13	14	15
	S-factor			
40	0.127	0.136	0.145	0.153
60	0.352	0.373	0.394	0.413
80	0.484	0.515	0.545	0.572
95	0.550	0.585	0.619	0.651

Table 20

Parameters of cross-section of ^{50}Ti(γ,np)^{48}Sc reaction used in simulations

E, MeV	*Γ*, MeV			
	12	13	14	15
	σ_{max}, mb			
40	2.7	2.5	2.4	2.2
60	3.3	3.1	3.0	2.8
80	3.7	3.5	3.3	3.1
95	3.9	3.7	3.5	3.3

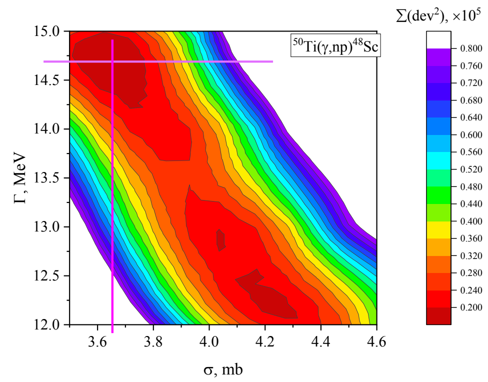

Fig. 8. Distribution of deviations square sums of calculated ^{48}Sc activity, produced by ^{50}Ti(γ,np)^{48}Sc reaction, from experimental data

The optimal σ_{max} and Γ values lie in the range 3.8…4.0 mb and 13…14 MeV, respectively.

CONCLUSIONS

The comparison of the $^{46-48}$Sc yield in a photonuclear converter (PNC) from natural titanium, obtained by MC simulations with the use of TALYS cross-section data (see Tables 3-5) and that measured experimentally (see Table 6) shows, that the last is from 1.5 to 3 times higher. In its turn, the yield of the ^{48}Ti(γ,p)^{47}Sc reaction measured in this work is twice lower than that calculated with the use of the cross-section data determined experimentally earlier [5, 6]. At the same time, the ratios of the relative yields of scandium isotopes, measured in this work at E_e = 60 MeV and in work [6] at E_e = 55 MeV, are in good agreement. Such contradiction poses the necessity to specify the cross-section data.

The developed method for estimation of gross-structure parameters of the giant dipole resonance [7] enables to establish the range of width and maximum of an excitation function under study on the basis of experimental data on the yield of the reaction in the readily reproducible conditions of photonuclear converter and the developed analytical model.

Application of the method for the determination of photo-proton cross-sections on the titanium isotopes gives an opportunity to specify the parameters of the reactions of $^{46-48}$Sc production. So, for the ^{48}Ti(γ,p)^{47}Sc reaction, the determined range of σ_{max} 12.5…14 mb is in good agreement with the TALYS predictions. At the same time, the obtained FWHM value 11.5…13 MeV is considerably higher but close to the experimental data [5]. The significant differences with the findings of the TALYS package take place also for other reactions under study (Table 21).

It should be noted, that the checking of variability of the cross-section data given by the proposed technique for a two-channel pathway of the isotope-product generation by changing the relative yield of each reaction has shown the proportional change of maximum cross-section σ_{max} while keeping the FWHM value.

Table 21

Characteristics of photo-proton reactions on titanium isotopes

Isotope-product	Reaction	Data obtained		Data available		
		Γ, MeV	σ_{max}, mb	Γ, MeV	σ_{max}, mb	Ref.
^{46}Sc	^{47}Ti(γ,p)^{46}Sc	7.2	14.0	6.4	9.8	[4]
	^{48}Ti(γ,np)^{46}Sc	12.7	5.6	11.7	3.8	[4]
^{47}Sc	^{48}Ti(γ,p)^{47}Sc	12.6	13.1	7.5	13.4	[4]
				11.5	30.0	[5]
				7.3	6.8	[3]
^{48}Sc	^{49}Ti(γ,p)^{48}Sc	9.5	10.3	6.0	5.0	[4]
	^{50}Ti(γ,np)^{48}Sc	14	3.8	16.5	1.1	[4]

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Article received 19.01.2022

ОЦІНКА ПЕРЕРІЗІВ ФОТОПРОТОННИХ РЕАКЦІЙ НА ІЗОТОПАХ $^{47\text{-}50}$Ti

М.П. Дикий, О.О. Захарченко, Ю.В. Ляшко, В.Л. Уваров, В.А. Шевченко, А.Е. Тєнішев

Розвиток технології виробництва ізотопів на прискорювачах електронів, зокрема ^{47}Sc за реакцією ^{48}Ti(γ,p)^{47}Sc, потребує більш точних даних про перерізи цієї та інших фотопротонних реакцій на ізотопах титану, оскільки наявні дані характеризуються суттєвим розкидом. Раніш був запропонований та валідований простий метод оцінки максимуму і ширини функції збудження для реакції з домінуванням гігантського дипольного резонансу. Метод заснований на вимірюванні нормованого виходу реакції в тонкій мішені, яка повністю перекриває потік гальмівних фотонів, і обробці одержаних даних з використанням розробленої аналітичної моделі. Було проведено сумісну активацію фольг з природного нікелю, молібдену та титану гальмівним випромінюванням з граничною енергією в діапазоні 40…95 МеВ. З використанням нового методу досліджено параметри реакцій: ^{48}Ti(γ,p)^{47}Sc, ^{49}Ti(γ,p)^{48}Sc, ^{50}Ti(γ,np)^{48}Sc, ^{47}Ti(γ,p)^{46}Sc та ^{48}Ti(γ,np)^{46}Sc. Для верифікації одержаних результатів використані добре вивчені реакції ^{58}Ni(γ,n)^{57}Ni та ^{100}Mo(γ,n)^{99}Mo, що відбуваються у нікелі та молібдені.

ОЦЕНКА СЕЧЕНИЙ ФОТОПРОТОННЫХ РЕАКЦИЙ НА ИЗОТОПАХ $^{47\text{-}50}$Ti

Н.П. Дикий, А.А. Захарченко, Ю.В. Ляшко, В.Л. Уваров, В.А. Шевченко, А.Э. Тенишев

Развитие технологии производства изотопов на ускорителях электронов, в частности ^{47}Sc по реакции ^{48}Ti(γ,p)^{47}Sc, требует более точных данных о сечениях этой и других фотопротонных реакций на изотопах титана, поскольку имеющиеся данные характеризуются существенным разбросом. Ранее был предложен и валидирован простой метод оценки максимума и ширины функции возбуждения для реакции с доминированием гигантского дипольного резонанса. Метод основан на измерении нормированного выхода реакции в тонкой мишени, полностью перекрывающей поток тормозных фотонов, и обработке полученных данных с использованием разработанной аналитической модели. Была проведена совместная активация фольг из природных никеля, молибдена и титана тормозным излучением с граничной энергией в диапазоне 40…95 МэВ. С использованием нового метода были исследованы параметры реакций: ^{48}Ti(γ,p)^{47}Sc, ^{49}Ti(γ,p)^{48}Sc, ^{50}Ti(γ,np)^{48}Sc, ^{47}Ti(γ,p)^{46}Sc и ^{48}Ti(γ,np)^{46}Sc. Для верификации полученных результатов использованы хорошо изученные реакции ^{58}Ni(γ,n)^{57}Ni и ^{100}Mo(γ,n)^{99}Mo, которые происходят в никеле и молибдене.