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NUCLEI
Experiment

Investigation of Flux-Weighted Average Cross Sections for Reactions on ^{93}Nb with Bremsstrahlung of LUE-75

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Abstract—Studies of the cross section of gamma-neutron reactions on the $^{\rm nat}$Nb nucleus were carried out on the bremsstrahlung of the linear electron accelerator LUE-75 which is located at the A. Alikhanyan National Science Laboratory (Yerevan Physics Institute). The experiment was done at 30 and 40 MeV bremsstrahlung end-point energies. The reaction cross sections for $^{\rm nat}{\rm Nb}(\gamma, xn)^{90g,91m,92m}{\rm Nb}$ reactions were measured by the activation method with the spectrometric analysis using the High Purity Germanium detector (HPGe). The values of cross sections for different energies of photon beam were determined using the TALYS 1.95 and EMPIRE 3.2 nuclear codes. The energy distribution of photon spectra was performed using the GEANT4 package. The obtained experimental and theoretical results are compared with the available experimental data of other authors. Good agreement was observed between the theoretical and experimental data. The data on the reaction cross section for $^{\rm nat}{\rm Nb}(\gamma, 2n)^{91m}{\rm Nb}$ were obtained for the first time.

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1. INTRODUCTION

Photon-induced reactions are one of the sources of information about the nuclear structure and nuclear-reaction mechanisms. The niobium is of interest due to its usefulness in various applications, such as the industry, machine building, instrument-making technologies, and nuclear power engineering. Due to its small capture cross section of thermal neutrons (1.5×10^{-24} cm^2), niobium is used in structures of nuclear reactors.

The data available in the literature on the interaction of niobium with a photon beam refer mainly to monoenergetic photons. From this point of view, the results of both experimental and theoretical studies of bremsstrahlung-photon interactions with niobium nuclei are of interest.

2. EXPERIMENTAL PROCEDURE

The experiment was carried out on the bremsstrahlung beam of the linear electron accelerator LUE-75 at the A. Alikhanyan National Science Laboratory (Yerevan Physics Institute) at 30 and 40 MeV electron beam energies. Detailed description and technical features of the LUE-75 were published earlier [1]. In order to obtain the bremsstrahlung photon beam, the tantalum converter has been used. The thickness of the tantalum disk was determined by calculations based on GEANT4 [2]. The main requirement is the maximum yield of the photon numbers and it was in case of 2 mm [3]. After the tantalum converter the target holder was installed, in which the monitor natural copper target (^{65}Cu—30.83%, ^{63}Cu—69.17%) and the natural niobium target (^{93}Nb—100%) were lined up. In Table 1 the physical parameters of the copper and niobium targets, the beam energy, the beam current, and the irradiation time are given. The reaction thresholds, half-lives of radioactive isotopes, decay types, and gamma-line energies and intensities for reaction products as well as for the monitor nucleus are given in Table 2. Characteristic data on the decays of product nuclei were taken from the NuDat 2.8 [4].

The final products of $^{\rm nat}{\rm Nb}(\gamma, xn)$ reactions with a lower thresholds than the maximum energy of the bremsstrahlung beam were investigated. Since the ^{64}Cu is produced only on ^{65}Cu, as a monitor, the $^{65}{\rm Cu}(\gamma, n)^{64}{\rm Cu}$ reaction was used.

Two sessions of irradiation were carried out at 30 and 40 MeV energies, 2 h and 1 h, respectively. After irradiation, the targets were stored for 1 h in the experimental hall, then transported to the measurement hall. Spectrometric measurements were carried out on high purity germanium detector (HPGe) by ORTEC. The detector was calibrated using the

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Table 1. Parameters of ^{nat}Nb and ^{nat}Cu targets

Nuclide	Beam energy, MeV	Beam current, μA	Irradiation time, h	Target size, cm×cm	Target thickness, μm	Target mass, g
^{nat}Nb	30	0.3	2	2.5×2.3	150	0.65
	40	1.1	1	2.5×2.5	150	0.72
^{nat}Cu	30	0.3	2	2.5×2.5	40	0.23
	40	1.1	1	2.5×2.5	40	0.23

Table 2. Properties of reactions products

Reaction	Reaction thresholds, MeV	Product nucleus	Half-life ($T_{1/2}$)	Decay type	E_γ, keV	I_γ, %
^{65}Cu(γ, n)	10	^{64}Cu	12.7 h	β^+ (61%)	511	35.2
				β^- (39%)		
^{93}Nb$(\gamma, 3n)$	28.76	^{90g}Nb	14.6 h	β^+ (100%)	1129.22	92.7
					2318.96	82
	28.89	^{90m}Nb	18.8 s	IT (100%)	124.67	100
^{93}Nb$(\gamma, 2n)$	16.71	^{91g}Nb	680 yr	EC (100%)	511	0.34
	16.82	^{91m}Nb	60.86 d	IT (96.6%)	1204.67	2
				EC (3.4%)		
^{93}Nb(γ, n)	8.83	^{92g}Nb	3.47×10^7 yr	β^+ (99.95%)	561.1	100
				β^- (0.05%)	934.5	74
	8.96	^{92m}Nb	10.15 d	β^+ (100%)	912.6	1.78
					934.44	99.15

^{155}Eu, ^{57}Co, and ^{22}Na sources with the following gamma lines: 86.5 keV (^{155}Eu), 105.3 keV (^{155}Eu), 122.06 keV (^{57}Co), 136.47 keV (^{57}Co), 511 keV (^{22}Na), and 1274.6 keV (^{22}Na). The detector efficiency was determined at various distances between the detector and sources in the range from 0 to 50 cm. The measured spectra were processed by using the MAESTRO code [5].

3. DATA ANALYSIS

The ΔN activity of the considered reactions was measured as the area under the photopeak minus the Compton background. In Fig. 1 the gamma spectrum of ^{92}Nb and ^{90}Nb isotopes in case of 40 MeV electron beam energy obtained by the MAESTRO program is shown.

The flux-weighted average cross section $\langle\sigma\rangle$ is related to the measured activity by the following equation:

$$\sigma = \frac{\Delta N \lambda}{\varepsilon \eta k N_\Upsilon N_{\text{nucl}} (1 - e^{-\lambda t_1}) e^{-\lambda t_2} (1 - e^{-\lambda t_3})}, \quad (1)$$

where λ is the decay constant; ε is the detector efficiency; η is the gamma-line intensity; κ is the coefficient of absorption; N_γ is the photon flux; N_{nucl} is the number of target nuclei; t_1, t_2, and t_3 are the irradiation time, the time from the end of irradiation to the start of measurements, and the measurement time, respectively [3]. The experimental photon flux is determined by

$$N_\Upsilon = \frac{\Delta N \lambda}{\langle\sigma\rangle\, \varepsilon \eta k N_{\text{nucl}}\, (1 - e^{-\lambda t_1})\, e^{-\lambda t_2}\, (1 - e^{-\lambda t_3})}, \quad (2)$$

where notations are same as in Eq. (1).

The flux-weighted average cross section is calculated by

$$\langle\sigma\rangle = \frac{\sum \sigma\varphi}{\sum \varphi}, \quad (3)$$

where σ is the reaction cross section and φ is the photon flux [6]. For each energy E_γ, the photon flux φ is determined from the energy distribution

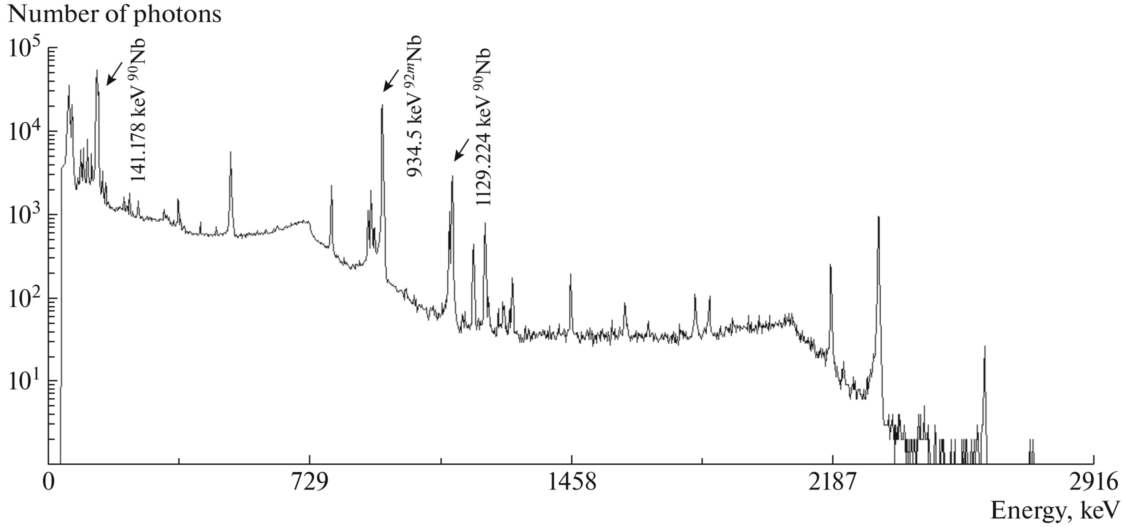

Fig. 1. Characteristic spectrum of photons from ^{92}Nb and ^{90}Nb nuclides after the irradiation of ^{93}Nb by bremsstrahlung photons of endpoint energy 40 MeV.

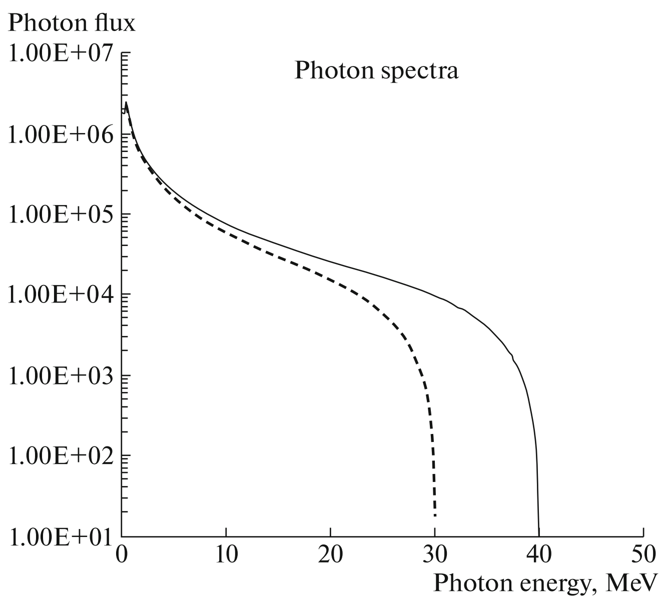

Fig. 2. Energy spectra of bremsstrahlung photons for the endpoint energies of (dashed curve) 30 MeV and (solid curve) 40 MeV received by GEANT4 code calculation.

of bremsstrahlung photons simulated by GEANT4 package [2] taking into account the size and shape of the beam collimator and converter. In order to compare the reliability of reaction process descriptions by different theoretical models, the σ values were calculated for the same E_γ energies by TALYS 1.95 [7] and EMPIRE 3.2 [8] codes.

The flux-weighted average cross sections $\langle\sigma\rangle$ calculated by Eq. (2) for the monitor reaction ^{65}Cu$(\gamma, n)^{64}$Cu by TALYS 1.95 and EMPIRE 3.2 codes, and the numbers of photons that were calculated by Eq. (2) are given in Table 3.

Since the thresholds of the studied reactions are different from the threshold of the monitor ^{65}Cu$(\gamma, n)^{64}$Cu reaction (see Table 2), the coefficients for the correction of the magnitudes of the photon fluxes were included. These coefficients are defined as

$$C_x = \int\limits_{E_{\rm thr}^{\rm Nb}}^{E_e} \Phi\,(E)\,dE \Big/ \int\limits_{E_{\rm thr}^{\rm Cu}}^{E_e} \Phi\,(E)\,dE, \qquad (4)$$

where the numerator is the integral of the photon flux from the threshold for the reaction being studied to

Table 3. Flux-weighted average cross sections calculated by TALYS 1.95 and EMPIRE 3.2 codes and corresponding numbers of photons at the endpoint energies of 30 MeV and 40 MeV

Isotope	Energy, MeV	Cross section $\langle\sigma\rangle$, mb		Number of photons, photon/h	
		TALYS 1.95	EMPIRE 3.2	TALYS 1.95	EMPIRE 3.2
^{64}Cu	30	33.77	31.38	6.04×10^{15}	6.5×10^{15}
	40	28.67	26.8	3.61×10^{16}	3.86×10^{16}

the endpoint energy of the electron beam, while the denominator is the analogous integral for the monitor reaction [9]. In Fig. 2 the here used energy spectra of bremsstrahlung photons for the endpoint energies calculated by GEANT4 are shown.

In Table 4 the correction coefficient for the electron beam energies of 30 and 40 MeV are given.

The experimental flux-weighted average cross sections for the ^{93}Nb(γ, xn) reactions were determined by Eq. (1) using the product nuclei parameters and the number of photons calculated by Eq. (2) based on the cross sections according to the TALYS 1.95 and EMPIRE 3.2 codes, taking into account correction coefficients listed in Table 4. Thus, for each endpoint 30 and 40 MeV photon beam energies, two values of the experimental flux-weighted average cross sections for the reactions ^{93}Nb(γ, xn) were obtained based on TALYS 1.95 and EMPIRE 3.2 calculations.

In order to compare the final results using the Eq. (3), the theoretical flux-weighted average cross sections of product nuclei have been calculated by TALYS 1.95 and EMPIRE 3.2 codes. In these calculations the number of photons was determined based on GEANT4 calculations. The obtained experimental and theoretical cross sections with the data from [6, 10] are summarized in Table 5. It shows that for ^{93}Nb$(\gamma, n)^{92m}$Nb reaction, when the emission of one neutron takes place, there is good agreement between the experimental data based on the calculation of the number of photons performed by calculations using the TALYS 1.95 and EMPIRE 3.2 codes and the purely theoretical calculations using the same codes. It is notable that for all reactions the values of flux-weighted average cross sections calculated by EMPIRE 3.2 code are lower than the results from TALYS 1.95 code.

Table 4. Correction coefficients for the photon flux

Energy, MeV	Isotope	Threshold energy, MeV	Correction coefficient, C_x
40	^{90g}Nb	28.7	0.08
40	^{91m}Nb	16.8	0.46
30	^{91m}Nb	16.8	0.31
40	^{92m}Nb	8.9	1.12
30	^{92m}Nb	8.9	1.16

For reactions with a large number of emitted neutrons ^{93}Nb$(\gamma, 3n)^{90}$Nb and ^{93}Nb$(\gamma, 2n)^{91m}$Nb, the experimental data based on the TALYS 1.95 and EMPIRE 3.2 codes are in good agreement, but they strongly differ from the theoretical calculations based on the same codes. In the case of the ^{90m}Nb isotope, due to the short lifetime (see Table 2), the total cross section of ^{90}Nb is measured, since ^{90m}Nb is converted into ^{90g}Nb by IT (isomeric transition).

Table 5 shows that our results for the ^{90}Nb isotope are in good agreement with the data of [6]. For the ^{92m}Nm isotope, the data from [6, 10] and our results reveal a growing tendency for the cross section with an increase in the endpoint bremsstrahlung energy of 30 MeV. As the photon energy increases further, new reaction channels open, which leads to decrease in the flux-weighted average cross sections. Since the experimental data for ^{91m}Nb isotope were obtained for the first time, there is no experimental data in the literature to compare with.

4. CONCLUSION

Measurements of the flux-weighted average cross sections of the ^{93}Nb(γ, xn) $(x = 1{-}3)$ reactions were carried out on the bremsstrahlung beam of the linear electron accelerator LUE-75 located at the A. Alikhanyan National Science Laboratory (Yerevan Physics Institute). The activation method was used. The measurements were carried out at 30 and 40 MeV endpoint energies of electron beam. Spectroscopic analysis of the irradiated targets were carried out on HPGe detector using the MAESTRO program. The comparison of theoretical calculations by TALYS 1.95 and EMPIRE 3.2 codes with experimental data for all reactions under study have been done. Particularly, the results for the ^{93}Nb$(\gamma, n)^{92m}$Nb and ^{93}Nb$(\gamma, 3n)^{90}$Nb reactions are compared with the available experimental data. There is a good agreement with the data of other authors.

Table 5. Comparison of the experimental and theoretical data of the flux-weighted average cross sections with data from [6, 10]

Isotope	Energy, MeV	Literature	Flux-weighted average cross sections, mb				
			experimental results			theoretical calculations	
				TALYS 1.95	EMPIRE 3.2	TALYS 1.95	EMPIRE 3.2
^{90}Nb	40	This work		2.88 ± 0.033	2.62 ± 0.031	2.25	1.56
	45	[6]	3.011 ± 0.35				
^{91m}Nb	30	This work		8.34 ± 0.61	7.75 ± 0.56	6.45	5.54
	40	This work		6.33 ± 0.69	5.91 ± 0.68	5.16	4.57
^{92m}Nb	12	[6]	8.73 ± 0.196				
	14	[6]	14.61 ± 1.31				
	16	[6]	20.371 ± 1.65				
	30	This work		36.79 ± 0.38	34.19 ± 0.35	31.06	26.2
	32	[10]	29.9 ± 1.9				
	40	This work		26.81 ± 0.14	25.06 ± 0.14	27.1	22.8
	45	[6]	23.939 ± 1.89				

The experimental data for ^{93}Nb$(\gamma, 2n)^{91}$Nb reaction were obtained for the first time.

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