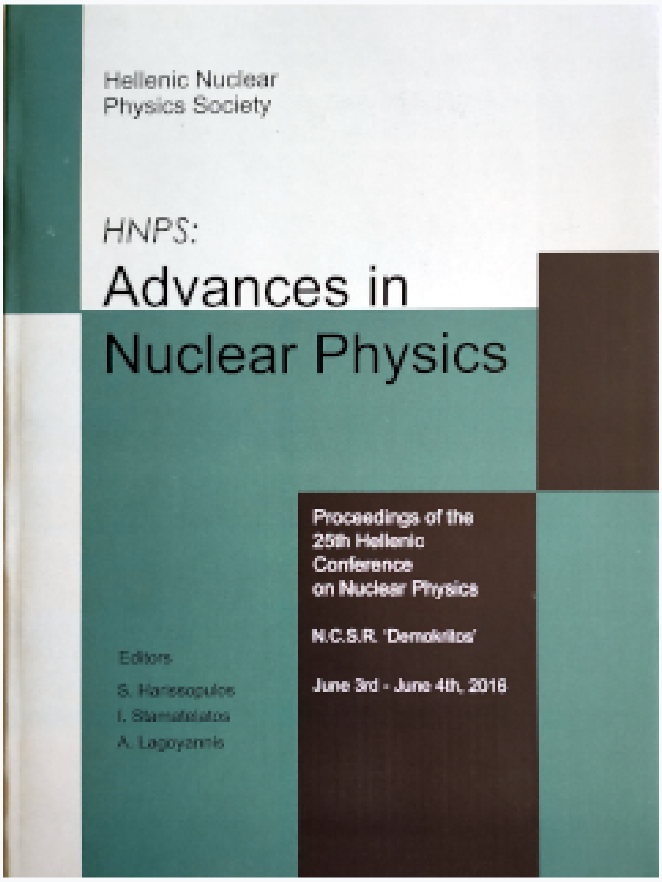
HNPS Advances in Nuclear Physics

Vol 24 (2016)

HNPS2016



Average cross section measurement for 162Er(γ,n) reaction compared with theoretical calculations using TALYS

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doi: 10.12681/hnps.1854

Average cross section measurement for ^{162}Er (γ, n) reaction compared with theoretical calculations using TALYS

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Abstract

Bremsstrahlung photon beam delivered by a linear electron accelerator has been used to experimentally determine the near threshold photonuclear cross section data of nuclides. For the first time, (γ, n) cross section data was obtained for the astrophysical important nucleus ^{162}Er. Moreover, theoretical calculations have been applied using the TALYS 1.6 code. The effect of the gamma ray strength function on the cross section calculations has been studied. A satisfactorily reproduction of the available experimental data of photonuclear cross section at the energy region below 20 MeV could be achieved. The photon flux was monitored by measuring the photons yield from seven well known (γ, n) reactions from the threshold energy of each reaction up to the end-point energy of the photon beam used. An integrated cross-section 87 ± 14 mb is calculated for the photonuclear reaction ^{162}Er (γ, n) at the energy 9.2 - 14 MeV. The effective cross section estimated using the TALYS code range between 89 and 96 mb depending on the γ-strength function used. The result for ^{162}Er (γ, n), is found to be in good agreement with the theoretical values obtained by TALYS 1.6. So, the present indirect process could be a valuable tool to estimate the effective cross section of (γ, n) reaction for various isotopes using bremsstrahlung beams.

Keywords: ^{162}Er (γ, n) reaction cross-section; photonuclear reaction; activation method; TALYS model

INTRODUCTION

In the recent years there is a renewed interest in photonuclear reaction data due to its significant importance in various applications such as the radioactive ion beam or neutron production, cosmic nucleosynthesis as well as in the investigation and understanding of the nuclear structure. The majority of photonuclear reaction cross-section data have been obtained in some part of the energy region and especially for incident energies below 20 MeV. At low energies the giant dipole resonance (GDR) is the dominant excitation mechanism, in which a collective bulk oscillation of the neutrons against protons occurs. In the giant resonance region, the incident photon interacts with the dipole moment on the target nucleus and the nucleus deexcites by fission or emitting particles and/or γ-rays depending on the nuclear structure of the nuclei [1].

The measurement of the photonuclear reaction cross sections using bremsstrahlung photons on series of middle and heavy nuclei at stellar nucleosynthesis relevant energy region are available in the literature. Most of the studies referred to astrophysical p- or γ-process that leads to a neutron deficient heavy nuclei via (γ, n), (γ, p) and (γ, α) reactions induced to nuclei previously synthesized by neutron capture during s-process and r-process at temperatures ranged between 2- 3 x10^9 K. The produced nucleus, so-called p-nuclei has relative abundance of 0.01 – 1 %. The photonuclear cross-section of a heavy p-nucleus in the

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energy range near the neutron-escaping threshold is of particular interest in astrophysical studies, since the astrophysical relevant energy window for (γ, n) reactions is located slightly above the energy threshold of the (γ, n) reaction measured at the lab [2].

Most of the experiments have been carried out using bremsstrahlung beams with endpoint energy up to 30 MeV. In this case, the high cross section of (γ, n) reaction around GDR gives excellent sensitivity of the photoactivation technique performed at a medical accelerator that can provide suitable photons beam intensity for such experiments [6]. Therefore, in the present research irradiations of natural Erbium foil performed using medical linac operating at energies slightly above the neutron threshold using. The element Er has six stable isotopes: ^{170}Er (14.93%), ^{168}Er (26.78%), ^{167}Er (22.93%), ^{166}Er (33.61%), ^{164}Er (1.61%) and the p-nuclei of ^{162}Er (0.14%). The only experimental data set presented in the literature is referred to ^{nat}Er (γ, xn) reaction for E_γ up to 30 MeV [3].

A method to calculate the ^{162}Er (γ, n) effective cross section for the energy region from the neutron threshold (9.2 MeV) to the end-point energy of the photon beam (14 MeV) is presented in this study. The method incorporates seven different metallic discs that are irradiated by a bremsstrahlung photon spectrum, emitted by a linac accelerator. The set of materials has been selected based on their reaction products that appear to have a suitable half-life and γ-rays with good intensity. The photon-induced activities are measured and the photon flux is calculated from each reaction's threshold energy up to the end-point energy. The (γ, n) reaction cross sections for the selected reactions are available in the EXFOR compilation [4]. Moreover, the corresponding theoretical values were calculated using the TALYS 1.6 code [5], which is based on the Hauser-Feshbach formalism. The effect of the gamma ray strength function on the cross section calculations has been studied to reproduce satisfactorily the available experimental data of photonuclear cross section at the energy region below 20 MeV.

EXPERIMENTAL DETAILS

The experiment was performed at the Radiotherapy Department of University Hospital in Larisa using an ELEKTA SL medical linear accelerator. The accelerator was operated at 15 MV with the collimators opened to 20x20 cm^2. Although the nominal energy of the medical linac is 15 MeV, the actual endpoint energy of the bremsstrahlung distribution was determined by the operators as E_0 = 14 MeV. Eight metals (Au, As, Ir, Er, Mn, Ni, Se, and Sn) had been irradiated to determine the photon flux from the reaction threshold energy (E_{thresh}) and up to the end-point energy (E_0), through the number of radioactive nuclei produced in the photo-activation measurements. The targets were placed on the patient support table at the isocenter, 100 cm distance from the target and irradiated under the same photon field for 1.11 h.

The use of different metals is based on their different threshold values of the photonuclear reactions (γ, n). Details of the activation metals and the induced reactions, along with other important parameters such as the decay radiation information and the threshold values are shown on Table 1.

Table 1 Nuclear data of the studied (γ, n) reactions as well as the decay characteristics of the radionuclides produced.

Reaction	E_{thresh} (MeV)	Produced Nuclide ($J^{+}\pi$)	Decay mode (%)	$T_{1/2}$	γ- energy (keV)	Branching ratio (%)
^{191}Ir (γ, n)	8.02	**^{190g}Ir (4-)**	ε (100)	11.78 d	371 518.55 557.95	22.8 34.0 30.1
^{197}Au (γ, n)	8.07	**^{196g}Au (2-)**	ε (93) β^- (7)	6.169 d	332.03 355.73	22.9 87
^{162}Er (γ, n)	9.2	**^{161}Er (3/2-)**	ε (100)	3.21 h	826.6	64
^{55}Mn (γ, n)	10.23	**^{54}Mn (3+)**	ε (100)	312.12 d	834.8	99.97
^{75}As (γ, n)	10.24	**^{74}As (2-)**	ε (66) (34)	17.77 d	595.83	59
^{112}Sn (γ, n)	10.79	**^{111}Sn (7/2+)**	ε (100)	35.3 m	761.97 1152.9 1914.7	1.48 2.7 2.0
^{74}Se (γ, n)	12.06	**^{73g}Se (9/2+)**	ε (100)	7.15 h	361.2	97.0
^{56}Ni (γ, n)	12.22	**^{57}Ni (3/2-)**	ε (100)	35.60 h	127.16 1377.63	81.7 99.45

After irradiation, radionuclide activities were measured using a γ-spectrometry system. The peaks were analyzed using a low background and high-purity Germanium (Ge) detector. The Ge detector that was used was a p-type detector of a 1.8 keV resolution in the 1332 keV gamma-line and efficiency 42%. All the obtained spectra were analyzed using the software SPECTRW [6].

Monte Carlo simulations using the Geant4 code [7] were used regarding the characterization of the HPGe detector and the precise calculation of its efficiency due to the different geometries of the materials used in the experiment. Moreover, the photon self-absorption as well as the true coincidence effect were calculated and were embedded to simulation runs performed for each material [8-9].

RESULTS AND DISCUSSION

The experimental cross section was weighted according to the simulated photon energy spectrum using the Geant4 code, so as the photon flux to be calculated accurately. The most important uncertainty contributor to the photon fluence determination is the effective cross section used (varying from 5 to 13 %). Moreover, the activity induced by photon reactions introduces the uncertainty of peak area determination (< 8%) as well as HPGe detector efficiency calculation (~3%). The uncertainty of produced isotope's half-life, γ-ray abundance and foil mass was lower than 1%.

The calculated photon flux for each photo activation reaction is displayed in the scatter plot in Fig. 1. In Figure 1 the photon energy spectrum calculate using GEANT simulations has been presented as well. A good agreement between experimental data and simulations is obviously for energies lower than 11 MeV. The same energy bound is demonstrated by the linear regression model applied to experimental data; since the linearity is presented to be valued for photons capture thresholds up to 11MeV lower than the thresholds of ^{74}Se and ^{58}Ni (γ, n) reactions. Therefore, for the specific bremsstrahlung photons endpoint (< 15 MeV) only the rest five well know (γ, n) reactions has to be considered as proper calibration set. The full set including the seven reactions proved to be applicable for photon beams with endpoint higher than 15 MeV.

The photon fluxes determined using only the five reactions with threshold lower than 11 MeV is presented in Fig. 1. An improved linear fitting is achieved and the fitting parameters have been estimated with uncertainties 3 – 4 %. The corresponding photon flux can be determined using the fitting linear equation obtained. This procedure results to total photon flux 1.24 (± 0.21) x10^8 γ/cm^2/s for energy range 9.2 - 14 MeV. Given the photon flux and the calculated activity based on the 826.6 keV γ-line of ^{161}Er, the effective cross section of the ^{162}Er (γ, n) reaction is estimated as 87 (± 14) mb. The specific cross section of (γ, n) reaction has been calculated using TALYS simulations taken under consideration the five γ-strength functions. The effective cross-section differs between 89 ± 4, 96 ± 4, 185± 8, 128 ± 6 and 73± 3 mb for the Kopecky-Uhl, the Brink-Axel, the Hartree-Fock, the Hartree-Fock-Bogolyubov and Goriely's hybrid model, respectively, with the two first values to be the most probable.

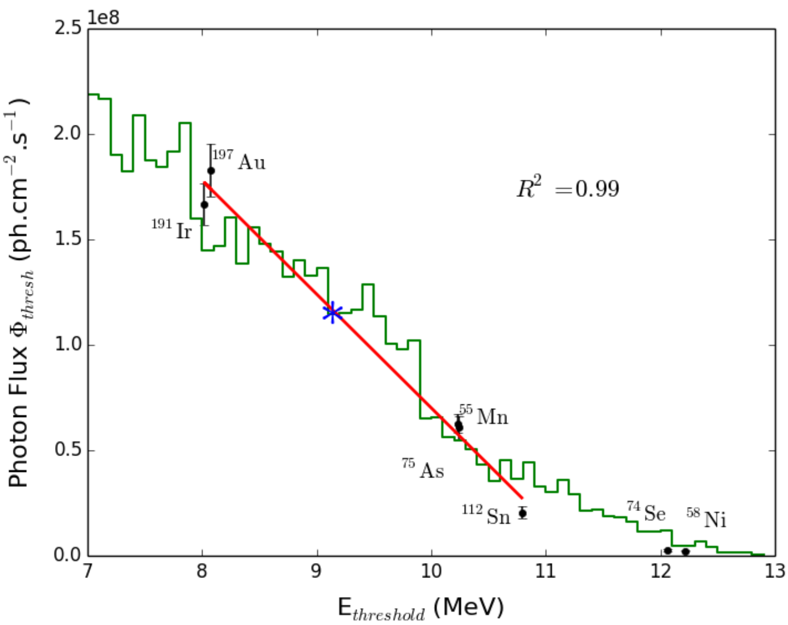

Fig. 1 The calculated predictions regarding the photonuclear reaction (γ, n) of ^{40}Ca, ^{56}Fe, ^{94}Mo, ^{82}Se, ^{154}Sm, ^{120}Sn uses the various γ-strength models. The different lines correspond to the options for the gamma ray strength functions.

The value of effective cross section for ^{162}Er (γ, n) reaction obtained has been compared with the only available in the literature cross sections data set of ^{nat}Er (γ, xn) [3]. The experimental data of natural Er at the energy range 9 – 14 MeV corresponding only to ^{nat}Er (γ, n) reaction is presented in Fig. 2. The Brink-Axel as well as the Kopecky-Uhl model gives the most reliable coincidence to the data set. The effective average cross-section of (γ, n) reaction for Er isotopes in the energy region from the E_{thresh} up to E_0=14 MeV, as they estimated using the TALYS code are presented in Table 2. The average effective cross section has been estimated for ^{nat}Er (γ, n) reaction corresponding to the experimental data set [3] and is presented in the same table. Although, ^{162}Er has the lowest abundance the experimentally estimated average cross section for ^{162}Er (γ, n) reaction 87 ±14 mb is presented to be representative of the ^{nat}Er (γ, n) reaction as well, since TALYS simulates values that ranged between 77 and 95 mb. The average effective cross section experimentally estimated for ^{nat}Er (γ, n) reaction as 96 ±7 mb is also agrees well with simulation values. The higher value of natural Er cross section compared to ^{162}Er one could be attributed to the lower energy threshold of ^{nat}Er (6.5 MeV) than ^{162}Er (γ, n) reaction (9.2 MeV).

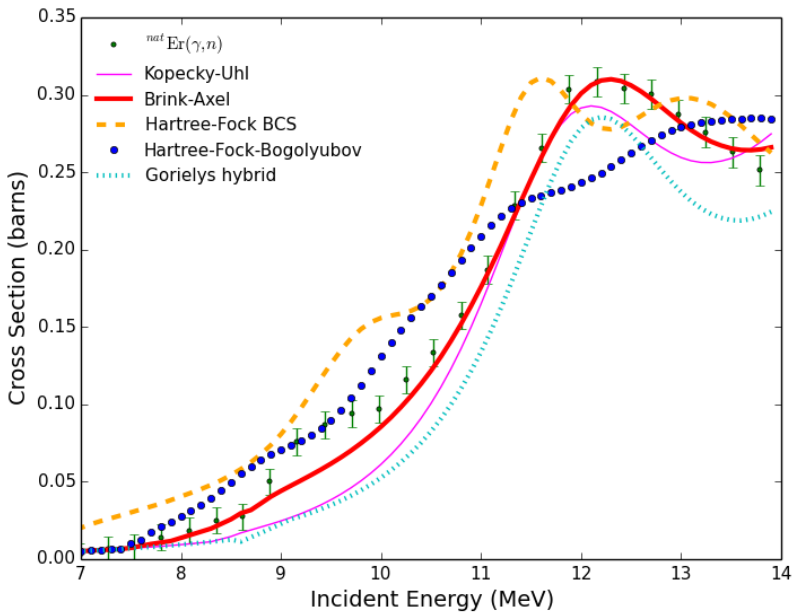

Fig. 2 The calculated predictions using TALYS code regarding the photonuclear cross sections of natural Er (γ, n) reaction using the only available in the literature experimental data [3].

Table 2 Effective average cross-section simulated using TALYS code of (γ, n) reaction for natural Er and its isotopes in the energy region from E_{thresh} up to the photon beam end-point energy E_0=14 MeV. The experimental value of ^{nat}Er (γ, n) reaction occurred using the only available set of data [3].

Isotope	**Abundance (%)**	**E threshold (MeV)**	**σ_{eff} (TALYS)* (mb)**	**σ_{eff} (Experiment) (mb)**
^{162}Er	0.14	9.2	89 - 96	87 ± 14
^{164}Er	1.61	8.9	82 - 96	
^{166}Er	33.61	8.5	119 - 135	
^{167}Er	22.93	6.5	45 - 60	

^{168}Er	26.78	7.8	64 - 84	
^{170}Er	14.93	7.3	55 - 75	
^{nat}Er	100	6.5	77 - 95	96 ± 7

CONCLUSIONS

The measured yield due to photo-activation via (γ, n) reactions with various energy thresholds allowed the determination of the number of photons from each energy threshold up to the end-point energy of the bremsstrahlung photon beam used. The linearity presented in the photon flux vs. energy thresholds data gives the opportunity to monitor the photon flux in any necessary energy intervals. A calibration set of natural elements with well know reaction cross sections and erbium foil have been irradiated at the same time using a medical linac with photon beam endpoint 14 MeV. The unknown averaged effective cross section of the ^{162}Er (γ, n) reaction can be estimated since the photon flux at 9.2 – 14 MeV energy interval can be determined.

Reaction cross-sections have been simulated as well using the TALYS 1.6 code. The theoretical cross section calculations are based on the γ-ray strength function (model) applied. TALYS code includes five functions: the Brink-Axel model that uses a Standard LOrentzian (SLO) to describe GDR, the Kopecky-Uhl model uses a Generalized Lorentzian (GLO), as well as the Hartree-Fock, Hartree-Fock-Bogolyubov and Goriely's hybrid model.

The effective cross-section for the photonuclear reaction ^{162}Er (γ, n) was for the first time determined experimentally as 87 ± 14 mb, for energy interval from 9.2 - 14 MeV bremsstrahlung end-point energy. The specific effective cross section estimated using the TALYS code range between 89 and 96 mb. These values agree with the experimentally estimated effective cross section of natural Er (γ, n) reaction, within the measurement uncertainties. The relatively higher value of natural Er cross section compared to ^{162}Er one could be attributed to the lower energy threshold (6.5 MeV) than (9.2 MeV).

References

[1] J. R Wu, C.C. Chang, Phys. Rev. C 16 (1977)

[2] C. Nair, M. Erhard, A. R. Junghans, D. Bemmerer, R. Beyer, E. Grosse, J. Klug, K. Kosev, G. Rusev, K. D. Schilling, R. Schwengner, A. Wagner, Phys. Rev. C 78 (2008) 055802

[3] R. Bergere, H. Beil, P. Carlos, A.Veyssiere, Nucl. Phys. A133, p.417 (1969)

[4] IAEA-EXFOR, Experimental nuclear reaction data (http://www-nds.iaea.org/exfor)

[5] A. J. Koning, S. Hilaire, M.C. Duijvestijn, TALYS-1.6, A nuclear reaction program, NRG-1755 NG Petten, The Netherlands, 2008 (http://www.talys.eu)

[6] C.A. Kalfas, E. Tsoulou, Nucl. Instr. Meth. A 500, p.386 (2003)

[7] S. Agostinelli et al, Geant4 - a simulation toolkit, Nucl. Instr. Meth. A 506, p.250 (2003)

[8] E. Vagena, S. Stoulos, M. Manolopoulou, Nucl. Instr. Meth. A. 806, p.271 (2016)

[9] E. Vagena, S. Stoulos, M. Manolopoulou, Rad. Phys. Chem. 120, p.89 (2016)