MONTE CARLO MODELLING OF THE YIELDS OF ^{232}Th PHOTOFISSION PRODUCTS ON THE M-30 MICROTRON

V.V. Pyskach, E.V. Oleinikov, I.V. Pylypchynets, A.N. Gomonai, A.I. Lengyel, O.O. Parlag
Institute of Electron Physics, NAS of Ukraine, Uzhhorod, Ukraine
E-mail: v.pyskach@gmail.com

The paper presents the results of modelling the predicted yields of ^{232}Th photofission products initiated by bremsstrahlung photons in the first-chance energy region on the M-30 microtron electron accelerator. The GEANT4 toolkit was used to calculate the characteristics of bremsstrahlung photon beams, taking into account the technical characteristics of the M-30 microtron and the parameters of the photofission stimulation schemes. The yields of ^{232}Th photofission products at fixed excitation energies were calculated using the Monte Carlo code GEF. The results of the simulations will make it possible to optimise experimental investigations of the yields of ^{232}Th photofission products on the M-30 microtron.

PACS: 24.75.+1, 25.85.-w, 25.85.Ec, 25.85. Ca

INTRODUCTION

Product (fragment) yields are among the principal parameters characterising the actinide fission process [1]. One of the promising directions in the study of fission is the investigation of product yields under photon irradiation, since the interaction of gamma quanta with nuclei is purely electromagnetic, which simplifies the interpretation of the results obtained and makes it possible to draw practically unambiguous conclusions regarding the role of the effects under investigation [2].

Information on the yields of ^{232}Th photofission products is of particular interest for both experimental and theoretical studies, because this nucleus lies on the boundary between pre-actinides and light actinides [3]. However, the experimental data currently available on the yields of ^{232}Th photofission products do not satisfy present needs either for the development of model concepts or for applied uses, including the development of next-generation power systems such as fast-neutron reactors (the ^{232}Th-^{233}U fuel cycle), accelerator-driven reactors (controlled subcritical systems), methods for producing nuclear beams with an excess of neutrons, and non-destructive methods of isotopic analysis of fertile nuclear materials [3, 4]. It should be noted that existing experimental values of ^{232}Th photofission product yields obtained by similar methods differ from one another even at close excitation energies [3, 5]. Therefore, their investigation remains an important task.

Since experimental studies of the yields of actinide photofission products are costly and time-consuming, nuclear Monte Carlo codes are widely used to predict them [6].

The aim of the present work was to model, that is, to predict using nuclear Monte Carlo codes, the yields of ^{232}Th photofission products on the electron accelerator of the Institute of Electron Physics of the NAS of Ukraine, namely the M-30 microtron.

1. MATERIALS AND METHODS

The nuclear Monte Carlo code GEF was used to calculate the yields of ^{232}Th photofission products. This code is widely used to solve applied problems in nuclear engineering [7–9]. It should be noted that the GEF code provides reliable predictions of product yields for fissile nuclei for which no experimental data are available [10]. Version GEF 2025/1.3 was used for the simulations [11]. Fig. 2 shows a screenshot of the programme's simulation-parameter input panel.

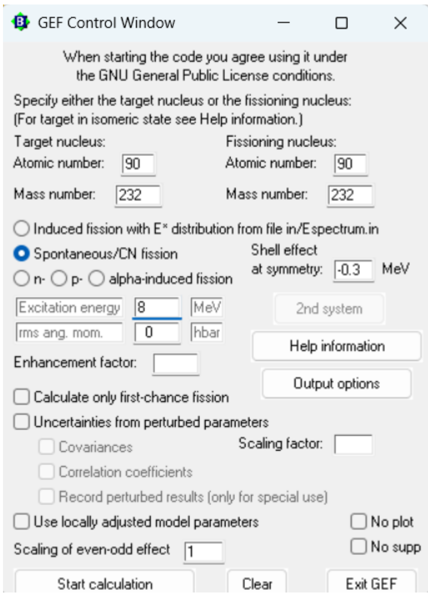

Fig. 1. Screenshot of the GEF simulation-parameter input panel [11]

The input data required to implement the GEF code are the average excitation energies (E^*) of the fissile actinides, in our case ^{232}Th*, which are calculated using formula (1) [12]:

$$E^* = \frac{\sum_{i=1}^{n} E_i \sigma(E_i, E_{\gamma\,max}) \Delta E \sigma_f(E_i)}{\sum_{i=1}^{n} \sigma(E_i, E_{\gamma\,max}) \Delta E \sigma_f(E_i)},$$

where $\sigma(E_i, E_{\gamma\,max})$ is the number of bremsstrahlung photons with energy E_i produced by an electron, and $\sigma_f(E_i)$ is the value of the cross section of the ^{232}Th photofission reaction as a function of the energy Ei [13].

The energy spectrum of bremsstrahlung photons $\sigma(E_i, E_{\gamma max})$ was calculated using a programme developed with GEANT4 10.7 class libraries [14]. To calculate the energy spectra of the photons that stimulated the ^{232}Th photofission reaction, that is, those interacting with the experimental sample, a programme was developed in C++ using the GEANT4 class library. The input parameters used in the modelling reproduced the technical characteristics of the M-30 microtron, specifically the electron beam extraction unit in air [15, 16], and the irradiation geometry of the experimental sample.

The calculations were carried out for the following scheme of stimulation of the ^{232}Th photofission reaction on the M-30 microtron electron accelerator, shown in Fig. 1: (1) electron beam extraction unit in air; (2) titanium window of the extraction unit (elliptical shape, axis dimensions 22 mm and 6 mm, thickness 50 µm); (3) tantalum converter (rectangular plate measuring 100x50 mm, thickness 1 mm); and (4) 232Th sample (disc of radius 6 mm and thickness 2 µm).

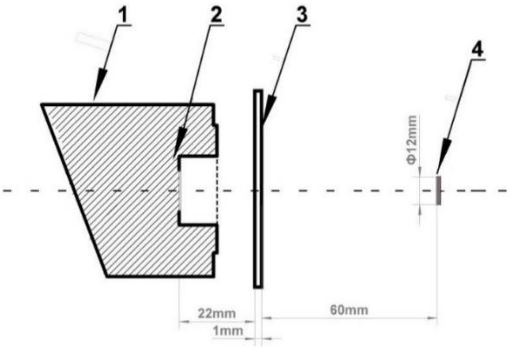

Fig. 2. Irradiation scheme of the ^{232}Th sample

2. RESULTS

Fig. 3 shows the simulated energy spectra of bremsstrahlung photons in the energy range from 6 to 18 MeV, which stimulated the ^{232}Th photofission reaction and were used to calculate the average excitation energies of the fissile nuclei ^{232}Th* [12]. The same figure also presents the cross section of the ^{232}Th(γ,f) reaction [13].

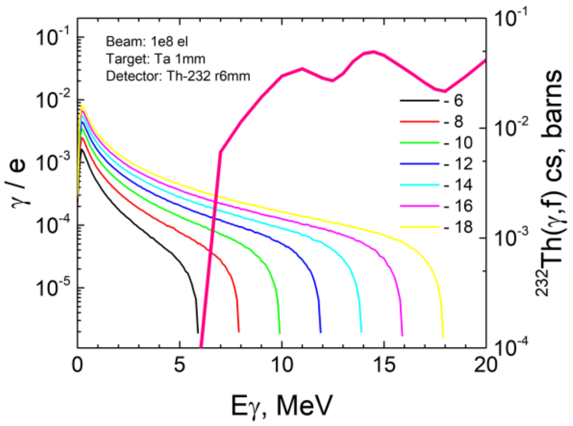

Fig. 3. Energy spectra of bremsstrahlung photons and the cross section of the ^{232}Th(γ,f) reaction [16]

Fig. 4 shows the dependence of the average excitation energy of the fissile nucleus ^{232}Th* on the bremsstrahlung photon endpoint energy for the energy range from 6 to 18 MeV. The average excitation energies vary from 5 to 12.2 MeV.

Fig. 5 presents the predicted yields of ^{232}Th photofission products for the energy range from 5 to 12.2 MeV, obtained from simulations using the nuclear Monte Carlo codes GEANT4 [14] and GEF [11]. For comparison, Fig. 6 presents the simulated product-yield values for the ^{232}Th photofission fissile nucleus at E* = 7 MeV together with existing experimental data at close excitation energies [12, 17]. The simulation results are in agreement with the available data within the uncertainties of the experimental studies.

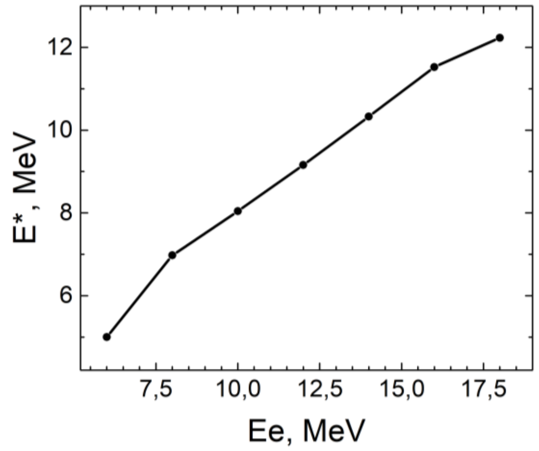

Fig. 4. Energy spectra of bremsstrahlung photons and the cross section of the ^{232}Th(γ,f) reaction

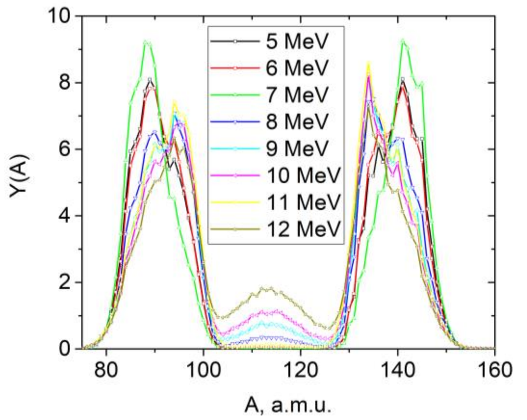

Fig. 5. Predicted yields of ^{232}Th photofission products

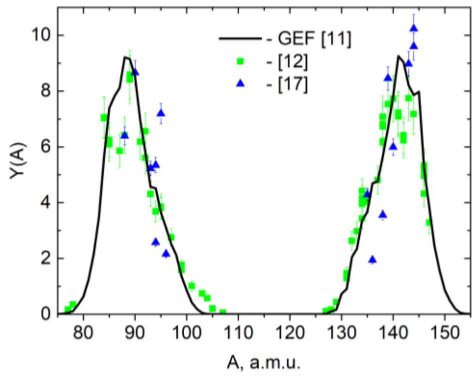

Fig. 6. Predicted yields of ^{232}Th photofission products

CONCLUSIONS

The use of the nuclear Monte Carlo codes GEANT4 and GEF made it possible to predict the yields of ^{232}Th photofission products initiated by bremsstrahlung photons on the M-30 microtron electron accelerator, taking into account its technical characteristics and the irradiation geometry.

The proposed calculation approach may be used to optimise the determination of photofission product yields on electron accelerators while taking into account their technical characteristics and irradiation schemes.

The present work was carried out within the framework of the topic "Implementation of simulation technologies into experimental studies of photofission of the ^{232}Th nucleus", state registration No. 0126U002601.

REFERENCES

1. T. Mukhopadhyay, D.N. Basu. Photonuclear reactions of actinides in the giant dipole resonance region // *The European Physical Journal A*. 2010, v. 45, p. 121-124; https://doi.org/10.1140/epja/i2010-10993-y
2. D. Filipescu, I. Gheorghe, S. Goriely, et al. Giant dipole resonance photofission and photoneutron reactions in ^{238}U and ^{232}Th // *Physical Review C*. 2024, v. 109, p. 044602; https://doi.org/10.1103/PhysRevC.109.044602
3. A. Zilges, D.L. Balabanski, J. Isaak, N. Pietrall. Photonuclear reactions–From basic research to applications // *Progress in Particle and Nuclear Physics*. 2022, v. 122, p. 103903; https://doi.org/10.1016/j.ppnp.2021.103903
4. O.O. Parlag, V.T. Maslyuk, E.V. Oleynikov, et al. Structure of mass-yield distributions of ^{232}Th photofission product by bremsstrahlung at energy 17.5 MeV // *Scientific Herald of Uzhhorod University. Series "Physics"*. 2021, v. 49, p. 54-60; https://doi.org/10.54919/2415-8038.2021.49.54-60
5. EXFOR: Experimental nuclear reaction data. Available from: https://www-nds.iaea.org/exfor/
6. O.O. Parlag, O.I. Lengyel, E.V. Oleinikov, et al. *Use of simulation technologies in the practice of experimental research of the characteristics of actinides photofission on the electron accelerator – microtron M-30*: Moderní aspekty vědy. Svazek LI mezinárodní kolektivní monografie. Česká republika. 2024, p. 383-402; https://doi.org/10.52058/51-2024
7. K.-H. Schmidt, B. Jurado, C. Amouroux, C. Schmitt. General description of fission observables: GEF model code // *Nuclear Data Sheets*. 2016, v. 131, p. 107-221; https://doi.org/10.1016/j.nds.2015.12.009
8. Benchmark of the GEF code for fission-fragment yields over an enlarged range in fissioning nucleus mass, excitation energy, and angular momentum *// Physical Review C*. v. 98, (18), p. 044605. https://doi.org/10.1103/PhysRevC.98.044605
9. K.-H. Schmidt, M. Estienne, M. Fallot, et al. Extensive study of the quality of fission yields from experiment, Evaluation and GEF for antineutrino studies and applications // *Nuclear Data Sheets*. 2021, v. 173, p. 54-117; https://doi.org/10.1016/j.nds.2021.04.004
10. K.-H. Schmidt, B. Jurado, C. Schmitt. General description of fission observables: The GEF code // *The European Physical Journal Conferences*. 2017, v. 146, p. 04001; https://doi.org/10.1051/epjconf/201714604001
11. GEF 2025/1.3. (A General Description of Fission Observables). Available from: https://www.khschmidts-nuclear-web.eu/GEF-2025-1-3.html
12. H. Naik, B.S. Shivashankar, H.G. Raj Prakash, et al. Measurements of fission yield in 8 MeV bremsstrahlung induced fission of ^{232}Th and ^{238}U // *Journal of Radioanalytical and Nuclear Chemistry*. 2014, v. 299, p. 127-137; https://doi.org/10.1007/s10967-013-2719-0
13. Evaluated Nuclear Data File (ENDF). Database Version of 2026-01-09. Available from: https://www-nds.iaea.org/exfor/ endf.htm
14. GEANT4 11.1 (9 December 2022). Available from: https://geant4. web.cern.ch/support/download
15. E.V. Oleinikov, I.V. Pylypchynets, O.O. Parlag, V.V. Pyskach. Photon and photoneutron outputs simulation from a tantalum converter at the M-30 microtron // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2024, N 5(153), p. 148-153; https://doi.org/10.46813/2024-153-148.
16. O.O. Parlag, V.V. Pyskach, E.V. Oleinikov, et al. Modeling the characteristics of photons and residual electrons in bremsstrahlung beams generated by a tantalum converter on the M-30 microtron // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2025, N 3(157), p. 169-175; https://doi.org/10.46813/2025-157-169
17. A. Foley, H. Yang. Short-lived photofission product yields from ^{238}U and ^{232}Th at Bremsstrahlung X-ray endpoint energies of 8, 14, and 20 MeV for nuclear forensics isotope production applications // *Nuclear Inst. and Methods in Physics Research, A*. 2021, v. 1013, p. 165621; https://doi.org/10.1016/j.nima.2021.165621

МОНТЕ-КАРЛО-МОДЕЛЮВАННЯ ВИХОДІВ ПРОДУКТІВ ФОТОПОДІЛУ ^{232}Th НА МІКРОТРОНІ М-30

В.В. Пискач, Є.В. Олейніков, І.В. Пилипчинець, Г.М. Гомонай, О.І. Лендел, О.О. Парлаг

Представлено результати моделювань прогнозованих виходів продуктів фотоподілу ^{232}Th ініційованих гальмівними фотонами (область енергій першого шансу) на електронному прискорювачі – мікротроні М-30. Для розрахунків характеристик пучків гальмівних фотонів, з врахуванням технічних характеристик мікротрону М-30 та параметрів схем стимуляції реакції фотоподілу, використовувався інструментарій GEANT4. Виходи продуктів фотоподілу ^{232}Th при фіксованих енергіях збудження розраховувалися Монте-Карло кодом – GEF. Результати проведених моделювань дозволять оптимізувати процес експериментальних досліджень виходів продуктів фотоподілу ^{232}Th на мікротроні М-30.