YIELDS OF ^{241}Am PHOTOFISSION PRODUCTS INDUCED BY BREMSSTRAHLUNG PHOTONS WITH AN ENERGY OF 12.5 MeV

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The paper presents the results of investigations of 19 relative (cumulative) yields of ^{241}Am photofission products (^{85m}Kr, ^{87}Kr, ^{91}Sr, ^{92}Sr, ^{97}Zr, ^{99}Mo, ^{105}Ru, ^{129}Sb, ^{131}I, ^{132}Te, ^{133}I, ^{134}I, ^{135}I, ^{139}Ba, ^{141}Ba, ^{142}La, ^{143}Ce, ^{146}Pr, ^{149}Nd), obtained at a bremsstrahlung photon energy of 12.5 MeV, generated at the M-30 microtron electron accelerator of the Institute of Electron Physics of the NAS of Ukraine. The relative yields of ^{241}Am photofission products were determined by semiconductor gamma spectrometry of an unseparated mixture of fragments accumulated in aluminium foil. The GEANT4 toolkit was used to model the bremsstrahlung spectrum. The experimental data obtained are in agreement with the results of simulations performed with the nuclear Monte Carlo code GEF (version 2025.1.3).

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INTRODUCTION

Although the process of actinide photofission has been studied for more than 80 years, it remains relevant today [1]. The yields of actinide fission fragments (products) are among the principal parameters characterising the mechanism of excited-nucleus decay [2]. However, it should be noted that the currently available experimental data on the yields of actinide photofission products do not meet current needs for developing model concepts and applications in nuclear engineering [3].

This is especially true for the minor actinide ^{241}Am. At present, only measurements of the isomeric yield ratios of the products ^{90}Rb, ^{130}Sb, ^{133}Te, ^{134}I, and ^{135}Xe formed as a result of ^{241}Am photofission at bremsstrahlung endpoint energies of 9.8 and 17 MeV have been carried out [4, 5]. Therefore, experimental studies of the yields of ^{241}Am photofission products are an extremely important task, driven by the need for new experimental data for a wide range of applied uses, for example, the transmutation of spent nuclear fuel [6], control of nuclear material circulation [7], environmental applications [8], and others.

This paper presents the results of studies of the yields of ^{241}Am photofission products at a bremsstrahlung photon maximum energy of 12.5 MeV.

1. MATERIALS AND METHODS

The relative (cumulative) yields of ^{241}Am photofission products were determined by semiconductor gamma spectrometry of an unseparated mixture of fragments accumulated in aluminium foil [9–11].

In the experimental studies, a ^{241}Am sample was used, in which an active ^{241}Am layer 11 mm in diameter was deposited on a disc-shaped substrate of 12Kh18N10T stainless steel (diameter 24 mm, thickness 1 mm). The isotopic content of ^{241}Am in the sample exceeded 99%. Fig. 1 shows the experimental ^{241}Am sample in plexiglass packaging.

Photofission fragments were accumulated in aluminium foil fixed in front of the active ^{241}Am layer by an aluminium ring.

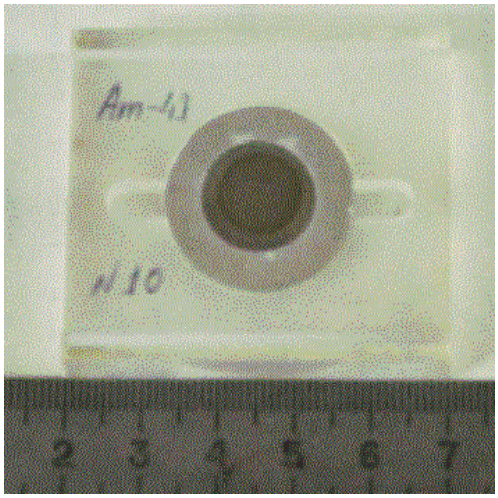


Fig. 1. Experimental ^{241}Am sample

The fissile assembly was irradiated on the electron accelerator of the Institute of Electron Physics of the NAS of Ukraine, the M-30 microtron, at an electron energy of 12.5 MeV and an average beam current of approximately 5 μA. Three irradiation series of the ^{241}Am sample were carried out. The activation times were 0.23; 0.9, and 4.0 h.

The sample irradiation scheme is shown in Fig. 2: (1) electron beam extraction unit in air; (2) titanium window of the extraction unit (elliptical shape, axis dimensions 22 and 6 mm, thickness 50 μm); (3) tantalum converter (rectangular plate measuring 100 x 50 mm, thickness 1 mm); (4) filter for purifying the bremsstrahlung beam from residual electrons and secondary photoneutrons (a cylindrical lithium tetraborate single crystal, diameter 30 mm and height 19 mm) [12]; (5) ^{241}Am sample; (6) aluminium foil holder (ring with inner diameter 11 mm, outer diameter 14 mm, thickness 0.5 mm, material aluminium); and (7) aluminium foil for accumulation of fission fragments (diameter 14 mm, thickness 0.2 mm).

The GEANT4 Monte Carlo code [13] was used to model the irradiation process of ^{241}Am. The input parameters used in the calculations reproduced the technical parameters of the M-30 microtron, specifically the electron beam extraction unit in air [14, 15] and the irradiation geometry of the fissile assembly.

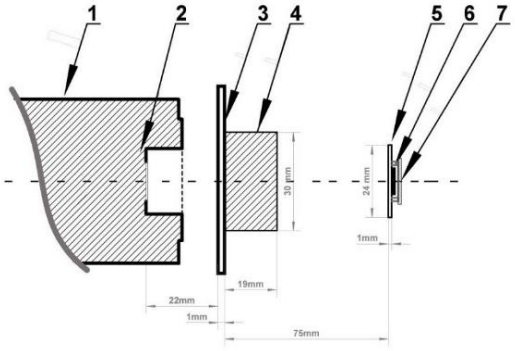


Fig. 2. Irradiation scheme of the ^{241}Am sample

Fig. 3 presents the simulated energy spectrum of bremsstrahlung photons that stimulated the ^{241}Am photofission reaction; this spectrum was used to calculate the average excitation energy of the fissile nucleus ^{241}Am* [10]. The cross section of the ^{241}Am(γ,f) reaction [16] is also shown in the same figure.

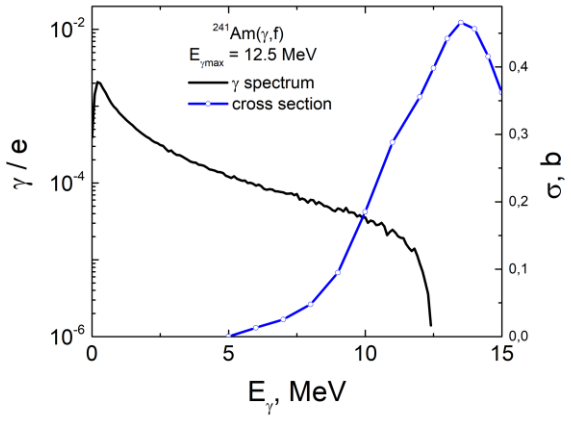


Fig. 3. Photon energy spectrum and cross section of the ^{241}Am(γ,f) reaction [16]

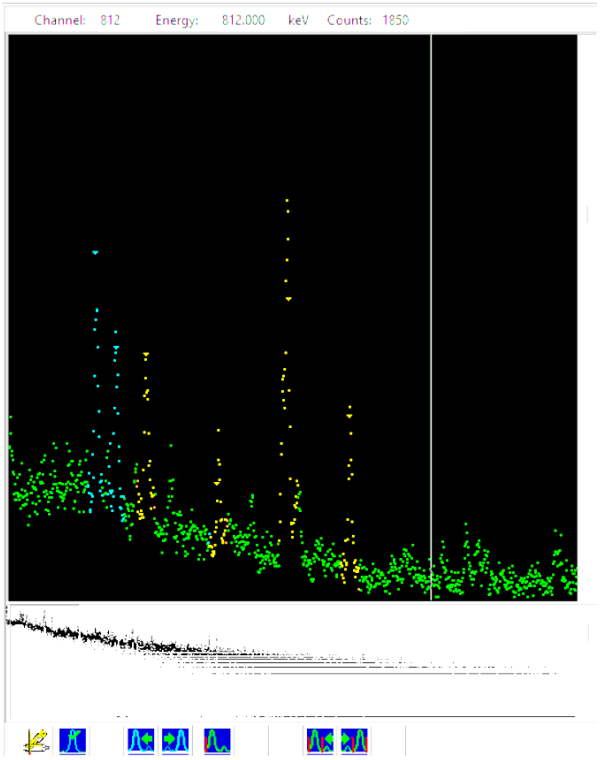
The average excitation energy of the fissile nucleus ^{241}Am* was 9.72 MeV.

After the accumulation of the fission products by the aluminium collector had been completed, their gamma activity was measured over a period of 491.3 h. The duration of individual measurement series varied from 0.08 to 4.5 h.

For the spectrometric measurements, HPGe and Ge(Li) semiconductor detectors with volumes of 150 and 100 cm^3, respectively, were used [10]. The spectrometric information was processed using the Winspectrum software package [17].

Fig. 4 shows fragments of the spectra of ^{241}Am photofission products (a screenshot from the Winspectrum processing software): in case (a), the irradiation, cooling, and measurement times were 4.0; 0.131, and 0.25 h, respectively; and in case (b), 4.0; 72.31, and 1.67 h, respectively.

The fission products were identified by the energies of their characteristic gamma lines, taking into account their half-lives and, for isobaric chains, those of their precursors. The irradiation, cooling, and measurement times were also taken into account. The values of the nuclear spectroscopic data used in identifying the fission products for the calculations, namely gamma-quantum energies, gamma-line intensities, half-lives of the products formed and of their precursors in the isobaric chain, were taken from the NNDC nuclear data library (USA) [18, 19].



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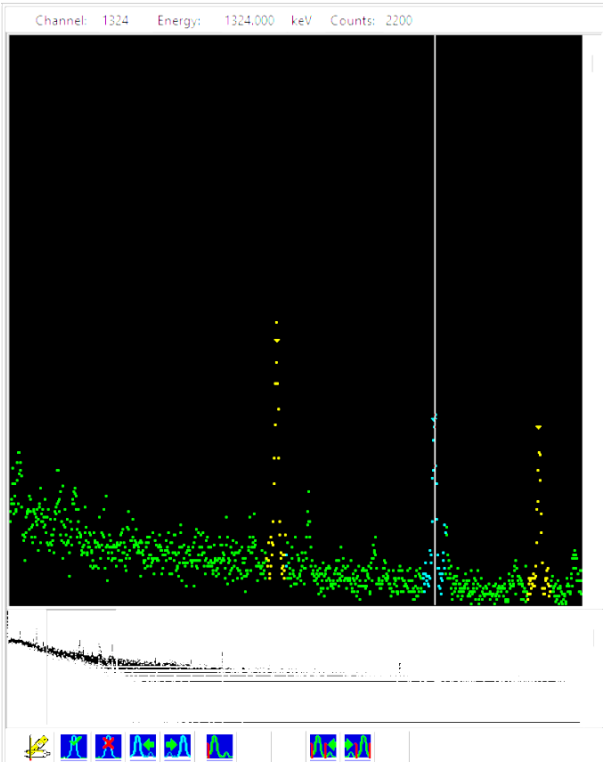

b

Fig. 4. Fragments of gamma spectra of ^{241}Am photofission products

2. RESULTS

As a result of the experiment, the following relative (cumulative) yields of ^{241}Am photofission products were measured: ^{85m}Kr (151.2 [75.2]), ^{87}Kr (402.6 [50.0]), ^{91}Sr (1024.3 [33.0]), ^{92}Sr(1383.9 [90.0]), ^{97}Zr (743.4

[50.0]), ^{99}Mo (140.5 [89.0]), ^{105}Ru (724.3 [47.3]), ^{129}Sb (813.0 [48.2]), ^{131}I (364.5 [81.5]), ^{132}Te (228.2 [88.0]), ^{133}I (529.9 [87.0]), ^{134}I (847.0 [96.0]), ^{135}I (1260.4 (28.7)), ^{139}Ba (165.9 (23.7)), ^{141}Ba (190.3(45.5)), ^{142}La (641.3 (47.4)), ^{143}Ce (293.3 (42.8)), ^{146}Pr (453.9 (46.0)), ^{149}Nd (211.3 (25.9)). The energies of the analytical gamma lines (keV) are given in round brackets, and their intensities (%) in square brackets [18, 19]. Product yields were determined relative to the yield of ^{131}I.

Because of the small size of the ^{241}Am sample, only a limited number of fission products could be measured.

The statistical uncertainty of the gamma-line peak intensities used in the analysis did not exceed 5% throughout the measurements. The total uncertainty of the relative product yields was estimated by taking into account the statistical uncertainty of the product gamma-line peak intensity, the analysis of time dependences, the spread of values averaged over individual measurements, and the uncertainties of interpolated efficiency values and nuclear-physical constants. The overall uncertainty in determining the relative yields of ^{241}Am photofission products did not exceed 12%.

The experimental values of the relative yields of ^{241}Am photofission products at a maximum bremsstrahlung photon energy of 12.5 MeV are shown by red circles in Fig. 5. In the same figure, the blue line shows the results of modelling the mass distribution of post-neutron product yields for the fissile nucleus ^{241}Am* at an excitation energy of approximately 10 MeV; for correct comparison with the experimental results, the yield values were normalised to the A = 133 yield. The nuclear Monte Carlo code GEF 2025/1.3 [20] was used for the modelling.

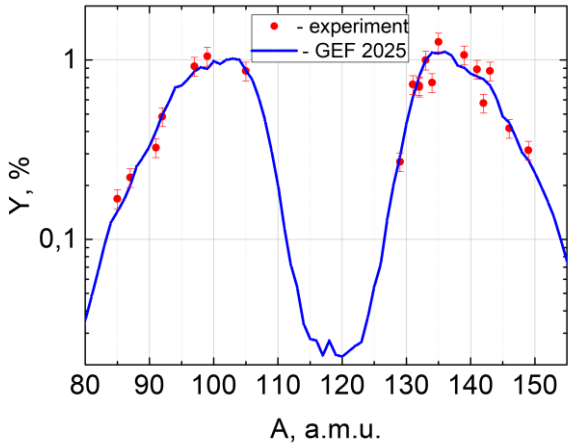

Fig. 5. Relative yields of ^{241}Am photofission products

Most of the obtained values of the relative yields of ^{241}Am photofission products agree with the GEF-code calculations within the experimental uncertainties.

CONCLUSIONS

As a result of the experimental studies, 19 relative yields of 241Am photofission products, namely ^{85m}Kr, ^{87}Kr, ^{91}Sr, ^{92}Sr, ^{97}Zr, ^{99}Mo, ^{105}Ru, ^{129}Sb, ^{131}I, ^{132}Te, ^{133}I, ^{134}I, ^{135}I, ^{139}Ba, ^{141}Ba, ^{142}La, ^{143}Ce, ^{146}Pr, and ^{149}Nd, were determined for the first time at a bremsstrahlung photon endpoint energy of 12.5 MeV.

It should be noted that the modelling performed using the GEF code describes and predicts the product yields for the fissile nucleus ^{241}Am* at an average excitation energy of approximately 9.72 MeV.

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ВИХОДИ ПРОДУКТІВ ФОТОПОДІЛУ ^{241}Am ГАЛЬМІВНИМИ ФОТОНАМИ З ЕНЕРГІЄЮ 12,5 МеВ

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

Представлено результати досліджень 19 відносних (кумулятивних) виходів продуктів (^{85m}Kr, ^{87}Kr, ^{91}Sr, ^{92}Sr, ^{97}Zr, ^{99}Mo, ^{105}Ru, ^{129}Sb, ^{131}I, ^{132}Te, ^{133}I, ^{134}I, ^{135}I, ^{139}Ba, ^{141}Ba, ^{142}La, ^{143}Ce, ^{146}Pr, ^{149}Nd) фотоподілу ^{241}Am, отриманих при енергії гальмівних фотонів – 12,5 МеВ (які були згенеровані на електронному прискорювачі Інституту електронної фізики НАН України – мікротроні М-30). Визначення відносних виходів продуктів фотоподілу ^{241}Am здійснювалось методом напівпровідникової гамма-спектрометрії несепарованої суміші уламків, накопичених у алюмінієвій фользі. Для моделювання спектра гальмівного випромінювання було використано інструментарій GEANT4. Отримані експериментальні данні узгоджуються з результатами моделювання ядерним Монте-Карло кодом GEF (version 2025.1.3).