MODELLING THE YIELDS OF RARE EARTH ELEMENT ACTIVATION PRODUCTS UNDER DIRECT STIMULATION OF THE (γ,n) REACTION ON THE M-30 MICROTRON

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The paper presents the results of modelling the yields of activation products of rare earth elements (^{44}Sc, ^{88}Y, ^{141}Ce, ^{140}Pr, ^{147,149}Nd, ^{153}Sm, ^{152}Eu, ^{159}Gd, ^{158}Tb, ^{157}Dy, ^{164}Ho, ^{169}Er, ^{168}Tm, ^{169,175}Yb, ^{174}Lu) under direct stimulation of the (γ,n) reaction, that is, when the electron beam interacts directly with the rare earth element samples. For the simulations, a computer programme based on the GEANT4 toolkit was developed to calculate the characteristics of bremsstrahlung photons generated within rare earth element samples during irradiation by the direct electron beam of the M-30 microtron, which interacts directly with the sample under study. A comparison was made with the results of modelling the yields of activation products of rare earth samples using the conventional irradiation scheme on the M-30 microtron, in which bremsstrahlung photons are generated by a tantalum converter. The results obtained make it possible to optimise the non-destructive photon activation analysis of rare earth elements using electron accelerators.

PACS: 28.60.+s; 87.53.Jw

INTRODUCTION

To determine the isotopic composition of rare earth elements in the samples under study, the (γ,n) reaction is used, initiated by bremsstrahlung photons generated on electron accelerators [1, 2]. One method of stimulating the (γ,n) reaction in experimental samples is to use a direct electron beam, which generates bremsstrahlung photons within the samples, for example, in the production of medical radioisotopes [3–5].

This paper presents the results of modelling the yields of radionuclide products of rare earth elements (^{44}Sc, ^{88}Y, ^{141}Ce, ^{140}Pr, ^{147,149}Nd, ^{153}Sm, ^{152}Eu, ^{159}Gd, ^{158}Tb, ^{157}Dy, ^{164}Ho, ^{169}Er, ^{168}Tm, ^{169,175}Yb, ^{174}Lu) formed through the (γ,n) reaction channel for a direct stimulation scheme, in which bremsstrahlung gamma quanta were generated by electrons directly inside the experimental samples, on the electron accelerator of the Institute of Electron Physics of the NAS of Ukraine, namely the M-30 microtron, at an electron energy of 12 MeV.

1. MATERIALS AND METHODS

The modelling of the yields of irradiation products from rare earth element samples formed via the (γ,n) reaction channel was carried out for a direct stimulation scheme, in which bremsstrahlung photons were generated by the electron beam within square experimental samples measuring 10 x 10 x 0.1 mm. The samples were positioned perpendicular to the electron-beam axis at a distance of 83 mm from the electron-beam extraction unit in air, using a 50 μm-thick, elliptical titanium window with axes of 22 and 6 mm. The sample activation scheme is shown in Fig. 1.

This scheme was analogous to the indirect activation scheme of rare earth samples, in which bremsstrahlung photons were generated by a tantalum (Ta) converter, used for determining the yields of products formed through the (γ,n) reaction channel [1]. The parameters of the experimental studies [2] were used in the calculations.

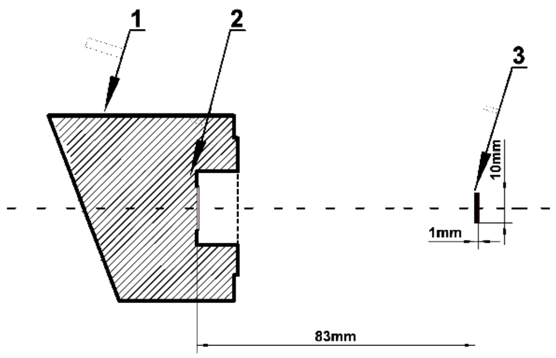

Fig. 1. Irradiation scheme of the experimental samples

The GEANT4 toolkit [6] was used to model the characteristics of the electron beam, namely the energy spectra, their integral values, and transverse distributions in the plane, both in the plane of potential sample placement (1000 x 1000 mm) and on the sample itself. The technical characteristics of the M-30 microtron [7] were taken into account in the calculations.

Additionally, a probability map of the transverse electron distribution in the sample-placement plane was modelled using the inverse cumulative Gaussian distribution.

In the calculations, the electron energy spectra and their integral values were normalised to one primary electron.

2. RESULTS

As a result of simulations performed with the developed programme, the energy spectra of electrons reaching the plane of potential placement for the rare earth element samples and the samples themselves during irradiation on the M-30 microtron were calculated. Fig. 2 shows the energy spectrum of electrons incident on the experimental sample, which generates bremsstrahlung photons within the sample and thereby stimulates the (γ,n) reaction with the nuclei of rare earth elements.

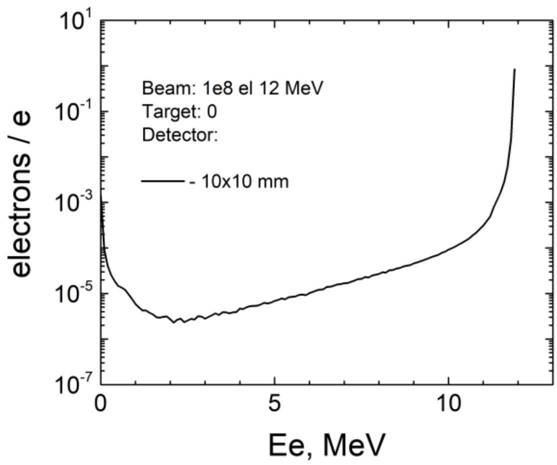

Fig. 2. Energy spectra of electrons stimulating the (γ,n) reaction inside the experimental sample

The integral values of electrons interacting with the experimental sample, with energies from 0 to 12 MeV, and the integral values of electrons generating bremsstrahlung photons within it, with energies from 8 MeV (corresponding to the threshold values of the (γ,n) reaction for most rare earth element isotopes) to 12 MeV (Fig. 5), were calculated. Their values are 0.8738 e/e and 0.8715 e/e, respectively. Electrons stimulating the (γ,n) reaction in the experimental samples account for 99.74% of the total number of electrons reaching the sample. In the case of the conventional stimulation scheme with a tantalum converter, 3.654% (0.00176 γ/e in the 8…12 MeV range) of the total number of photons reaching the sample (0.0482 γ/e in the 0…12 MeV range) interact with the sample.

Fig. 3 shows the transverse distributions of electrons in the plane where the rare earth element samples are placed during irradiation. The number of electrons stimulating the reaction in the sample amounts to 89.1% (4.910E6) of the number of electrons reaching the plane (5.511E6).

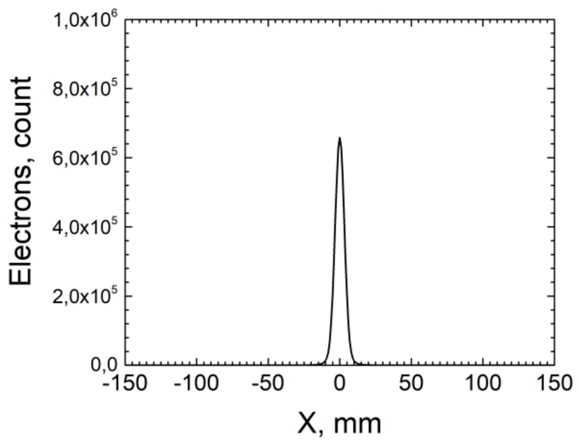

Fig. 3. Transverse distribution of electrons in the plane of placement of the experimental samples

Fig. 4 presents the energy spectra of photons generated inside ^{44}Sc and ^{175}Yb samples. For comparison, the figure also presents the photon spectrum generated by the Ta converter for the indirect stimulation scheme [1, 2]. The results of modelling the energy spectra of bremsstrahlung photons are consistent with calculations performed using the NIST `ESTAR` programme [8] for photon yields arising from the radiative deceleration of monoenergetic electrons in the nuclei of rare earth elements.

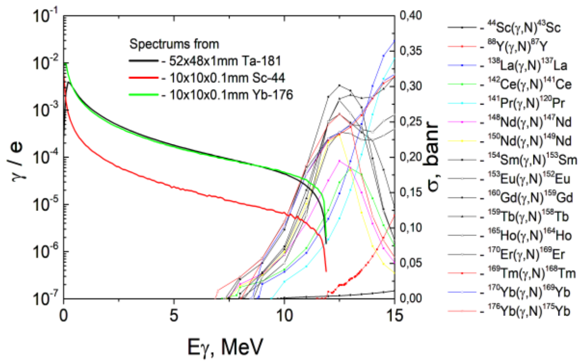

Fig. 4. Energy spectra of bremsstrahlung photons and cross sections of the (γ,n) reaction [9]

Table presents the results of calculations of the yields of products formed through the (γ,n) reaction channel for the direct and indirect irradiation schemes of the experimental samples.

Yields of rare earth element products (radioisotopes) formed through the (γ,n) reaction channel for the direct and indirect irradiation schemes of the experimental samples

Elements	**Isotopes**	**Indirect**	**Direct**
1	**2**	**3**	**4**
$_{21}$Sc	Sc-45	3.395E-13	5.465E-14
$_{39}$Y	Y-89	1.589E-14	1.053E-14
$_{58}$Ce	Ce-142	7.615E-12	5.598E-12
$_{59}$Pr	Pr-141	1.734E-11	1.586E-11
$_{60}$Nd	Nd-148	2.434E-10	2.091E-10
$_{60}$Nd	Nd-150	2.569E-10	2.254E-10
$_{62}$Sm	Sm-154	6.503E-12	6.327E-12
$_{63}$Eu	Eu-153	1.399E-11	1.542E-11
$_{64}$Gd	Gd-160	1.940E-11	1.668E-11
$_{65}$Tb	Tb-159	2.219E-10	2.525E-10
$_{67}$Ho	Ho-165	9.436E-11	1.189E-10
$_{68}$Er	Er-170	1.933E-10	2.378E-10
$_{69}$Tm	Tm-169	2.455E-10	3.254E-10
$_{70}$Yb	Yb-170	1.172E-11	1.394E-11
$_{70}$Yb	Yb-176	1.605E-11	1.822E-11
$_{71}$Lu	Lu-175	2.846E-11	3.545E-11

CONCLUSIONS

The results obtained make it possible to optimise the process of non-destructive photon activation analysis of rare earth element content in the samples under study using different types of electron accelerators.

The present work was carried out within the framework of the topic “Monte Carlo modelling of rare earth element activation schemes for non-destructive isotope analysis”, state registration No. 0125U002853.

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МОДЕЛЮВАННЯ ВИХОДІВ ПРОДУКТІВ АКТИВАЦІЇ РІДКІСНОЗЕМЕЛЬНИХ ЕЛЕМЕНТІВ ПРИ ПРЯМІЙ СТИМУЛЯЦІЇ (γ,n)-РЕАКЦІЇ НА МІКРОТРОНІ М-30

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Представлено результати моделювання виходів продуктів активації рідкоземельних елементів (^{44}Sc, ^{88}Y, ^{138}La, ^{141}Ce, ^{140}Pr, ^{147,149}Nd, ^{153}Sm, ^{152}Eu, ^{159}Gd, ^{158}Tb, ^{157}Dy, ^{164}Ho, ^{169}Er, ^{168}Tm, ^{169,175}Yb, ^{174}Lu) при прямій (тобто при взаємодії пучка електронів зі зразками рідкоземельних елементів) стимуляції (γ,n)-реакції. Для проведення моделювань була створена комп'ютерна програма (на базі інструментарію GEANT4) розрахунку характеристик гальмівних фотонів, згенерованих у середині зразків рідкісноземельних елементів при їх опроміненні прямим пучком електронів мікротрону М-30, що безпосередньо взаємодіють з досліджуваним зразком. Проведено порівняння отриманих даних з результатами моделювань виходів продуктів активації зразків рідкісноземельних елементів із використанням традиційної схеми опромінення на мікротроні М-30 (генерація гальмівних фотонів танталовим конвертером). Отримані результати дозволяють оптимізувати процес недеструктивного фотонного активаційного аналізу рідкісноземельних елементів на електронних прискорювачах.