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MODELING THE YIELDS OF RARE EARTH ELEMENTS ACTIVATION PRODUCTS FOR DIRECT SCHEME OF (γ,n)-REACTION STIMULATION ON THE M-30 MICROTRON

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The results of modelling the yields of rare-earth element activation products (^{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) for the direct scheme of (γ,n)-reaction stimulation are presented (direct interaction of the electron beam with rare-earth element samples took place). For the modelling, a computer program was developed (based on the GEANT4 toolkit) to calculate the characteristics of bremsstrahlung photons generated inside rare-earth element samples during their irradiation by the direct electron beam of the M-30 microtron, which interacts directly with the sample under study. The obtained data were compared with the results of modelling the yields of rare-earth element sample activation products using the traditional irradiation scheme on the M-30 microtron (generation of bremsstrahlung photons by a tantalum converter). The results obtained make it possible to optimise the process of non-destructive photon activation analysis of rare-earth elements using electron accelerators.

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INTRODUCTION

The (γ,n)-reaction, initiated by bremsstrahlung photons generated on electron accelerators, is used to determine the isotopic composition of rare-earth elements in the samples under study [1, 2]. One method of stimulating the (γ,n)-reaction in experimental samples is the use of a direct electron beam, which generates bremsstrahlung photons directly in the experimental samples (for example, in the production of the medical radioisotope ^{99}Mo) [3–5].

As a result of the theoretical and experimental studies carried out [3–5], it was established that the yields of the radioisotopes formed (normalised to one initial electron) have higher numerical values when the direct scheme of (γ,n)-reaction stimulation is used, compared with the indirect stimulation scheme (using a bremsstrahlung photon converter).

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 via the (γ,n)-reaction channel for the direct stimulation scheme (bremsstrahlung gamma quanta were generated by electrons directly in the experimental samples) on the electron accelerator of the Institute of Electron Physics of the National Academy of Sciences of Ukraine, the M-30 microtron.

1. MATERIALS AND METHODS

The yields of products formed via the (γ,n)-reaction channel during irradiation of rare-earth element samples (^{45}Sc, ^{89}Y, ^{142}Ce, ^{141}Pr, ^{148,150}Nd, ^{154}Sm, ^{153}Eu, ^{160}Gd, ^{159}Tb, ^{158}Dy, ^{165}Ho, ^{170}Er, ^{169}Tm, ^{170,176}Yb, ^{175}Lu) were determined according to [1].

Modelling of the yields of products from irradiated rare-earth element samples, formed via the (γ,n)-reaction channel, was carried out for the direct stimulation scheme (bremsstrahlung photons were generated by the electron beam inside square experimental samples (10x10x0.1 mm)). The electron energy was 12 MeV.

The samples were installed perpendicular to the electron beam axis at a distance of 83 mm from the electron extraction unit, into air (a 50 μm-thick titanium window), which was elliptical with axes of 22 and 6 mm. The sample activation scheme is shown in Fig. 1.

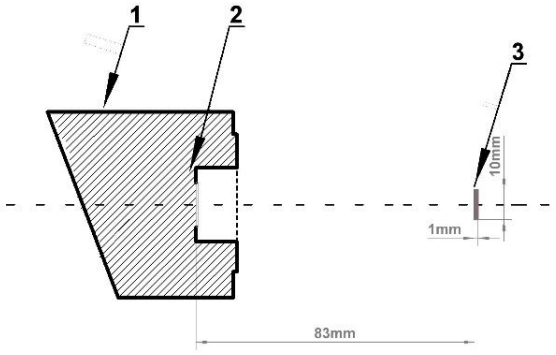


Fig. 1. Irradiation scheme for the experimental samples (1 – electron extraction unit; 2 – titanium window; 3 – experimental sample)

The specified scheme was analogous to the scheme of indirect activation of rare-earth element samples (bremsstrahlung photons were generated by a tantalum (Ta) converter) when determining the yields of products formed via the (γ,n)-reaction channel [1]. The calculations used the parameters of the experimental studies (data on the nuclear and technical parameters of the samples, namely their geometrical dimensions, molecular composition and the number of atoms participating in the reaction) presented in [2].

The GEANT4 toolkit [6] was used to model the characteristics (energy spectra, their integral values and transverse distributions in the plane) of the electron beam

incident on 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. The calculations were performed for an initial number of electrons of 10E8. During the simulations, bremsstrahlung photons generated by electrons inside the experimental samples of rare-earth elements were recorded.

Fig. 2 presents a visualisation of the modelling scheme for direct stimulation of the (γ,n)-reaction using the GEANT4 toolkit (designations: electron extraction unit – grey, titanium window – blue, experimental sample – pink, electron beam – red, generated photons – green).

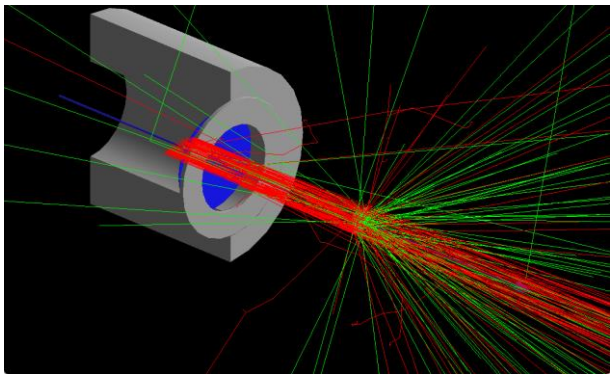


Fig. 2. Visualisation of the modelling of direct reaction stimulation using the GEANT4 toolkit

In addition, a probability map of the transverse distribution of electrons 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 initial electron.

2. RESULTS

As a result of the modelling carried out using the developed program, the energy spectra of electrons incident on the plane of potential placement of rare-earth element samples and on the samples themselves during irradiation on the M-30 microtron were calculated.

Fig. 3 presents the energy spectrum of electrons incident on the experimental sample, which form bremsstrahlung photons inside it and stimulate the (γ,n)-reaction with rare-earth element nuclei.

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 in it (with energies from 8 [corresponding to the threshold values of the (γ,n)-reaction for most rare-earth element isotopes] to 12 MeV (Fig. 6)) were calculated. Their values are 0.8738 and 0.8715 e/e, respectively. The electrons that stimulate the (γ,n)-reaction in the experimental samples constitute 99.74% of the total number of electrons incident on the sample. When the traditional stimulation scheme with a tantalum converter is used, 3.654% (0.00176 γ/e – 8 to 12 MeV) of the total number of photons incident on the sample (0.0482 γ/e – 0 to 12 MeV) interact with the sample [1].

From the modelling results, the electron beam profile in a section through the 1000 x 1000 mm plane at the location of the experimental samples was obtained (Fig. 4).

Fig. 5 presents the transverse distribution of electrons in the plane of placement of rare-earth element samples during their irradiation. The number of electrons stimulating the reaction in the sample is 89.1% (4.910E6) of the number of electrons incident on the plane (5.511E6).

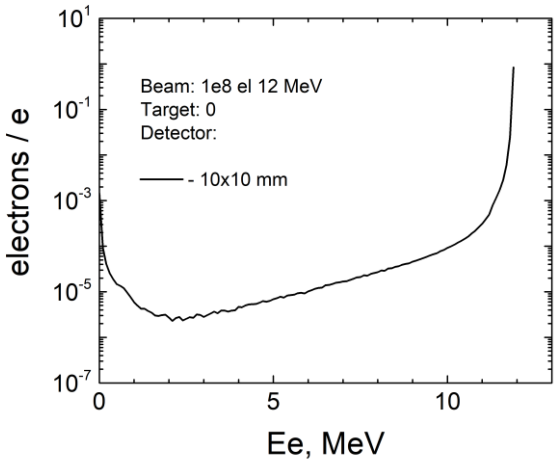


Fig. 3. Energy spectrum of electrons stimulating the (γ,n)-reaction inside the experimental sample

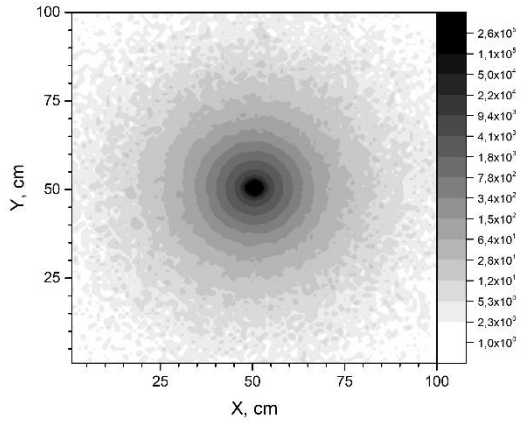


Fig. 4. Electron profile in the plane at the location of the rare-earth element samples

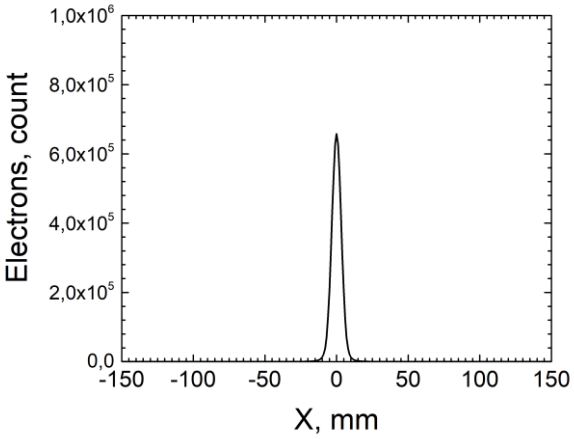


Fig. 5. Transverse distribution of electrons in the plane of placement of the experimental samples

In the case of the indirect scheme of (γ,n)-reaction stimulation, the number of photons incident on the sample is 28.3% (537948) of the total number of photons in the plane (1.90083E6) [1].

Fig. 6 presents the energy spectra of photons generated inside the ^{44}Sc and ^{175}Yb samples. For comparison, this figure shows the spectrum of photons generated by the Ta converter for the indirect stimulation scheme [1].

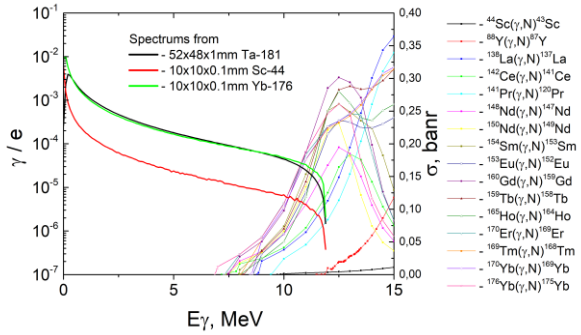


Fig. 6. Energy spectra of bremsstrahlung photons and cross-sections of the (γ,n)-reaction [9]

The results of modelling the generated energy spectra of bremsstrahlung photons are consistent with calculations performed using the NIST "ESTAR" program [8] for the yields of photons formed during radiative braking of monoenergetic electrons by atoms of rare-earth elements. The results of the "ESTAR" program calculations are shown in Fig. 7. For comparison, the yield for tantalum is also shown in this figure.

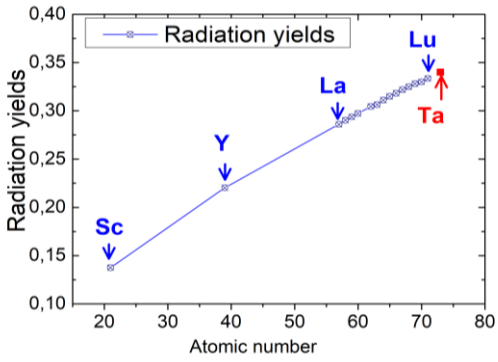


Fig. 7. The photon yields from radiative braking of 12 MeV electrons with rare earth elements

Yields of products (radioisotopes) of rare-earth elements formed via the (γ,n)-reaction channel for the direct and indirect irradiation schemes of rare-earth element nuclei ^{45}Sc, ^{89}Y, ^{142}Ce, ^{141}Pr, ^{148,150}Nd, ^{154}Sm, ^{153}Eu, ^{160}Gd, ^{159}Tb, ^{158}Dy, ^{165}Ho, ^{170}Er, ^{169}Tm, ^{170,176}Yb, ^{175}Lu

Elements	Isotopes	Indirect	Direct	Diff, %
1	2	3	4	5
$_{21}$Sc	Sc-44	3.395E-13	5.465E-14	-83.90
$_{39}$Y	Y-88	1.589E-14	1.053E-14	-33.73
$_{58}$Ce	Ce-141	7.615E-12	5.598E-12	-26.49
$_{59}$Pr	Pr-140	1.734E-11	1.586E-11	-8.54
$_{60}$Nd	Nd-147	2.434E-10	2.091E-10	-14.09
$_{60}$Nd	Nd-149	2.569E-10	2.254E-10	-12.26
$_{62}$Sm	Sm-153	6.503E-12	6.327E-12	-2.71
$_{63}$Eu	Eu-152	1.399E-11	1.542E-11	+10.22
$_{64}$Gd	Gd-159	1.940E-11	1.668E-11	-14.02
$_{65}$Tb	Tb-158	2.219E-10	2.525E-10	+13.79
$_{67}$Ho	Ho-164	9.436E-11	1.189E-10	+26.01
$_{68}$Er	Er-169	1.933E-10	2.378E-10	+23.02
$_{69}$Tm	Tm-168	2.455E-10	3.254E-10	+32.55
$_{70}$Yb	Yb-169	1.172E-11	1.394E-11	+18.94
$_{70}$Yb	Yb-175	1.605E-11	1.822E-11	+13.52
$_{71}$Lu	Lu-174	2.846E-11	3.545E-11	+24.56

Table presents the results of calculations of the yields of products formed via the (γ,n)-reaction channel for the direct and indirect irradiation schemes of rare-earth element experimental samples. The fifth column of the table gives the difference between the numerical yield values for the direct stimulation scheme relative to the indirect scheme. A positive value means that the numerical yield value was higher, while a negative value means that it was lower.

CONCLUSIONS

As a result of the modelling carried out, the yield values of the products ^{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 as a result of the (γ,n)-reaction initiated directly by electrons during interaction with experimental samples of rare-earth elements, were calculated.

The obtained results will make it possible to optimise the process of non-destructive photon activation analysis of the rare-earth element content in the samples under study on different types of electron accelerators by selecting activation schemes (direct or indirect).

The presented 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 ВИДХОДІВ АКТИВАЦІЇ РІДКІСНОЗЕМЕЛЬНИХ ЕЛЕМЕНТІВ ДЛЯ ПРЯМОЇ СХЕМИ СТИМУЛЯЦІЇ (γ,n)-РЕАКЦІЇ НА МІКРОТРОНІ М-30

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

Представлено результати моделювання виходів продуктів активації рідкісноземельних елементів (^{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) для прямої схеми стимуляції (γ,n)-реакції (відбувалася безпосередня взаємодія пучка електронів зі зразками рідкісноземельних елементів). 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 із 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.