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MODELING THE CHARACTERISTICS OF PHOTONS AND RESIDUAL ELECTRONS IN BREMSSTRAHLUNG BEAMS GENERATED BY A TANTALUM CONVERTER ON THE M-30 MICROTRON

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The results of simulations are presented: the characteristics (energy spectra, their integral characteristics, transverse distributions in the plane) of the beam of electrons and secondary photons at the output of the electron accelerator, specifically, in the placement plane of the tantalum converter, and the characteristics of photons and residual electrons in the bremsstrahlung beams generated by the tantalum converters (thicknesses of 0.04, 0.4, 1.0, 4.0, and 10.0 mm) in the placement plane of irradiated samples. Calculations were performed for the electron accelerator IEP NAS of Ukraine – microtron M-30, considering its technical characteristics at a fixed initial electron energy of 17.5 MeV. The GEANT4 toolkit was used for the simulations. The information obtained was utilized to optimize the process of stimulating photonuclear reactions on actinide nuclei and to predict the results.

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INTRODUCTION

Photonuclear reactions play a central role in studying various properties of nuclear structure [1, 2]. They are stimulated by the electromagnetic interaction (photon beams), which is the most studied fundamental interaction and may be the purest and most direct way to obtain information [3]. It should be noted that photonuclear reactions on actinide nuclei are also used to solve a wide range of applied problems. These problems are related to the reduction of radioactive waste [4], non-destructive methods of isotopic identification of nuclear materials [5], alternative methods of producing medical radioisotopes [6, 7], and many others.

Despite the development of modern methods for obtaining photon beams (for example: virtual excitation of photons by proton scattering and real absorption of photons by a gamma-ray beam created by laser Compton scattering [8]) for stimulating photonuclear reactions, the use of bremsstrahlung photons continues to play a key role for scientific and applied applications [9].

As a rule, tantalum (Ta) is used to generate bremsstrahlung photons in electron accelerators, due to its nuclear-physical and technical properties (high photon yield as a result of radiative braking of electrons, reduced photoneutron yield, high melting point, possibility of mechanical processing) [10-12].

Since the optimal thickness Ta of the converter (when the bremsstrahlung photon output is maximum [13,14]) is less than the mean free path of an electron in it, residual electrons will be present in the generated bremsstrahlung beams, which is confirmed by theoretical [15] and experimental studies [16, 17].

Fig. 1 shows the energy dependence of the yield of bremsstrahlung photons produced during radiative braking of monoenergetic electrons at Ta, and the maximum range (in the approximation of continuous deceleration), calculated by the NIST program “ESTAR” [18].

In the absence of a process for cleaning the bremsstrahlung photon beam from residual electrons using deflecting magnets or filters [19, 20], these residual electrons will also interact with the irradiated sample during experimental studies. When interacting with the samples under study, they will generate secondary particles (photons, photoneutrons) in them, and additionally stimulate electronuclear and photonuclear reactions and cause damage to the samples due to their heating (thermalization) [21]. These factors can significantly affect the final results of studies of the characteristics of photonuclear processes [21].

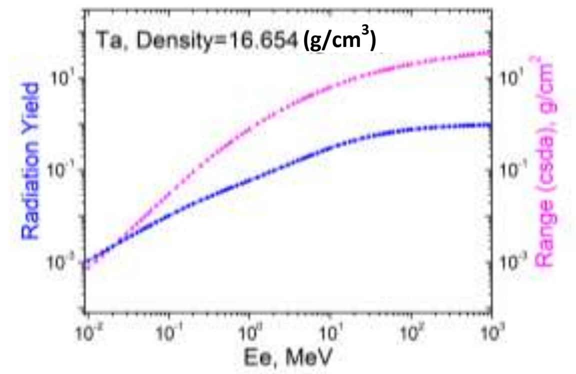


Fig. 1. Dependence of the yield of bremsstrahlung photons and the electron path on their energy

Therefore, when planning the process of stimulating photonuclear reactions in electron accelerators (using Ta radiators) and their optimization, reliable information is required about the characteristics (particle energy spectra, their integral values, and transverse distributions in the plane) of bremsstrahlung photons and residual electrons and their correlations [9, 21, 22]. Information about the energy spectra of bremsstrahlung photons, residual electrons and their integral values is necessary for predicting the yields of formed radionuclides during the activation of samples of the studied nuclei [23], as well as for analyzing the contribution of possible accompanying electronuclear reactions to the yields of photonuclear reactions [21], and developing possible schemes for cleaning bremsstrahlung photon beams from residual electrons [19, 20]. Information on the transverse distributions of particles (bremsstrahlung photons, residual electrons) along the plane of installation of samples during their activation is necessary to optimize their geometric dimensions to increase the yields of formed radionuclides [24, 25].

As a result of the analysis of existing experimental and theoretical studies, it was found that the final characteristics of the bremsstrahlung photon and residual electron beams, in addition to their initial energies, technical characteristics of Ta converters, and irradiation schemes (the mutual arrangement of the electron output unit, Ta converter, and the sample under study relative to the axis of the initial electron beam [21]), will also be significantly influenced by the characteristics of the initial electron beams at the accelerator output [26]. The characteristics of the electron beams at the accelerator output will depend on the technical characteristics of the electron output units (between vacuum and air [27, 28]). They may differ significantly even for accelerators of the same type [26, 29]. Therefore, these factors must be considered when preparing schemes for stimulating photonuclear reactions and optimizing the irradiation process of the samples under study.

Conducting experimental studies of the characteristics of bremsstrahlung photon and residual electron beams in the plane of the studied samples (those that stimulate photonuclear reactions) is associated with significant difficulties (expensive and long-term measurements), and in many cases is practically impossible [7, 12, 21]. Therefore, to determine the characteristics of bremsstrahlung photon and residual electron beams obtained at electron accelerators, taking into account their technical parameters, computer modeling is used using Monte Carlo codes (for example: MCNP6, FLUKA, GEANT4) [9, 12, 30]. These codes provide the opportunity to obtain the necessary information with a maximum approximation to the real conditions of formation of bremsstrahlung photons and residual electrons interacting with samples [12].

The paper presents the results of modeling the characteristics of bremsstrahlung beams (its components are bremsstrahlung photons and residual electrons) generated by Ta converters (of different thicknesses) at the electron accelerator of the Institute of Electron Physics of the National Academy of Sciences of Ukraine – the M-30 microtron for optimizing the process of stimulating photonuclear reactions.

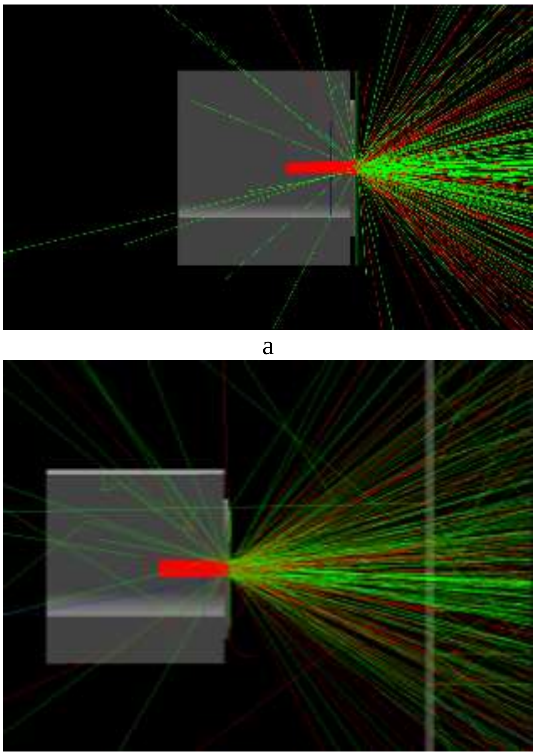
1. MATERIALS AND METHODS

To conduct computer simulation of the process of electron transport and generated bremsstrahlung photons in a titanium window (Ti, ellipse shape 22x6 mm, thickness – 50 μm) of the electron output unit into the air of the M-30 microtron [31,32] and the generated bremsstrahlung radiation in Ta converters, a program was developed based on the GEANT4 v11.1 toolkit [33]. Calculations were performed for the initial electron energy of 17.5 MeV.

During the simulations, all electrons and the photons generated by them that hit the plane perpendicular to the electron beam axis (100x100 mm) at the output of the accelerator electron output unit (the plane of Ta converter placement) and in the plane of irradiated samples placement – 1000x1000 mm at a distance of – 100 mm from the Ta converter were recorded.

The program was implemented under the Windows platform using multi-threading mode. Two computers with 6-core Intel (R) Core (TM) i7-9750H CPU@2.60GHz processors and 32 and 16 GB of RAM were used to perform the calculations [12].

Visualization of the simulation schemes of electron transport and photon generation in the planes of placement of the Ta converter (a) and irradiated samples (b) is presented in Fig. 2.



a

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Fig. 2. Visualization of the modeling scheme using the GEANT4 toolkit

The integral values (N) of generated photons and residual electrons were calculated according to formula (1) from the obtained particle energy spectra ($\phi(E)$):

$$N = \int_0^{E_{max}} \phi(E) dE. \quad (1)$$

The percentage of secondary photons in the electron beam was determined by the formula

$$C = \frac{N_\gamma}{N_e} \cdot 100\%, \quad (2)$$

where $N\gamma$ and N_e are the integral values of secondary photons and electrons calculated by formula (1), respectively.

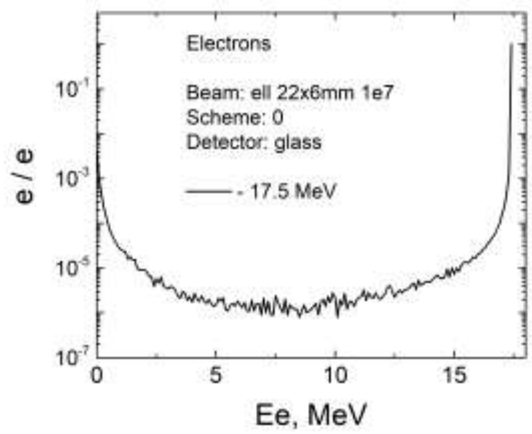
The calculated particle spectra and their integral values were normalized to one initial electron.

Based on the simulation results, probability maps of the transverse distribution of photons and residual electrons in the planes (placement of the Ta converter and irradiated samples) were created using the inverse Gaussian cumulative distribution (the ORIGIN package [34] was used to create the figures).

2. RESULTS AND DISCUSSION

2.1. CHARACTERISTICS OF THE ELECTRON BEAM AT THE ACCELERATOR OUTPUT

As a result of the simulations, the characteristics of the electron beam and secondary photons (generated in the Ti window of the electron output unit of the M-30 microtron) at the accelerator output, the Ta converter placement was calculated. Fig. 3 presents the energy spectra of electrons and secondary photons. Their numerical integral values are – 1.0071 e/e and 0.0010 γ/e. The percentage content of bremsstrahlung photons in the electron beam does not exceed 0.1012%.



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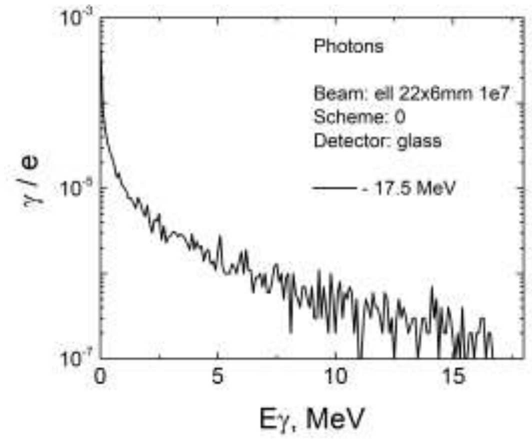

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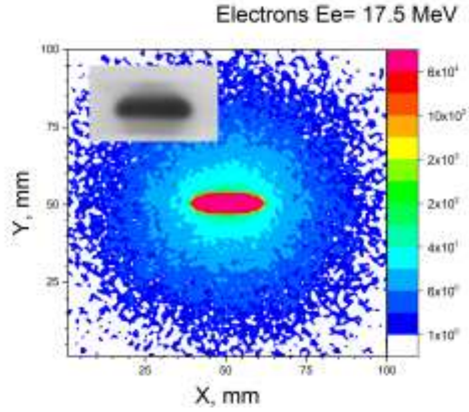
Fig. 3. Dependence of the energy spectra of a) electrons and b) bremsstrahlung photons at the output of the output unit, the plane of the Ta converter placement

From the simulation results, the profiles of electron beams and bremsstrahlung photons in a section on a plane measuring 100x100 mm at the installation location of the Ta converter (Fig. 4) and the transverse distribution (Fig. 5). The inset of Fig. 4,a presents a photograph of an electron beam taken using a window glass in the plane of placement of the Ta converter [31, 32], which is identical to the simulation result.



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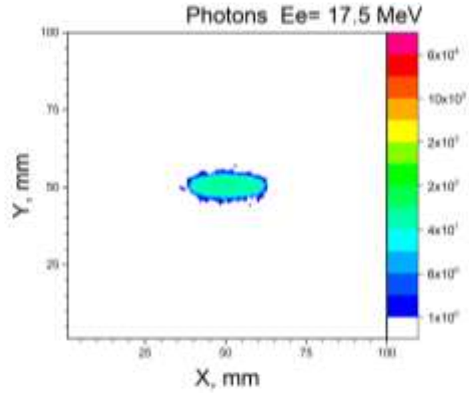

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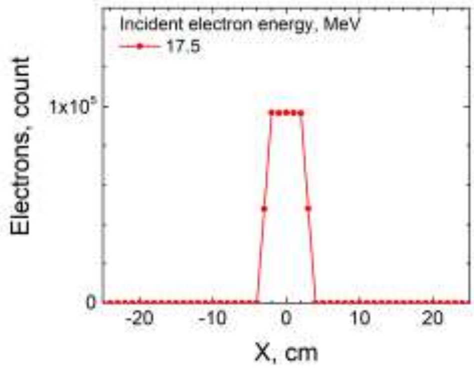
Fig. 4. Profiles of electrons and photons in the plane of placement of the Ta converter



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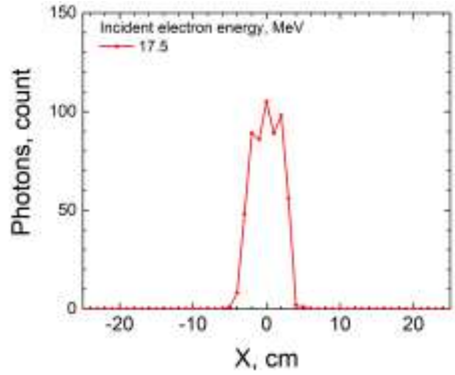

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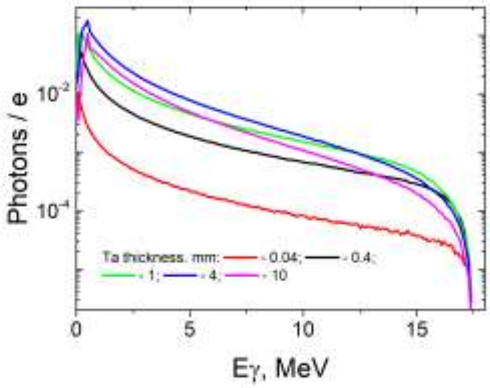
Fig. 5. Transverse distribution of electrons and bremsstrahlung photons in the plane of Ta converter placement

The calculations performed reflect the general patterns of the characteristics of electron beams at the output of accelerators, where Ti plates are used for the schemes of extracting electrons from vacuum into air [27, 28], and the possible difference is related to the initial energy of the electrons and their technical parameters (geometric dimensions).

2.2. INFLUENCE OF THE CONVERTER THICKNESS TA ON THE CHARACTERISTICS OF THE BREMSSTRAHLUNG PHOTON AND RESIDUAL ELECTRON BEAM

As a result of the simulations, the dependences of the energy spectra of the generated bremsstrahlung photons and residual electrons in the plane of sample placement on the thickness Ta of the converter were investigated, taking into account the characteristics of the initial electron beam (Fig. 6).



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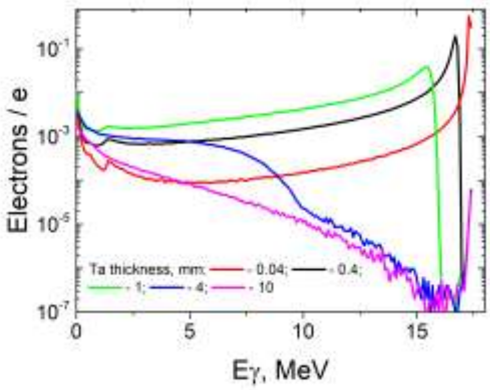

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Fig. 6. Dependence of the energy spectra of a) bremsstrahlung photons and b) residual electrons in the plane of sample placement on the thickness of the Ta converter

It was found that with increasing thickness of the Ta converter, the initial energy of electrons changes. Its nominal values are: 17.3 MeV (0.04 mm), 16.7 MeV (0.4 mm), 15.4 MeV (1.0 mm). Further, with increasing thickness from 4.0 to 10.0 mm, there is a continuous energy decline. The loss of energy by electrons during interaction with the Ta converter occurs due to inelastic collisions in the form of ionization or excitation of Ta atoms and generation of bremsstrahlung [30].

The obtained energy spectra were used to determine their integral values and the percentage of residual electrons in bremsstrahlung photon beams depending on the thickness Ta of the converters (Table 1).

Table 1

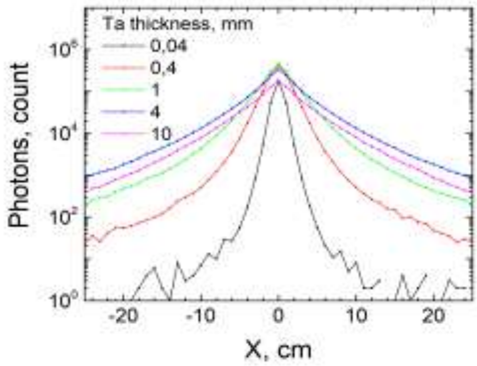
Dependence of the integral values of bremsstrahlung photons and residual electrons on the thickness Ta of the converter and the percentage of electrons in the bremsstrahlung photon beam

Thickness, mm	Nγ, γ/e	Ne, e/e	C, %
0.04	0.0704	1.0165	93.53
0.4	0.5560	1.0204	64.73
1.0	1.3132	0.9530	42.05
4.0	2.1747	0.0766	3.40
10.0	1.2286	0.0197	1.58

With increasing thickness Ta of the converter, the integral values of bremsstrahlung photons increase up to 4.0 mm, then there is a decrease. The integral values of residual electrons decrease (from 1.0165 to 0.0197 e/e) with increasing thickness from 0.01 to 10.0 mm. The percentage content of residual electrons decreases from 93.53 to 1.58 %.

The obtained results reproduce the general regularities of bremsstrahlung photon generation by Ta converters and are consistent with similar works of similar research [12-15]. Differences in the numerical results will be associated with the initial parameters of the calculations (parameters of the initial electron beam, sample irradiation schemes [21, 26]).

The simulation results obtained transverse distributions of residual electrons and photons generated by the Ta converter in the plane of sample placement at different thickness values (Fig. 7).



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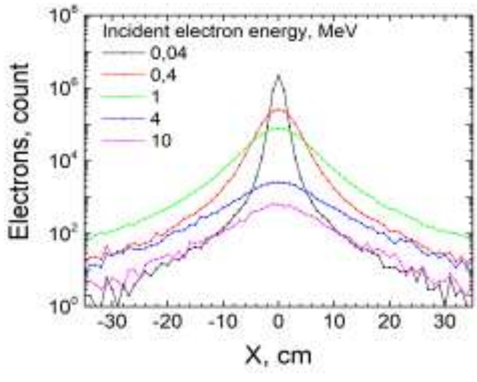

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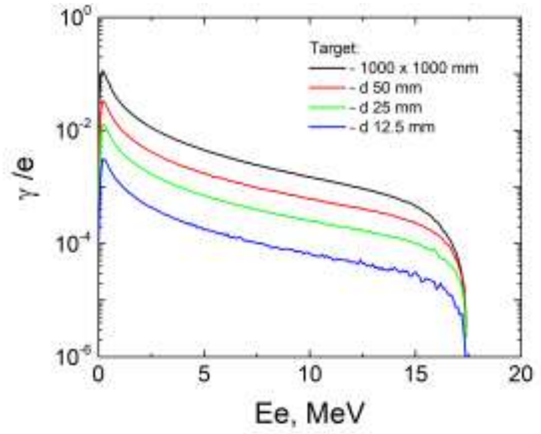
Fig. 7. Dependence of transverse distributions in the plane of placement of samples of a)bremsstrahlung photons and b) residual electrons, and on the thickness Ta of the converter

Fig. 7,a and tabular values (see Table 1) show that with increasing converter thickness Ta, the largest value of the integral number of bremsstrahlung photons is achieved at a thickness of 4 mm, after which they decrease, with the angular distribution along the plane constantly increasing, which leads to the escape of a certain number of photons beyond the boundaries of the irradiated plane. The peak values of photons in the plane's center and their distribution remain practically the same for thicknesses of 0.4…4 mm, which confirms previous studies on the optimality of the thickness of 1 mm [5, 7, 12].

From Fig. 7,b it can be seen that increasing the thickness of the Ta converter leads to a decrease in the number of electrons and an increase in the angular distribution of electrons in the plane.

To verify the calculated transverse distributions of photons and residual electrons in the plane of sample placement, their characteristics' dependence on the plane's geometric dimensions was investigated.

Fig. 8 shows the dependences of the energy spectra of bremsstrahlung photons and residual electrons in the plane of sample placement on their geometric dimensions at a fixed converter thickness Ta of 1.0 mm. Their integral characteristics and the percentage of residual electrons in bremsstrahlung photon beams are presented in Table 2.



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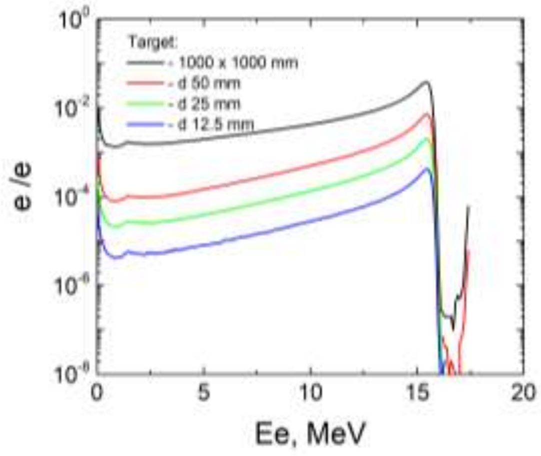

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Fig. 8. Dependence of the energy spectra of a) bremsstrahlung photons and b) residual electrons on the sample dimensions at a converter thickness Ta of 1 mm

Table 2

Dependence of the integral values of bremsstrahlung photons and residual electrons on the dimensions of the particle detection plane and the percentage of electrons in the bremsstrahlung photon beam

Dimensions	**Nγ, γ/e**	**Ne, e/e**	**C, %**
diameter 12.5 mm	0.0450	0.0078	14.72
diameter 25 mm	0.1771	0.0376	17.52
diameter 50 mm	0.4458	0.1364	23.42
1000x1000 mm	1.3048	0.9530	42.21

The integral values of photons and residual electrons and the percentage of residual electrons in bremsstrahlung photon beams increase with increasing plane dimensions, which is consistent with the results of modeling transverse distributions on the plane.

CONCLUSIONS

Computer simulations of the characteristics of bremsstrahlung photon and residual electron beams generated on the M-30 microtron, taking into account its technical parameters of the output unit, allowed optimizing the process of stimulating photonuclear processes for a wide range of actinide nuclei and predicting the yields of the formed radioactive isotopes.

As a result of the research conducted:

the initial characteristics of the electron beam and secondary photons (generated by Ti window) are established at the output of the electron output unit, the plane of placement of the Ta converter;

the influence of the converter thickness Ta on the characteristics of the beams of generated bremsstrahlung photons and residual electrons in the plane of potential sample placement for stimulating photonuclear reactions on the M-30 microtron was investigated;

the modeled energy spectra of bremsstrahlung photons and their integral values are input parameters for a computer program for assessing the efficiency of using a beam of bremsstrahlung photons to stimulate photonuclear reactions, taking into account the nuclear-physical characteristics of the samples under study and the parameters of their irradiation schemes [35];

the calculated energy spectra of residual electrons, their integral characteristics, and percentage content in the bremsstrahlung beam are necessary for analyzing the contribution of accompanying nuclear reactions to the photonuclear outputs and developing possible schemes for cleaning bremsstrahlung photon beams from residual electrons;

modeled transverse particle distributions (bremsstrahlung photons, residual electrons) along the sample mounting plane during their activation is necessary to optimize their geometric dimensions.

This work was carried out within the framework of the topic "Study of the influence of closed nuclear shells on the processes of excitation/conversion of photonuclear reaction products in the M-30 microtron," state registration number: 0124U000962.

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МОДЕЛЮВАННЯ ХАРАКТЕРИСТИК ФОТОНІВ ТА ЗАЛИШКОВИХ ЕЛЕКТРОНІВ У ПУЧКАХ ГАЛЬМІВНОГО ВИПРОМІНЮВАННЯ, ЗГЕНЕРОВАНИХ ТАНТАЛОВИМ КОНВЕРТЕРОМ НА МІКРОТРОНІ М-30

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Представлено результати моделювань характеристик (енергетичні спектри, їх інтегральні характеристики, поперечні розподіли у площині) пучка електронів і вторинних фотонів на виході електронного прискорювача – у площині розміщення танталового конвертера та характеристик фотонів і залишкових електронів у пучках гальмівного випромінювання, згенерованого танталовими конвертерами (товщина – 0,04; 0,4; 1,0; 4,0; 10,0 мм) у площині розміщення опромінюваних зразків. Розрахунки проводилися для електронного прискорювача ІЕФ НАН України – мікротрона М-30, з врахуванням його технічних характеристик при фіксованій початковій енергії електронів 17,5 МеВ. Для моделювань використовувався інструментарій GEANT4. Отримана інформація використовувалася для оптимізації процесу стимуляції фотоядерних реакцій на ядрах актинідах та прогнозування отриманих результатів.