https://doi.org/10.46813/2024-153-148

PHOTON AND PHOTONEUTRON OUTPUTS SIMULATION FROM A TANTALUM CONVERTER AT THE M-30 MICROTRON

E.V. Oleinikov, I.V. Pylypchynets, O.O. Parlag*, V.V. Pyskach
Institute of Electron Physics NAS of Ukraine, Uzhhorod, Ukraine
****E-mail: parlag.oleg@gmail.com***

Reliable information about the outputs of bremsstrahlung photons and secondary photoneutrons from converters on electron accelerators with mandatory consideration of their technical characteristics is necessary for optimizing the process of sample irradiation and predicting the results of experimental studies. The results of modeling the dependence of photon and photoneutron yields and their ratios on the thickness of the tantalum converter (thickness – 0.04; 0.4; 1.0; 4.0; 10.0 mm) are presented at fixed energies of the initial electron beam – 10.0, 12.5, 14.5, 17.5, and 20 MeV. Calculations were carried out for the electron accelerator of the National Academy of Sciences of Ukraine, the M-30 microtron, taking into account its technical characteristics (electron discharge node). The GEANT4 toolkit was used for computer simulation.

PACS: 29.17.+w, 29.27._a

INTRODUCTION

Bremsstrahlung radiation generated at electron accelerators is widely used to study the characteristics of photonuclear reactions [1, 2] and solve a wide range of applied problems. These tasks are related to the development of energy-generating systems of a new generation - reactors with accelerators [3], non-destructive methods of isotopic identification of nuclear materials [4], alternative methods of production of medical radioisotopes [5], and many others.

To generate bremsstrahlung photons on electron accelerators, converters are used – materials that have a high atomic number (the cross-section of bremsstrahlung photons generation by (e,γ)-reaction channel is proportional to the square of the charge of the target), a high melting point and, preferably, high thermal conductivity [2, 6]. These conditions are well satisfied by tantalum (Ta), which is usually used as a bremsstrahlung converter [7–9].

Photoneutrons are generated simultaneously with bremsstrahlung beams formed during the interaction of electrons with converters [2, 10].

Neutrons, which are formed as a result of accelerated electron beams passing through the converter, are generated as a result of two types of reactions: photonuclear reactions caused by bremsstrahlung radiation [11] and electronuclear reactions under the action of virtual photons emitted by electrons [12]. The cross sections of electronuclear reactions are approximately two orders of magnitude smaller than those of photonuclear reactions [13]. Their accounting is necessary only when the converter's thickness is very small, and the bremsstrahlung output is small.

For all nuclei heavier than oxygen, the thresholds of photonuclear reactions are in the range of photon energies from 6 to 18 MeV [14, 15]. Basically, neutrons are produced in reactions (γ,n) and (γ,2n) [16, 17]. Reactions (γ,pn) and (γ,αn) are other possible channels. However, their cross sections are small for all nuclei except Li, B, and N [15]. For nuclei heavier than bismuth, the formation of neutrons due to induced photofission is also possible.

In the energy range of the giant dipole resonance during the interaction of photons with heavy nuclei, two groups of photoneutrons can be distinguished: vaporized neutrons formed during the interaction of photons with the nucleus as a whole and neutrons formed as a result of the direct mechanism of photon energy transfer to one of the nucleons of the nucleus. Neutrons of the first group have a Maxwellian energy distribution, an isotropic angular distribution, and make up the majority of all photoneutrons. Neutrons of the second group have an anisotropic angular distribution, high energies, and make up approximately 15% [18, 19] of all photoneutrons.

Therefore, when planning the process of irradiation of the studied samples on electron accelerators, both for studying the characteristics of photonuclear reactions [20] and applied applications (for example, creating high-intensity neutron sources [21, 22], optimizing the processes of isotope analysis of nuclear materials [23], radiation treatment of materials to improve their physical and technical properties, etc. [24]) requires reliable information about the yields of bremsstrahlung photons, secondary photoneutrons and their ratios [25, 26].

Through theoretical and experimental studies, it was established that photon and photoneutron yields primarily depend on electron energy, the nuclear-physical properties of converters, and their geometric dimensions [2, 4, 27–30].

It should be noted that the quantitative (integral) content of photons and secondary photoneutrons and their ratio in the bremsstrahlung beams that interact with the samples under study are significantly influenced by geometric factors (the relative location of the converter, the sample under study relative to the axis of the initial electron beam [2, 4]), and the presence of additional structural elements (filters, screens, collimators), which are used in their formation [2, 4, 20].

Also, the final parameters of the bremsstrahlung beams will be influenced by the design features of the devices (assemblies) for outputting the electron beams into the air, which differ significantly for different types of electron accelerators [31]. Therefore, these factors must be considered when developing actinide sample activation schemes.

Conducting experimental studies of the characteristics of bremsstrahlung spectra, secondary photoneutrons, and their integral values [32, 33] is associated with significant difficulties (expensive and long-term measurements) and is, in many cases, practically impossible.

To obtain information about the characteristics of bremsstrahlung beams and secondary photoneutrons interacting with the samples under study, generated on electron accelerators taking into account their design features and irradiation schemes, computer modeling using Monte Carlo software codes is widely used [2, 28–30, 33] as they make it possible to obtain results as close as possible to the actual conditions of their formation.

The paper presents the results of computer modeling of the outputs of bremsstrahlung photons, secondary photoneutrons, and their ratios from the Ta-converter on the M-30 microtron electron accelerator of the National NAS of Ukraine, taking into account the technical characteristics of its output unit.

1. MATERIALS AND METHODS

To carry out computer modeling of the energy spectra of photons and photoneutrons generated by the bremsstrahlung target, a C++ program was developed using the GEANT4 v11.1 toolkit [34]. The materials of the experimental setup and the position of the structural elements were defined in our program's DetectorConstruction class. The initial parameters of the electron beam were defined in the PrimaryGeneratorAction class. The list of physical processes FTFP_BERT_HP, which uses the standard GEANT4 physical model of electromagnetic interaction, was used in the simulation. GEANT4 visualization methods based on the Win32 API were used to validate the irradiation scheme.

The program was implemented for the Windows platform using the multi-threading mode. The calculations used two computers with 6-core Intel(R)Core(TM) i7-9750H CPU@2.60GHz processors and 32 and 16 GB of RAM. The calculations were performed for the initial number of electrons – 10E8.

Calculations were performed for initial electron energies from 10 to 20 MeV. The output beam had the shape of an ellipse with axes of 22 and 6 mm. In all calculations, an equal probability distribution of the initial electrons on the plane was specified (taking into account the design features of the electron output node – a titanium window with a thickness of 0.05 mm). The distance from the output node to the Ta-converter (dimensions: 52×45×T mm [T = 0.04; 0.4; 1.0; 4.0; 10.0 mm]) was 12 mm. The size of the Ta-converter was determined by the design features of the electron accelerator output node and ease of use. The geometric dimensions of the converter did not affect the integral values of the bremsstrahlung photons and secondary photoneutrons, provided that the area of the Ta-converter was larger than the geometric dimensions of the initial electron beam [2]. The distance from the Ta-converter to the sample installation plane was 100 mm. At the specified distance, it was established that the ratio of bremsstrahlung photons and residual electrons is optimal [2, 4].

During the simulations, all particles (bremsstrahlung photons and photoneutrons) generated by the bremsstrahlung target and hitting the plane of potential installation of the studied samples (1000x1000 mm) and on real samples (diameter – 11.2 and 50 mm) were recorded.

Figs. 1 and 2 present the modeling scheme and its visualization by the GEANT4 toolkit, respectively.

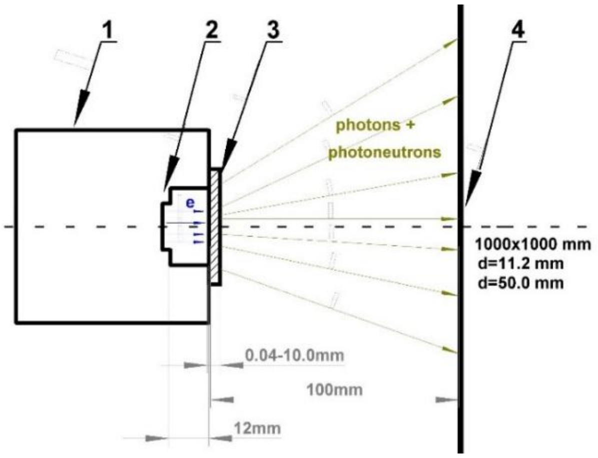
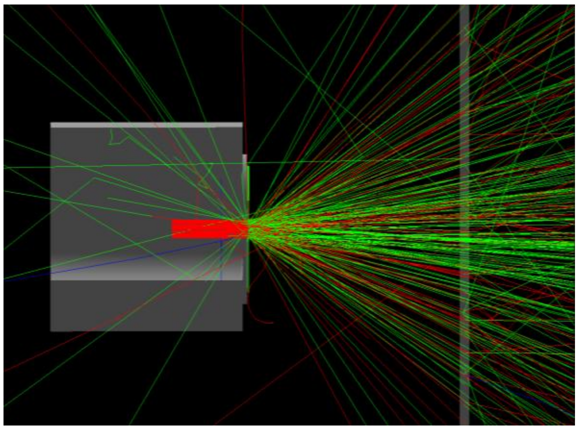
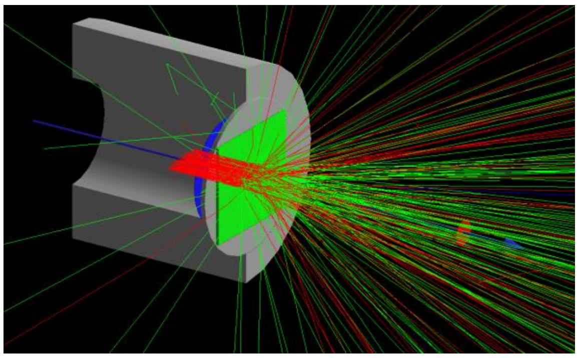


Fig. 1. Modeling scheme:
1 – block of the output of electrons into the air;
2 – the window of the output node; 3 – Ta-converter;
4 – the plane at the place of the installation of the tested sample



a



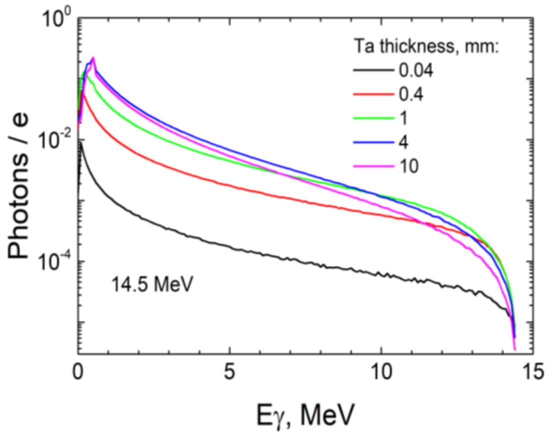
b

Fig. 2. Visualization of the modeling scheme with the GEANT4 toolkit: a – with a plane (1x1 m) at the location of the samples and b – with a real sample (diameter = 11 mm)

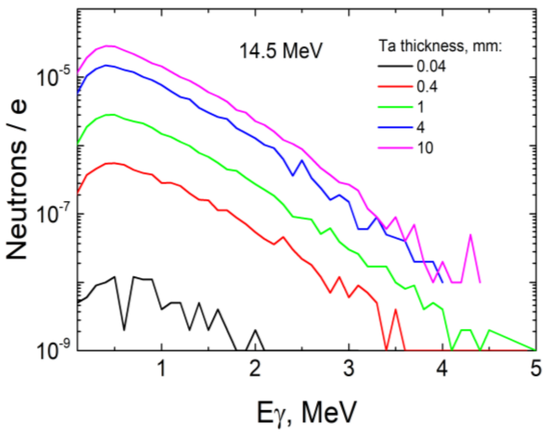
2. RESULTS AND DISCUSSION

As a result of computer studies, the dependences of energy spectra of bremsstrahlung photons and secondary photoneutrons were established from the thickness of the Ta-converter (0.04; 0.4; 1.0; 4.0; 10.0 mm), which hit the plane of potential sample installation (1000x1000 mm). Calculations were carried out at fixed values of initial electron energies – 10.0, 12.5, 14.5, 17.5, 20.0 MeV.

The obtained spectra were used to determine their integral characteristics and the ratios between them. The energy spectra of photons, photoneutrons, and their integral values were normalized to one electron.



a



b

Fig. 3. Dependence of the energy spectra of: a – bremsstrahlung photons and b – photoneutrons on the thickness of the Ta-converter at an electron energy of 14.5 MeV

The results of calculations of the dependence of the energy spectra of photons and photoneutrons on the thickness of the Ta-converter at a fixed value of the electron energy – 14.5 MeV are presented in Fig. 3.

Figs. 4 and 5 present the dependences of the integral values of the outputs of bremsstrahlung photons and secondary photoneutrons on the thickness of the Ta-converter that fell into the plane of installation of the studied sample at fixed values of the initial electron energy, respectively.

The integral values of the outputs of all photons and photons with energies >6 MeV, which stimulate photonuclear reactions, were calculated (see Fig. 4).

Numerical values of integral outputs of all photons and photons with energies >6 MeV are presented in Tables 1 and 2, respectively. Table 3 presents the numerical values of integral photoneutron yields.

The obtained results reproduce the general regularities of the formation of bremsstrahlung photons and secondary photoneutrons during the interaction of electrons with converters. The dependence of their outputs on the thickness of the Ta-converter and the initial energy of electrons is consistent with the results of similar studies [2, 4, 27–30, 33]. The differences in the numerical values are related to the initial conditions of the calculations (parameters of the initial electron beam, geometric factors: the position of the converter relative to the electron output node, and the particle detection plane [2, 4]).

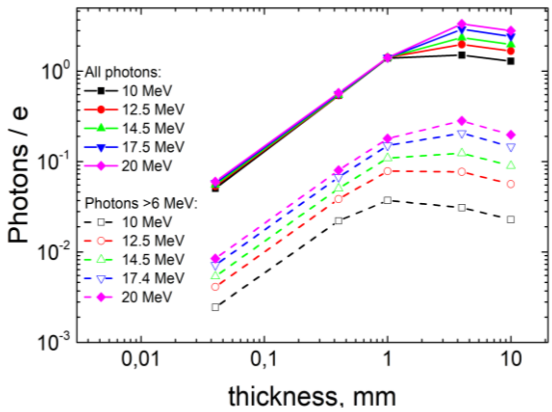


Fig. 4. Dependence of the total integral yield of photons with energy >6 MeV on the thickness of the Ta-converter at fixed electron energies

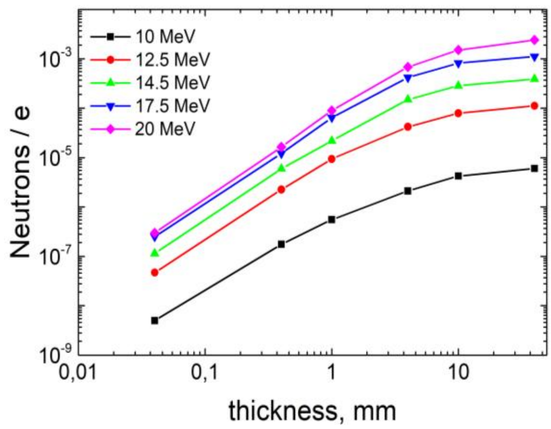


Fig. 5. Dependence of the integrated yield of photoneutrons on the thickness of the Ta-converter at fixed electron energies

For a thick converter, the angular distribution becomes wider due to multiple scattering effects [27]. To improve the signal-to-noise ratio, the target thickness must be optimized to capture more photons with energy above the threshold energy (~6 MeV for photonuclear reactions) while minimizing the number of photons with energy below the threshold.

Table 1

Integral values of photon outputs (of the entire spectrum) depending on the thickness of the Ta-converter at fixed energies

Ta, mm	10 MeV	12.5 MeV	14.5 MeV	17.5 MeV	20 MeV
0.04	0.0505	0.0535	0.0555	0.0582	0.0600
0.4	0.5373	0.5401	0.5468	0.5620	0.5745
1	1.3944	1.4232	1.4161	1.4096	1.4103
4	1.5056	1.9751	2.3554	2.9106	3.3336
10	1.2912	1.6741	1.9779	2.4301	2.8008

Table 2

Integral values of photon outputs (with energies > 6 MeV) depending on the thickness of the Ta-converter at fixed energies

Ta, mm	10 MeV	12.5 MeV	14.5 MeV	17.5 MeV	20 MeV
0.04	0.0024	0.0041	0.0054	0.0072	0.0085
0.4	0.0221	0.0385	0.0505	0.0673	0.0802
1	0.0371	0.0782	0.1094	0.1503	0.1799
4	0.0309	0.0771	0.1241	0.2062	0.2821
10	0.0228	0.0563	0.0899	0.1467	0.1985

Table 3

Integral values of the yields of photoneutrons that hit the plane at the place of sample installation, depending on the thickness of the Ta-converter at fixed energies

Ta, mm	10 MeV	12.5 MeV	14.5 MeV	17.5 MeV	20 MeV
0.04	5.00E-9	4.70E-8	1.14E-7	2.51E-7	2.99E-7
0.4	1.76E-7	2.26E-6	5.98E-6	1.21E-5	1.64E-5
1	5.53E-7	9.33E-6	2.18E-5	6.48E-5	8.96E-5
4	2.11E-6	4.18E-5	1.49E-4	4.18E-4	6.83E-4
10	4.24E-6	7.94E-5	2.85E-4	8.16E-4	1.51E-3

The result in Fig. 4 shows that the total number of photons with E > 6 MeV remains almost constant for the thickness of the Ta-converter – 1 mm, which is consistent with the results of existing simulations [2, 4, 27].

As a result of the calculations, the ratio between the integral outputs of photoneutrons to photons (all and those with energies > 6 MeV) was established depending on the thickness of the Ta-converter at fixed initial electron energies (Fig. 6) and on the energy of initial electrons at fixed values of the Ta-converter (Fig. 7).

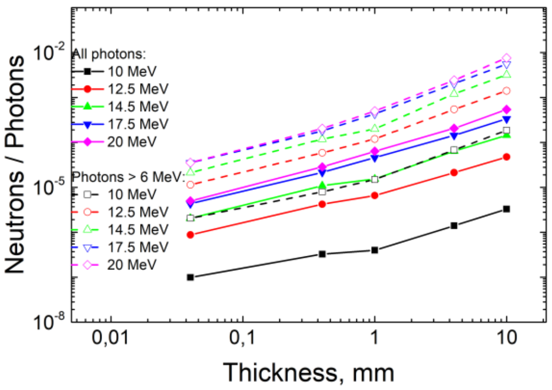


Fig. 6. Dependence of the ratio of the integral outputs of photoneutrons to the integral outputs of all photons and with energy > 6 MeV on the thickness of the Ta-converter at fixed electron energies

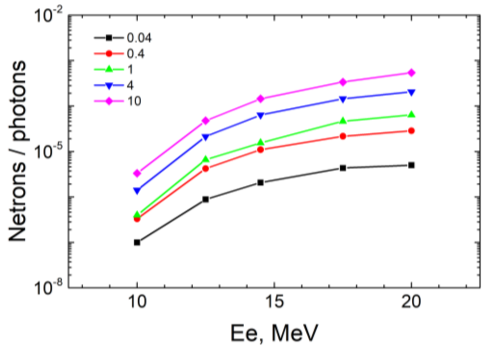
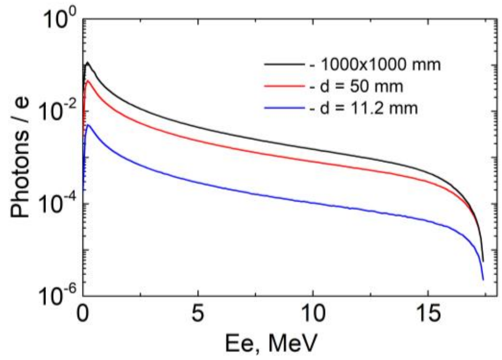


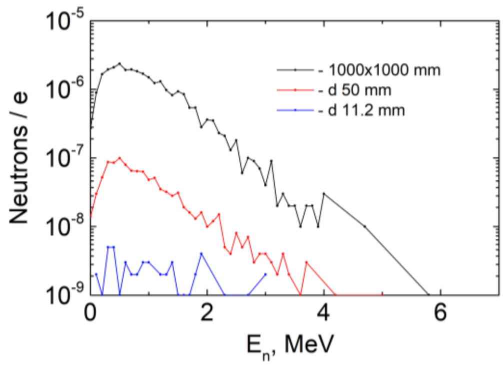
Fig. 7. Dependence of the ratios of integral outputs of photoneutrons to integral outputs of photons on electron energy at fixed thicknesses of the Ta-converter

The obtained results reproduce the general regularities of the ratio of photoneutrons to bremsstrahlung photons during the interaction of electrons with the Ta-converter. The dependence of their outputs on the initial electron energy is consistent with the results of similar studies [25, 25].

In addition, simulations of the energy spectra of photons and photoneutrons interacting with the studied samples of fixed dimensions (diameter – 11 and 50 mm) were carried out at the initial energy of electrons - 17.5 MeV (Fig. 8).



a



b

Fig. 8. Spectra of: a – bremsstrahlung photons and b – photoneutrons at a fixed electron energy of 17.5 MeV

The calculated integral values of photon yields (all, >6 MeV) and photoneutrons falling into the plane at the location of the test samples (1000x1000 mm) and on samples with diameters of 11.2 and 50 mm are presented in Table 4.

Table 4

Integral values of the outputs of photons (all, > 6 MeV) and photoneutrons hitting the plane in place of installation of the studied samples (1000x1000 mm) and the samples (diameter – 11.2 and 50 mm)

Size	Photons all	Photons > 6 MeV	Photoneutrons
d 11 mm	0.0710	0.0103	4.70E-8
d 50 mm	0.5947	0.0797	1.02E-6
1 x 1 m	1.3134	0.1469	2.76E-5

The performed calculations can be used as input data for modeling the optimization parameters of the irradiation schemes of the studied samples on the M-30 microtron, taking into account the technical features of its electron output node and sample characteristics.

CONCLUSIONS

The research conducted using the GEANT 4 toolkit calculated the energy spectra of photons and photoneutrons falling into the plane of potential sample placement (1000x1000 mm) for irradiation on the M-30 microtron.

The values of the integral number of all photons and photons with energy > 6 MeV (which participate in the stimulation of photonuclear reactions), secondary photoneutrons, and their ratios, normalized to one electron, formed during the interaction of a real electron beam (energy – 10…20 MeV) with Ta-converter (thickness – 0.04…10 mm) were established.

In addition, calculations were made of the integral number of photons (and those with energy > 6 MeV), secondary photoneutrons falling on samples with fixed dimensions (diameter – 11.2 and 50 mm) at the initial electron energy – 17.5 MeV.

Information about the ratio of photons and photoneutrons allows for optimizing the activation process of samples, taking into account their nuclear-physical characteristics, and predicting the results of experimental studies at the electron accelerator of the IEF of the National Academy of Sciences of Ukraine – microtrons M-30.

REFERENCES

1. A.R. Balabekyan, S. Gaginyan, A. Aleksanyan, et al. Investigation of photonuclear reactions on isotopes ^{51}V, natCu, natMo, ^{115}In and ^{207}Pb at photon energy $E_{\gamma max}$ = 20–70 MeV // *Radiation Physics and Chemistry*. 2023, v. 204, p. 110651.
2. E. Oleinikov, I. Pylypchynets, O. Parlag Simulation of the optimal scheme for stimulating actinide photofission on the M-30 Microtron at 17.5 Mev bremsstrahlung energy // *Journal of Nuclear and Particle Physics.* 2023, v. 13, p. 7-16.
3. B. Liu, X. Zhang, F. Liu, et al. The electron accelerator driven sub-critical system // *Nuclear Engineering and Design.* 2022, v. 386, p. 111567.
4. I.V. Pylypchynets, O.O. Parlag, V.T. Maslyuk, et al. Isotopic identification of photofissed nuclear materials in stainless steel containers using delayed gamma-rays // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations".* 2022, №5(141), p. 103-109.
5. V.L. Uvarov, A.A. Zakharchenko, N.P. Dikiy, et al. Development and validation of an analytical model of isotope production by bremsstrahlung radiation // *Applied Radiation and Isotopes*. 2023, v. 199, p. 110890.
6. 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.
7. Atomic and Nuclear Properties of Materials for more than 350 materials. Last revised 30 October 2021. Available from: https://pdg.lbl.gov/2022/AtomicNuclearProperties/index.html
8. A. Šagátová, M. Fülöp, M. Pavlovič, et al. Electron-beam accelerator with conversion to X-rays: Optimal radiation type according to application // *Radiation Physics and Chemistry.* 2020, v. 172, p. 108789.
9. V.C. Petwal, S.C. Bapna, R.S. Sandha, et al. Bremsstrahlung converter for high power eb radiation processing facility // *Proceedings of 4th Asian Particle Accelerator Conference* (APAC 2007), 29 Jan – 2 Feb 2007, Indore, India. p. 667-669; https://accelconf.web.cern.ch/a07/PAPERS/THPMA088.PDF
10. C. Stieghorst, L. Szentmiklósi, B. Maróti, et al. Chapter 8 – Neutrons-characteristics and sources // *Non-Destructive Material Characterization Methods.* Publisher: Elsevier, 2023, p.189-204.
11. J.D.T. Arruda-Neto, M. Filadelfo. Feasibility study for the implementation of an intense linac-based neutron source facility in Sao Paulo // *Applied Radiation and Isotopes.* 1999, v. 50, p. 491-496.
12. M.I. Cataldi, E. Wolynec, M.N. Martins, et al. Electrodisintegration of 208Pb, 209Bi and 181Ta // *J. Phys. G: Nucl. Phys.* 1988, v. 14, p. 779-786.
13. M.N. Martins, E. Hayward, G. Lamaze, X.K. Maruyama, F.J. Schima, E. Wolynec Experimental test of the bremsstrahlung cross section // *Phys. Rev. C*. 1984, v. 30, p. 1855-1860 (The electron cross sections are roughly 100 times less than the corresponding photon cross sections).
14. T.T.H. Nguyen, T. Sanami, H. Yamazaki, et al. Photon energy dependence of photoneutron production from heavy targets // *EPJ Web of Conferences*. 2024, v. 292, p. 07004.
15. Evaluated Nuclear Data File (ENDF). Software Version of 2023-10-31; https://www-nds.iaea.org/exfor/endf.htm
16. O.S. Deiev, I.S. Timchenko, S.N. Olejnik, et al. Cross sections of photoneutron reactions on 181Ta at *Eγ*max up to 95 MeV // *Phys. Rev. C.* 2022, v. 106, p. 024617.
17. R.M. Wilenzick, P.R. Almond, G.D. Oliver, C.E. de Almeida. Measurement of fast neutron produced by high energy X-ay beams of medical electron accelerators // *Phys. Med. Biol.* 1973, v. 18, p. 396-408.
18. E.J. Axton, A.G. Bardell. Neutron production from electron accelerators used for medical purpose // *Phys. Med. Biol*. 1972, v. 17, p. 293-298.
19. R. Tursinah, S. Permana, Z. Su'ud, et al. Measurement and simulation of photoneutron spectra of 10 MW medical linac using single moderator-based

neutron spectrometer // *SSRN.* 2023, 24 p. Available at SSRN: https://ssrn.com/abstract=4591089

20. E. Oleinikov, O. Parlag, I. Pylypchynets. Simulation of the concomitant nuclear reaction's contribution to the actinide photofission on the M-30 microtron at 17.5 MeV Bremsstrahlung Energy *// Journal of Nuclear and Particle Physics*. 2023, v. 13, p. 17-23.

21. A.K. Gillespie, C. Lin, R.V. Duncan. Photoneutron yield for an electron beam on tantalum and erbium deuteride // *Nuclear Engineering and Technology*. Available online 8 April 2024.

22. V.G. Rudychev, M.O. Azarenkov, I.O. Girka, et al. Optimization of converter and bremsstrahlung characteristics for object irradiation // *Radiation Physics and Chemistry*. 2023, v. 206, p. 110815.

23. C. Besnard-Vauterin, B. Rapp, V. Blideanu. Neutron detection in mixed short-pulsed fields with intense photon flashes for LINAC-based active interrogation applications // *Nuclear Instruments and Methods in Physics Research A.* 2024, v. 1064, p. 169403.

24. A.G. Chmielew. Radiation technologies: The future is today // *Radiation Physics and Chemistry.* 2023, v. 213, p. 111233

25. T.V. Malykhina, A.O. Torgovkin, O.V. Torhovkin, et al. The research of mixed X,n-radiation field at photonuclear isotopes production // *Probl. Atom Sci. Tech*. 2008, N 5 (50), p. 184-188.

26. T. Malykhina, O. Torhovkin. Computer simulation and experimental investigation of Mo-99 yield in thick targets as a Tc-99m generator // *Nuclear Instruments and Methods in Physics Research B.* 2017, v. 406, p. 334-337.

27. H. Lee, S.H. Park, Y.U. Jeong, et al. A simulation for the optimization of bremsstrahlung radiation for nuclear applications using laser accelerated electron beam. // *Proceedings of FEL2010* (32nd International Free Electron Laser Conference. August 23 – 27, 2010, Malmoe, Sweden), p. 618-621; https://accelconf.web.cern.ch/FEL2010/papers/thpb13.pdf

28. M. Ghergherehchi, J. Ko, N. Arabyarmohammadi, et al. Optimisation of a hybrid photoneutron source in a linear accelerator using GEANT4 and MCNPX Monte Carlo codes // *Pramana – J. Phys*. 2018, v. 91, p. 35.

29. A. Didi, A. Dadouch, H. El Bekkouri, et al. Monte Carlo transport code use for optimization of neutron flux produced with 10-18 MeV electron beam energy // *IJNEST*. 2018, v. 12, p. 313-323.

30. D.-H. Han, K.-H. Jung, J.-O. Kim, et al. Evaluation by thickness of a linear accelerator target at 6-20 MeV electron beam in MCNP6 // *Nuclear Engineering and Technology*. 2023, v. 55, p. 1994-1998.

31. S. Yania, I. Budiansah, F.M. Rhanic, F. Haryanto. Monte Carlo model and output factors of Elekta infinityTM 6 and 10 MV photon beam // *Reports of Practical Oncology and Radiotherapy.* 2020, v. 25, p. 470-478.

32. I. Haysak, V. Martishichkin, Y. Harapko, et al. Production and Monitoring of Neutron Flux by Activation Detectors // *EPJ Web of Conferences*. 2021, v. 253, p. 01005.

33. G.S. Sahoo, S.P. Tripathy, M.S. Kulkarni. Simulation study on radiation fields around targets to apply CR-39 for photo-neutron measurement in electron accelerator near the threshold energy // *Applied Radiation and Isotopes.* 2022, v. 181, p. 110080.

34. GEANT4 11.1 (9 December 2022); https://geant4. web.cern.ch/support/download

Article received 25.09.2024

МОДЕЛЮВАННЯ ВИХОДІВ ФОТОНІВ ТА ФОТОНЕЙТРОНІВ З ТАНТАЛОВОГО КОНВЕРТЕРА НА МІКРОТРОНІ М-30

Є.В. Олейніков, І.В. Пилипчинець, О.О. Парлаг, В.В. Пискач

Достовірна інформація про виходи гальмівних фотонів, вторинних фотонейтронів з конвертерів на електронних прискорювачах із обов'язковим врахуванням їх технічних характеристик необхідна для оптимізації процесу опромінення зразків та прогнозування результатів експериментальних досліджень. Представлено результати моделювання залежності виходів фотонів, фотонейтронів та їх співвідношень від товщини танталового конвертера (товщина – 0,04; 0,4; 1,0; 4,0; 10,0 мм) при фіксованих енергіях початкового пучка електронів – 10,0; 12,5; 14,5; 17,5 та 20 МеВ. Розрахунки проводилися для електронного прискорювача ІЕФ НАН України – мікротрона М-30 з врахуванням його технічних характеристик (вузла виводу електронів у повітря). Для комп'ютерного моделювання використовувався інструментарій GEANT4.