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ACTIVATION METHOD FOR MEASUREMENT OF BREMSSTRAHLUNG PHOTON FLUX PRODUCED BY ELECTRON ACCELERATOR

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On the basis of the photon activation method in combination with simulation model calculation, we have determined bremsstrahlung photon flux produced by the electron accelerator Microtron MT-25 of JINR's Flerov Laboratory of Nuclear Reactions.

Определен поток тормозного излучения фотонов на электронном ускорителе МТ-25 Лаборатории ядерных реакций ОИЯИ с использованием активационного метода и расчетного метода моделирования.

INTRODUCTION

In general, for every kind of accelerators, including electron accelerators, the determination of their particle flux is of significant importance. From the particle flux one can estimate or determine characteristic of a nuclear reaction and different parameters, for example, the sensitivity of photon and photoneutron activation methods and the yields of emitted particles such as neutron, beta, alpha, heavy ions, ... for fundamental and applied investigations and radiation protection [1–5]. In the case of electron accelerators, for determination of their bremsstrahlung photon flux, ionzation cameras or dosimeters are usually used. In practice, the unit for bremsstrahlung photon flux measurement is 10^{-2} Gy $\cdot$ m^{-2} $\cdot$ min^{-1} or rad $\cdot$ m^{-2} $\cdot$ min^{-1} [6]. However, in photonuclear reaction investigations and photon activation analysis it is more proper to use unit photon $\cdot$ cm^{-2} $\cdot$ s^{-1}, i.e. numbers of photons passing 1 cm^2 per 1 second, and this unit will be used in our work.

In this paper, on the basis of photoactivation technique in combination with simulation model calculation, we have determined the bremsstrahlung photon flux at 20 and 24 MeV of the electron accelerator MT-25 of JINR's Flerov Laboratory of Nuclear Reactions (FLNR), Dubna. The microtron MT-25 produces bremsstrahlung with maximum energies which can be varied stepwise from 10 to 25 MeV.

1. THE BASIS OF EXPERIMENTAL METHOD

In the nuclear activation process, the number of radioactive nuclei formed during time t can be described by the following equation:

$$dN(t)/dt = N_0\sigma\phi - \lambda N(t), \tag{1}$$

where $N(t)$ is the number of radioactive nuclei formed at moment t; N_0 is the target density (cm^{-2}); σ is the reaction cross section (cm^{-2}); ϕ is the incident particle flux (cm$^{-2}\cdot$ s^{-1}); and λ is the decay constant of radioactive nuclei. In the case of activation with bremsstrahlung, ϕ is the bremsstrahlung photon flux.

Resolving Eq. (1) for three steps, namely irradiation, cooling and measurement times, we get the following expression for number of radioactive nuclei detected during the measurement time:

$$S_n = \frac{N_0\sigma\phi}{\lambda}\left(1 - \mathrm{e}^{-\lambda t_i}\right)\mathrm{e}^{-\lambda t_d}(1 - \mathrm{e}^{-\lambda t_m}). \tag{2}$$

In the experiment the number of radioactive nuclei is usually detected through gamma rays emitted from them. So the number of gamma rays detected is the area under photopeak and is expressed as follows:

$$S = \frac{I\varepsilon N_0\sigma\phi}{\lambda}\left(1 - \mathrm{e}^{-\lambda t_i}\right)\mathrm{e}^{-\lambda t_d}(1 - \mathrm{e}^{-\lambda t_m}), \tag{3}$$

where S is the area under photopeak characterizing investigated radioactive nucleus; I is the gamma intensity; ε is the detector efficiency; and t_i, t_d and t_m are the irradiation, cooling and measurement times, respectively.

Expression (3) is written for the case when the incident particle beam is monoenergetic. In our experiment, ϕ is the bremsstrahlung photon flux produced by the microtron MT-25. Therefore, expression (3) turns to

$$S = \frac{m\theta I\varepsilon N_A}{M\lambda}(1 - \mathrm{e}^{-\lambda t_i})\,\mathrm{e}^{-\lambda t_d}(1 - \mathrm{e}^{-\lambda t_m})\int\limits_{E_{\mathrm{th}}}^{E_{\max}}\phi(E, E_{\max})\sigma(E)dE. \tag{4}$$

Multiplying and dividing expression (4) by $\int\limits_{E_{\mathrm{th}}}^{E_{\max}} dE$, we get

$$S = \frac{m\theta I\varepsilon N_A(1 - \mathrm{e}^{-\lambda t_i})\,\mathrm{e}^{-\lambda t_d}(1 - \mathrm{e}^{-\lambda t_m})\phi_{\mathrm{th}}\sigma_{\mathrm{int}}}{M\lambda(E_{\max} - E_{\mathrm{th}})}, \tag{5}$$

where N_A is the Avogadro number; m is the target mass; M is the target grammol; E_{th} is the reaction threshold; $E_{\max}$ is the bremsstrahlung maximum energy; $\phi(E, E_{\max})$ is the bremsstrahlung energy distribution from 0 to $E_{\max}$; and $\sigma(E)$ is the giant resonance curve.

$\phi_{\mathrm{th}} = \int\limits_{E_{\mathrm{th}}}^{E_{\max}} \phi\,(E, E_{\max})dE$ is the bremsstrahlung photon flux for the region from E_{th} to $E_{\max}$.

$\sigma_{\text{int}} = \int\limits_{E_{\text{th}}}^{E_{\max}} \sigma(E)dE$ is the integrated cross section which can be exactly calculated on the basis of nuclear data taken from literature.

From expression (5) we can see that all parameters are known from experiment, therefore the value ϕ_{th} can be determined. However, our aim is to determine the bremsstrahlung photon flux $\phi_0(E, E_{\max})$ from 0 to $E_{\max}$.

To do this, we need the form or energy distribution of bremsstrahlung. So if we know the bremsstrahlung photon flux ϕ_{th} obtained from the experiment, we can determine the bremsstrahlung flux from 0 to $E_{\max}$ produced by an electron accelerator. The energy distribution of bremsstrahlung with different maximum energies from 15 to 35 MeV have been established by simulation model calculations published in [7, 8]. For calculation of the integrated cross section we have to choose spherical nuclei, which have single Lorentz giant resonance curves, making the calculations simplified. Besides, in our work we have chosen (γ, n) photonuclear reactions which produce radioactive nuclei having high-intensity gamma rays, simple gamma spectrum and high reaction cross section.

Table 1 shows the characteristics of giant resonance curve of nuclei which are suitable for calculation of the integrated cross sections. The data in this table is taken from [9].

Table 1. **Characteristics of giant resonance curve of nuclei which can be used for the experiment**

Nucleus	^{65}Cu	^{90}Zr	^{124}Sn	^{135}Ba	^{143}Nd	^{197}Au	^{208}Pb
E_0, MeV	16.70	16.85	15.19	15.26	15.01	13.82	13.46
σ_0, mb	75.20	185.00	283.00	327.00	349.00	560.00	491.00
Γ, MeV	6.89	4.02	4.81	4.61	4.75	3.84	3.90
E_{th}, MeV	9.90	12.00	8.50	8.60	6.10	8.10	7.40

2. EXPERIMENT

Figure 1 shows the experimental setup for determination of the bremsstrahlung photon flux produced by the electron accelerator Microtron MT-25 of the FLNR, JINR. For the experiment, copper foils of 99.99% purity, weighing 0.1425 g, with diameter of 1.5 cm were prepared and the photonuclear reaction used was ^{65}Cu$(\gamma, n)^{64}$Cu. The metal copper contains two isotopes ^{63}Cu and ^{65}Cu with abundances 61.9 and 30.9%, respectively.

The productive nucleus ^{64}Cu has half-life of 12.8 h and irradiates annihilation peak 511 keV and photopeak 1345 keV with intensities of 38 and 0.6%, respectively. In the case the annihilation peak was more intense, it was used for the experimental aim. As is shown in Figs. 2 and 3, the giant resonance curve of ^{65}Cu is a single Lorentz curve and the gamma spectrum of ^{64}Cu is very simple; therefore, calculation of the integrated cross section of the ^{65}Cu$(\gamma, n)^{64}$Cu reaction and processing the gamma spectra have been performed with high accuracy.

In order to determine the bremsstrahlung fluxes and the space distribution, the copper foils were placed at the axis of the electron beam and distances between them were 1 cm, while the first foil was placed at 1 cm distance from the W converter.

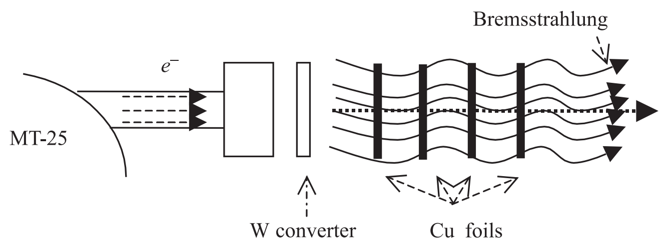

Fig. 1. The experimental setup for bremsstrahlung photon flux determination

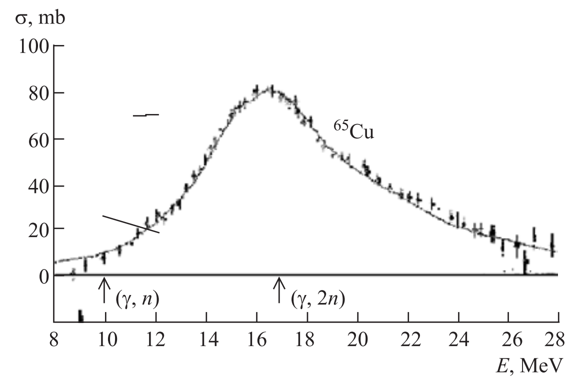

Fig. 2. The giant resonance curve of ^{65}Cu

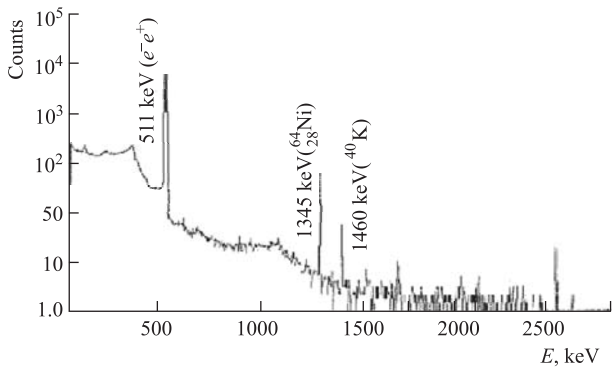

Fig. 3. Gamma spectrum of ^{64}Cu

After irradiation the copper foils were measured with the help of a gamma spectroscopic system, consisting of 40 cm^3 HPGe semiconductor detector ORTEC with 3.5 keV energy resolution at a photopeak of 1332 keV of ^{60}Co and 4096-channel spectroscopic amplifier ORTEC, connected to computer for data processing. The data for characteristics of gamma rays were taken from [10].

Table 2. **Integrated cross sections calculated for different nuclei**

Nuclei	σ^{int}, MeV · mb/E, MeV									
	15	16	17	18	19	20	21	22	23	24
^{65}Cu	142.3	208.5	282.9	354.1	414.3	462.3	500.0	529.8	553.8	573.3
^{90}Zr	139.0	263.5	439.6	605.9	721.2	795.6	845.5	880.9	907.2	927.7
^{124}Sn	701.5	976.5	1198.5	1356.2	1466.9	1547.3	1607.8	1658.1	1693.0	1742.2
^{138}Ba	761.2	1080.2	1337.8	1517.8	1642.3	1731.4	1798.0	1849.7	1890.9	1924.7
^{143}Nd	948.2	1279.8	1536.8	1717.0	1843.7	1936.1	2006.1	2060.9	2105.1	2141.0
^{208}Pb	1737.5	1990.8	2155.8	2269.3	2351.7	2414.5	2464.1	2504.3	2537.7	2566.6
^{197}Au	1819.3	2154.2	2368.0	2511.2	2613.0	2689.2	2748.4	2796.0	2835.2	2868.2

For determination of the bremsstrahlung photon flux at 20 MeV, there were two 30-min irradiations of Cu target with electron beams of 13 and 20 μA, respectively, and for 24 MeV bremsstrahlung there was one 30-min irradiation with electron beam of 13 μA.

3. RESULTS AND DISCUSSION

3.1. Integrated Cross Section of (γ, n) Photonuclear Reaction. As the giant resonance curve has Lorentz form and it cannot be integrated by dE, we used the program MATHEMATICA [11] to turn this integral in a sum in which the energy interval $E_{\max} - E_{\text{th}}$ was divided into 1000 subintervals as follows:

$$\sigma^{\text{int}} = \int\limits_{E_{\text{th}}}^{E_{\max}} \sigma(E) dE = \int\limits_{E_{\text{th}}}^{E_{\max}} \frac{\sigma_0 \Gamma^2 E^2}{\left(E_0^2 - E^2\right)^2 + \Gamma^2 E^2} dE =$$

$$= \text{sum}\left[\frac{\sigma_0 \Gamma^2 E^2}{\left(E_0^2 - E^2\right)^2 + \Gamma^2 E^2}, (E, E_{\text{th}}, E_{\max}, 0.001)\right].$$

Table 2 shows the integrated cross sections calculated for several nuclei suitable for determination of the bremsstrahlung photon flux of MT-25 including ^{65}Cu at different bremsstrahlung maximum energies.

3.2. Energy Distribution of Bremsstrahlung. The energy distribution of bremsstrahlungs produced by W converter have been calculated by the simulation model method described in [7, 8]. Table 3 shows the results for 20- and 24-MeV bremsstrahlungs.

3.3. Bremsstrahlung Photon Flux. The results of the determination of the bremsstrahlung photon flux produced by the microtron MT-25 of FLNR, JINR, are listed in Table 4. Here the bremsstrahlung photon flux at 1-cm distance from W converter was determined for an electron current of 1 μA.

The error of experiment is calculated by the following formula:

$$\frac{\Delta\Phi_0}{\Phi_0} = \sqrt{\sum_i \varepsilon_i^2},$$

Table 3. **Energy distribution of bremsstrahlungs with maximum energies of 20 and 24 MeV**

Energy region	Intensity, %	
	20 MeV	24 MeV
0–3	69.23	65.30
3–5	11.29	11.43
5–10	12.66	12.65
10–12	2.71	2.89
12–14	1.98	2.22
14–16	1.30	1.77
16–18	0.67	1.46
18–20	0.16	1.14
20–22		0.62
22–24		0.25

Table 4. **Bremsstrahlung photon flux of MT-25 at 20 and 24 MeV**

$E_{\max}$, MeV	Bremsstrahlung photon flux, $\text{cm}^{-1} \cdot \text{s}^{-1} \cdot (\mu\text{A})^{-1}$
20	$3.245 \cdot 10^{13}$
24	$5.540 \cdot 10^{13}$

where ε_i are errors of the target mass, the detector efficiency, the gamma intensity, the integrated cross section and the peak area, respectively.

In our experiment the error is about 10%.

In conclusion, we would like to say that the determination of the bremsstrahlung photon flux produced by electron accelerator by means of the photoactivation technique in combination with simulation model is a simple method without using any dosimeter. Besides, this method can be used not only for microtrons but also for other kinds of electron accelerator, for example, linear accelerator and betatron.

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REFERENCES

1. *Antonov A. D. et al.* JINR Preprint P15-89-318. Dubna, 1989.

2. *Antonov A. D. et al.* JINR Preprint P15-90-425. Dubna, 1990.

3. *Oganessian Yu. Ts. et al.* JINR Preprint E7-2000-83. Dubna, 2000.

4. *Sadatov A. S.* Report at the Intern. Seminar on Low and Intermediate Energy Electron Beams. Dubna, March 5–6, 2003.

5. *Kuznetzov R. A.* Activation Analysis. M.: Atomizdat, 1974.

6. Radiological Safety Aspects of the Operation of the Electron Linear Accelerators / International Atomic Energy Agency. Vienna, 1979.
7. *Khai N. T., Thiep T. D.* // Vietnamese J. Commun. Phys. 2002. V. 12, No. 2. P. 48.
8. *Khai N. T., Thiep T. D.* // Vietnamese J. Commun. Phys. 2003. V. 13, No. 3. P. 149.
9. *Berman B. L.* // At. Nucl. Tables. 1975. V. 15. P. 319.
10. *Lederer C. M., Shirley V. S.* Tables of Isotopes. 7th ed. N. Y.; Chichester; Brisban; Toronto: John Willey and Sons, 1978.
11. *Volfram S.* MATHEMATICA. Wesley Publishing Comp. Inc., 1988.

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