Generation of neutrons on Microtron M-10

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Abstract — **Uzhgorod National University's M-10 microtron is used for fundamental investigations of electrons, γ-quanta, and neutron reactions with atomic nuclei, as well as for applied studies of the effects of irradiation on new technological materials and substances. Due to some modifications that the microtron has undergone over time, it has become possible to use it to generate neutrons.**

Keywords - ***microtron; beryllium; generation; activation; target; scintillation spectrometer SBS-40; gamma spectrum; resolution; neutron.***

I. Introduction

The microtron is the first cyclic relativistic accelerator to resemble the ordinary Lawrence cyclotron. As in the first cyclic accelerator, in a microtron the particles move in a constant and homogeneous magnetic field. The acceleration occurs under the action of a variable electric field with a constant frequency. The microtron was created as an accelerator of relativistic particles whose energy is significantly higher than their rest energy. This relatively small machine effectively and simply accelerates electrons to energies of tens of MeV. Electrons are accelerated by repeatedly passing through a volumetric resonator excited by a pulse magnetron. The resonator is located in a constant homogeneous magnetic field, under the influence of which the electrons move in circular orbits that touch each other at a point located in the middle of the resonator. At each passage of the resonator, the energy of the electrons is increased by 0.511 MeV. A detailed description of the principle of operation of the M-10 microtron is given in the monograph [1]. The microtron of Uzhgorod National University is an analog of the 17-orbit microtron developed by the IFP of the Academy of Sciences of Russia under the guidance of Prof. Kapitsa S.P.

II. MAIN CHARACTERISTICS OF MICROTRONS

- Number of orbits – 17, electron withdrawal can be carried out with 11-15 orbits;

- Electron energy: maximum - 10 MeV, possible change in the energy of accelerated electrons in the range 6.5-10 MeV, by restructuring the output channel into different orbits and changing the magnetic field within one orbit; it is possible to get even lower energy by using a special insert, which moves the resonator closer to the center of the microtron camera.

- Diameter of the vacuum chamber – 75 cm;
- Ultra high frequency generator 10 – cm;
- Magnetron power – 2.5 kW;
- Radiation pulse duration – 2.5 μs;
- Impulse repetition rate – 400 Hz;
- Maximum impulse current – 15-20 mA;
- Efficiency of electron output – 80-90%;
- The working range of the output current of electrons at an energy of 6-9 MeV is:

0.01-10 μA ($5 \cdot 10^9$ $e^-/(cm^2 \cdot s)$ - $5 \cdot 10^{12}$ $e^-/(cm^2 \cdot s)$).

The electrons from the accelerator are taken out of the orbit on which the output channel is located (the orbit number determines the energy of the electrons), through titanium window 0.1 mm thick. When passing through the window, electrons with energy of 8.6 MeV approximately lose 80 keV of their initial energy.

To determine the number of electrons that fall on the irradiated object exploit a Faraday cylinder as an absolute device for measuring currents, which is made of aluminum and has the following dimensions, so that it can be used to measure the current of electrons up to 20 MeV [2]. Since it is not always convenient to use a Faraday cylinder directly to measure accelerated electron currents and for that, to control the current during irradiation of samples, out of microtron output window is installed a pass ionization chamber (the camera is a monitor), which is calibrated according to the readings of the Faraday cylinder (Fig. 1). Current on both devices measured by microampermeter of the type M-109. During the calibration of the passage chamber, there is a relationship between the Faraday cylinder current value and the current of the passage chamber [3].

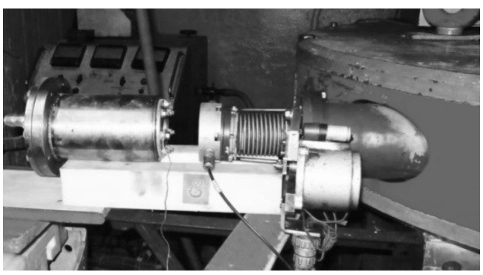

Fig. 1. The M-10 microtron together with a passage chamber and Faraday cylinder.

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After calibration, the Faraday cylinder is removed and the samples are irradiated in its place. The camera consists of three identical plates, which are located across the beam of electrons. In our case, copper plates 0.1 mm thick were used. The electron energy loss at the passage chamber is 320 keV. Depending on the distance to the irradiated sample, there is still an additional loss of electron energy in the layer of air between the output window and the irradiated sample.

At the output of the accelerator, the electron beam has dimensions of 25-30 mm horizontally and 8-10 mm vertically. When going through a window, monitor - camera and layer of air, electrons are scattered and beam sizes increase, but at the same time the electron flux density in the beam decreases. At the Department of Nuclear Physics, the methods of dosimetry and measurement of the electron beam parameters from the M-10 accelerator were developed, were certified and tested.

To determine the size of an electron beam on irradiated samples, glass is used which has the property of darkening under the action of electrons (radiation defects are formed). The magnitude of the darkened spot on the glass corresponds to the size of the electron beam at a given distance. If necessary, the size of the electron beam should be increased, and additionally an aluminum diffuser should be placed. Knowing the magnitude of the current in the chain of the Faraday cylinder, it is possible to calculate the average density of electron flux by the formula:

$$\varphi_e = \frac{n}{S} \quad (1)$$

Where - n is the number of electrons entering the Faraday cylinder in 1 s,

$$n = I_{cF}/(1.6 \cdot 10^{-19}) \frac{e}{s}$$

S - the area of the input window of the Faraday cylinder ($S = 12.56\ cm^2$).

$$\varphi_e = I_{cF}/(1.6 \cdot 12.56 \cdot 10 - 19) =$$

$$= 5 \cdot 10^{17} \cdot I_{cF} (\frac{e}{cm^2} \cdot s)$$

If express I_{cF} in μA (10^{-6} A), then

$$\varphi_e = 5 \cdot 10^{11} \cdot I_{cF} (\frac{e}{cm^2 \cdot s}) \quad (2)$$

that is, a current of 1 μA corresponds to the electron flux density $5 \cdot 10^{11}$ e / (cm^2·s).

The value of fluency Φ is determined from the time of irradiation:

$$\Phi_e = \varphi_e \cdot t \quad (3)$$

Keeping the electron beam current steady, we obtain the dose as a function of time. If the current is unstable for some reason during the irradiation period, then an additional ionization camera-monitor of the clinical dosimeter is used RFT 27012, which works in integral mode and passes calibration on the passage chamber.

The camera is positioned so that it detects scattered radiation, the magnitude of which changes in accordance with the change in the dose collected on the samples with the same geometry of the experiment. That is, the value of the required dose can be controlled both by the magnitude of the current of the passage chamber and the integral charge of the clinical dosimeter.

III. Brake Gamma Radiation

To obtain a beam of γ - quanta from a microtron, a tungsten braking target with thickness 2 mm is used, which is installed after the passage chamber. For the dosimetry of the braking radiation beam, we use an absolute ionization chamber (AIC) with current integrator based on RC circuit and electrometer amplifier. In absolute chambers there is a complete absorption of the energy of the secondary electrons formed by the braking radiation [4].

TABLE I. MAIN TECHNICAL CHARACTERISTICS OF MICROTRON – M-10

№	Technical parameters	Size
1	Power consumption	30 kW
2	High-voltage	380 V
3	Magnet current	40 A
4	Weight of the magnet	1.5 tone
5	Maximum energy of accelerated electrons	10 MeV
6	Number of orbits	17
7	Current of accelerated electrons	20 μA
8	Exposure dose on 1 m from the brake target	3000 R/min.
9	The length of the radiation pulse	2.5 μs
10	Frequency of repetition of pulses	400 Hz
11	Efficiency of electron output	90 %
12	Power supply of the resonator	2 MW

A thick-walled AIC in the form of an aluminum cylinder with a diameter of 10 cm is used at the microtrone of UzhNU. The thickness of the front wall, which is irradiated by a beam of γ - quanta, is 7.5 centimeters. The gas cavity has a diameter of 41 mm. at a thickness of 7 mm and is filled with air ($\rho = 1.21 \cdot 10^{-3} g/cm^3$, E = 34 eV). The cumulative electrode is shaped like a circle. In the insulator through which the output passes, there is a guard ring designed to reduce the flow of currents from the specified output. The high voltage electrode is the aluminum cylinder on which the high voltage (300 V) is applied.

The ionization current from the absolute ionization chamber via the cable RK - 50 is supplied to the integrating RC circuit connected to the input of the U5-11 electrometer amplifier. The output voltage is measured by a voltmeter. The values of the resistance R and the capacitance C are chosen so that their product is equal to the value of the half-life of the studied isomer [5].

Because intensity of the radiation $\Phi(E_m)$ is not constant throughout the irradiation time t, so in the case of intensity changes over time arbitrarily, or by any regularity, then the easiest way to account for the dose is by use RC is an integrating circuit connected to the output of the absolute ionization chamber.

In this case, the output voltage of the electrometric amplifier connected to the ionization chamber at different intervals V (E_m, t) after the onset of irradiation can be found from the differential equation:

$$\frac{dV(E_m,t)}{dt} = \Phi(E_m,t)\cdot k - \frac{1}{RC}\cdot V(E_m,t) \qquad (4)$$

if take that λ = 1/RC.

The solution of the equation (4) for the moment of time $t_1 = t_{irradiation} + t_{cooling}$ will look like:

$$I(E_m,t) = \Phi(E_m,t)\cdot k\cdot(1-e^{-\lambda t_{\text{опр}}})\cdot e^{-\lambda t_{\text{ох}}} \qquad (5)$$

Where k - is the coefficient that relates the magnitude of the current of the ionization chamber with the intensity of the beam of γ-quanta; I(E_m,t) – instantaneous current value of the ionization chamber at the output of the RC circuit.

The geometry of the measurements of the parameters of the beam of γ-quanta is the same as that of measurements of the electron beam, only a tungsten plate is placed behind the passage chamber and an absolute ionization chamber is installed instead of the Faraday cylinder.

IV. NEUTRONS

The microtron can be used as a neutron source. For this purpose, an accelerated electron beam in a tungsten target 3 mm thick is transformed into a flux of γ - quanta of continuous energy spectrum. Further, in the path of the γ - quantum flux, a beryllium block is used in the paraffin moderator, which serves as a neutron converter. The neutrons for activation were obtained by a nuclear reaction $^{9}Be(\gamma,n)^{8}Be$, with a reaction threshold 1.67 MeV, which is typical of microtron of this type. Dimensions of paraffin moderator 45x45 cm, beryllium block – 10x14 cm, weight 2 kg. The ^{115}In and ^{59}Co activation detectors were located close to the beryllium block and irradiated for 10 minutes (Fig. 2).

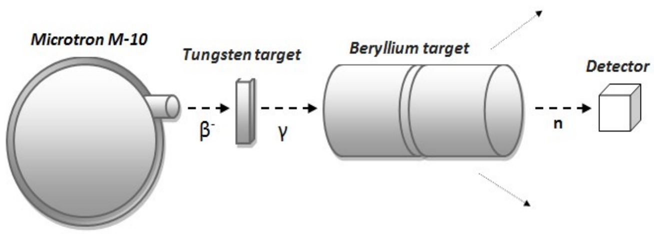

Fig. 2. Scheme of placement of the activation neutron detector

Studies of the energy spectrum of neutrons have shown that the neutron spectrum is almost heat. The neutron flux depends on the current of the electrons output from the accelerator, and thus on the number of γ-quanta [6].

To detect neutron we use ^{59}Co and ^{115}In activation targets. The study of the energy spectrum of activated targets shows that the isomeric level ^{60m}Co 58.6 keV is activated in the target and ground state ^{60}Co, which gives known levels 1173 keV and 1332 keV (Fig. 4, 7, 8). The indium target gives 4 levels 416 keV, 1096 keV, 1293 keV and 2112 keV (Fig. 5). At the energy of the output electrons beam 8.6 MeV and currents of 5 μA the flux density of thermal neutrons was $2\cdot10^{6}$ n/(cm^{2}·s).

Measurements of γ-radiation from the activation detector were performed with a spectrometer, which includes a scintillation detector with an SBS-40 amplifier-to-digital converter board, which is connected to a computer (the spectrum is built using AkWin).

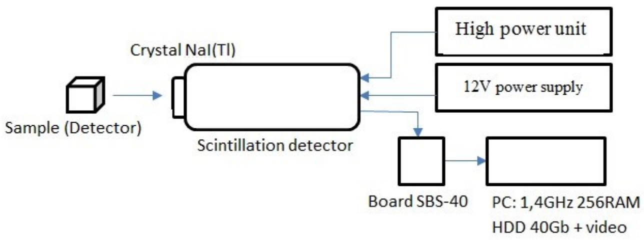

Fig. 3. Scheme of arrangement of elements for dosimetry of a neutron detector.

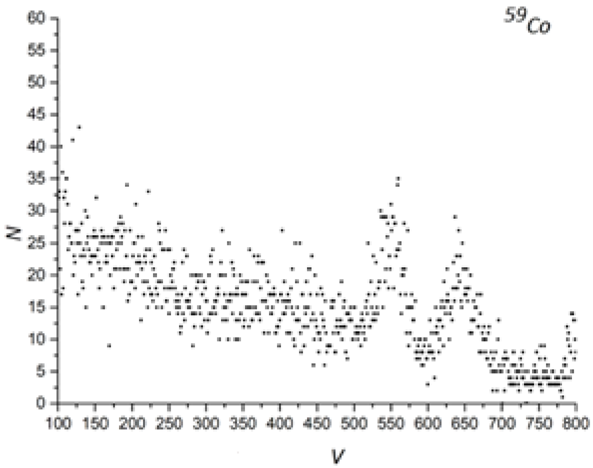

Fig. 4. Measurement of peaks of irradiated target ^{59}Co. (counts N vs channel number V).

V. RESULTS OBTAINED

To obtain accurate results from the spectrometer, it was calibrated using a reference source Ra-226 (OSIAI kit). The γ spectrum was obtained and the channel scale was converted to an energy scale (Fig. 5). Separated experimental peak was fitted by the Gaussian peak with polynomial background

$$y = y_0 + y_1\cdot x + y_2\cdot x^2 + A\cdot \exp\left(-\frac{(x-x_0)^2}{2\cdot\sigma^2}\right). \qquad (6)$$

For ^{226}Ra gamma line (Fig. 5) 600.7 keV we obtain resolution 10.5% (FWHM) and for line 351.92 keV resolution 8.9%.

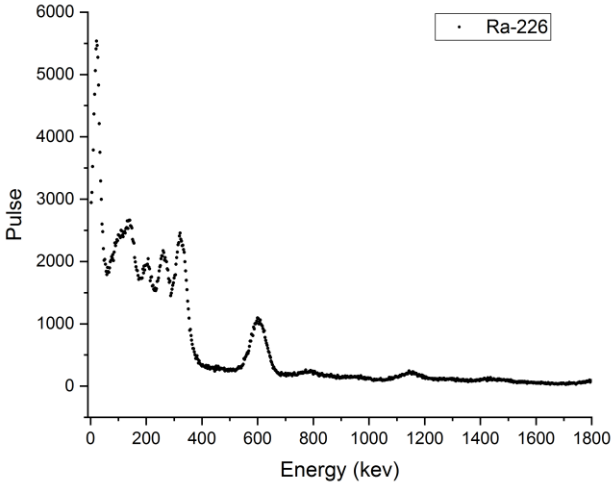

Fig. 5. γ – source spectrum ^{226}Ra.

Time of irradiation by thermal neutrons In-115 was 10 minutes, at the energy of the electron beam 8.6 MeV and currents of 5 μA, where the flux density of thermal neutrons was $2 \cdot 10^6$ n/(cm^2·s). Four peaks with energies are clearly tracked on spectrum (Fig. 6) 416.86, 1097.3, 1293.54 and 2112.1 keV and are consistent with the data [7], where measurements were made on a semiconductor detector.

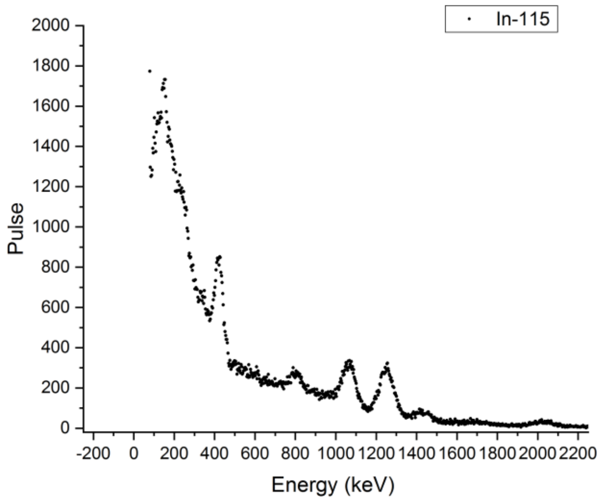

Fig. 6. γ – spectrum of activation neutron detector ^{115}In.

The same experiment was repeated for the ^{59}Co activation detector and the following spectrum was obtained for ground state (Fig. 7) and isomeric state (Fig. 8).

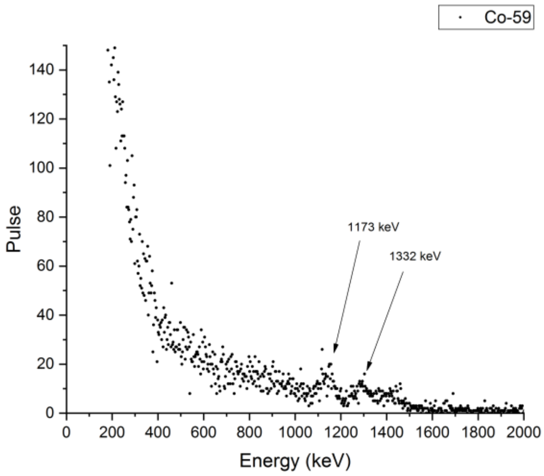

Fig. 7. γ – spectrum of activation neutron detector ^{59}Co.

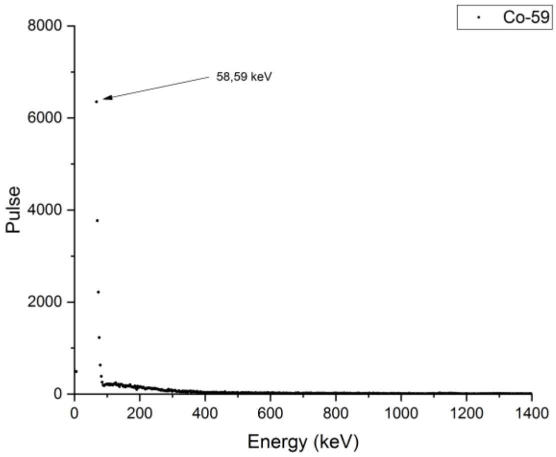

Fig. 8. γ - spectrum of activation neutron detector ^{59}Co (isomeric level)

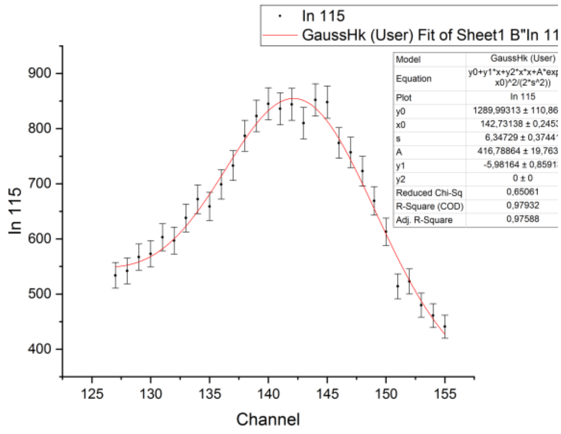

Fig. 9. Detector In-115. Peak 416.86 keV.

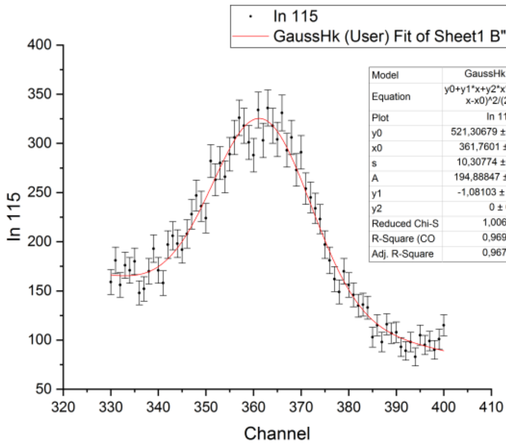

Fig. 10. Detector In-115. Peak 1097.8 keV

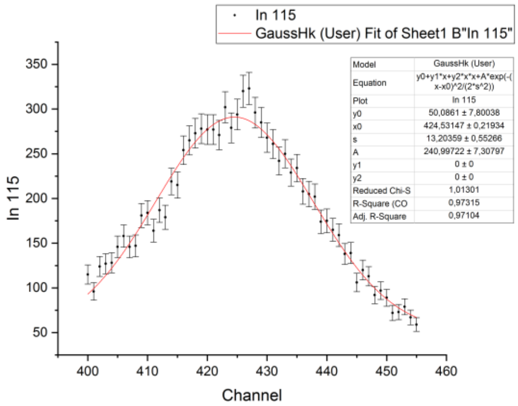

Fig. 11. Detector In-115. Peak 1294.54 keV

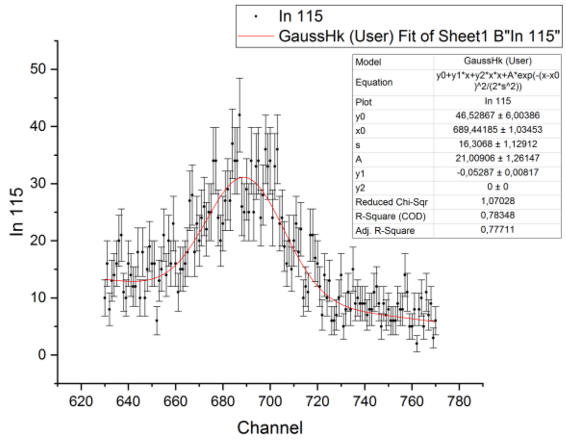

Fig. 12. Detector In-115. Peak 2112.1 keV.

Results of fitting gamma spectra from activated indium target are shown in Figs. 9-12 and in Table II where x_0, σ and A are parameters of the Gaussian peak (6), N is the total count of events under the peak and Δx_0, $\Delta\sigma$, ΔA, ΔN are their standard deviations.

TABLE II. PARAMETERS OF IN-115 SPECTRA

E (keV)	416.86	1097.3	1293,.	2112.1
x_0	142.73	361.76	424.53	689.44
Δx	0.24	0.31	0.22	1.03
σ	6.35	10.31	13.20	16.31
Δσ	0.37	0.37	0.55	1.11
A	416.78	194.88	240.99	21.00
ΔA	19.76	5.24	7.31	1.26
N	6613	5022	7971	856.1
ΔN	49	13	18	4.4

VI. CONCLUSION

From the results obtained, it is clear that the M10 microtron can serve as a neutron source. Neutrons can be obtained using a reaction (γ,n) on heavy elements or on beryllium. One of the advantages is that the neutron flux, in this case, can be controlled by changing the radiation intensity of the accelerator. The use of this method makes it possible to study the composition of various chemical materials and compounds. Unlike neutron sources, which have a constant flux and constantly emit neutrons, microtrons are safer in terms of radiation safety, since neutron generation occurs only during the accelerator operation.

The measurements were made on a scintillation detector with NaI(Tl) crystal and with the help of the SBS-40 amplitude analyzer board. The In-115 Neutron Activation Indicator was used to determine the flux. The results of irradiation are given in Table II. In this work, the energy of the output electron beam was 8.6 MeV at current 5 μA, the thermal neutron flux density was obtained $2{\cdot}10^6$ n/(cm^2·s).

In Table II the only number of registered photons is indicated. To estimate the neutron flux we used geometry efficiency of the spectrometer. However for more precise estimation of the neutron flux, it is necessary to simulate the efficiency of our spectrometer to exclude Compton scattered gammas. It is also possible to simulate all physical processes of experiment indicated in Fig. 2, namely, braking process of electrons on tungsten target, (γ,n) reaction on beryllium target, and (n,γ) reaction on activation target.

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REFERENCES

[1] S.P. Kapitsa, and V.N. Melekhin, “Microtron”, Moscow: Nauka, 1969. (in Russian)

[2] B.S. Dolbilkin, R.L. Kondratyev, V.P. Lisin, and A.L. Polonsky “Measurement of the charge of a pulsed beam on a computer line in electron scattering experiments”, Moscow: USSR Academy of Sciences, Institute of Nuclear Research, 1984. (in Russian)

[3] V.M. Andreyanov, O.G. Okunyev, O.M. Parlag et al. “Dosimetry technique of micron electron beam”, Deposited at the State Scientific and Technical Library of Ukraine on March 10, 1994. (in Ukrainian)

[4] O.V. Bogdankevich, and F.A. Nikolayev, “Work with a beam of brake radiation”, Moscow: Atomizdat, 1964. (in Russian)

[5] V.M. Andreyanov, O.G. Okunyev, O.M. Parlag et al. “Integral sections of the photoexcitation of the 198Au, 138Ba, 79Br, 179Hf isomers by brake radiation with a maximum energy of 6-9 MeV”, Deposited in the State Scientific and Technical Bureau of Ukraine on January 10, 1995. (in Ukrainian)

[6] N.A. Vlasov “Neutrons”, Moscow: State publisher of technical theory. Lit., 1955. (in Russian)

[7] O.O. Parlag, V.T. Maslyuk, P.P. Puga, and V.M. Golovey, “Catalog of gamma spectra of products of activation of chemical elements by micron brake radiation”, Kyiv: Naukova Dumka, 2008. (in Ukrainian)