PRODUCING THE PLANAR MULTIPHOTON SOURCES BY PHOTONUCLEAR TECHNIQUE: 2. EXPERIMENTAL STUDY

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Characteristics of the two-and three-photon sources are analyzed by gamma-ray spectrometric method. The sources are obtained by combining the inactive foils from indium, tantalum, tungsten and lead with planar γ-sources on the basis of the isotopes ^{57}Co and ^{179}Ta. The γ-sources are produced by activating the foils from nickel and tantalum in the bremsstrahlung field of an electron accelerator. The possibility to control the number, energy and intensity of the spectral bands of a combined source by selecting the material, thickness, order of arrangement and quantity of its components is demonstrated. The experimental results on band intensity of the sources under study are satisfactory agreed with the data calculated on the basis of a developed analytical model.

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INTRODUCTION

In the report [1], the possibility has been shown to produce a planar two-photon γ-source[1] by stacking the thin single-photon sources on the basis of the ^{179}Ta and ^{57}Co isotopes obtained by activating the tantalum and nickel foils. The further study has indicated, that a two-photon source with the manipulated spectrum can be manufactured by combining the one γ-source with the cold foils from various elementary substances. Thus the second low-energy spectral band arises as a result of excitation of the characteristic X-ray radiation in an inactive material by external γ-radiation (the gamma-fluorescence effect).

A model was developed for the description of such type sources with the two and more spectral bands [2]. This communication deals with the results of the experimental study of the two- and tree-photon sources, obtained by combining the ^{57}Co and ^{179}Ta sources, produced by photonuclear technique, with the inactive foils from various materials.

1. METHODS AND MATERIALS

1.1. ACTIVATION OF TARGETS

The photonuclear manufacturing of γ-sources was conducted at a LU-40 Linac of NSC KIPT [3]. An electron beam (40 MeV; 4 μA) was transformed into bremsstrahlung radiation with the use of a converter comprising four tantalum disks 3 cm diameter and 1 mm thick separated by 1 mm gaps for cooling. A part of the primary electrons, passed through the converter, was absorbed in an aluminium plate 40 mm thick followed by an isotope target. For determination of photonuclear yield of the target isotopes and by-products under similar irradiation conditions, the experimental targets included the pars of stacked tantalum and nickel foils each by 30 mm in diameter and 0.1 mm thick. After exposure for 2.5 h, the targets were cooled for decay of the short-lived admixtures.

1.2. GAMMA-SPECTROMETRIC ANALYSIS

A spectrometric station comprising a HPGe detector GRD-16195 with an amplifier ORTEC570 was applied for determination the isotopic composition and activity of the irradiated foils. Calibration of the spectrometer against efficiency was conducted using a set of the standard γ-sources with photon energy in the range 59.5 keV (^{241}Am) – 1332 keV (^{60}Co). The station provided the resolution 510 eV (FWHM) along the 122.1 keV line (^{57}Co). A number of measurements was executed with the use of a Ge(Li) detector. The activity of the isotopes in the foils was calculated by EOB with due regard to the radionuclide decay and self-absorption of their radiation in the samples. The uncertainty of the activity determination did not exceeded 7% (k=2).

1.3. SIMULATION

Investigation of the process of target activation was carried out also by a simulation technique with the use of a modified transport code PENELOPE-2008 [4].In calculations, the geometry of the target device as well as spatial radiant characteristics of the electron beam impinging on the converter were duly described. The photonuclear yield of the isotopes was determined by summation of microyields of the corresponding reactions along the trajectories of the above-threshold photons in a target [5].

2. RESULTS AND DISCUSSION

2.1. THE ISOTOPE YIELD IN THE EXPERIMENTAL TARGETS

In Figs. 1 and 2, the spectra of the activated targets after cooling are shown, when Table 1 lists the measured and calculated values of the yield of the principal isotopes. In the spectrum of the tantalum, in addition to expected ^{179}Ta, the lines of ^{92m}Nb are presented also. That radionuclide is generated via the reaction $^{93}\mathrm{Nb}(\gamma,\mathrm{n})^{92m}\mathrm{Nb} \xrightarrow[10.15\,day]{\varepsilon} {}^{92}\mathrm{Zr}_{stab}$ on niobium, commonly existing in tantalum as a natural admixture (~0.02%). The activity of the most long-lived by-product, ^{182}Ta ($T_{1/2}$=115 day), manufactured by the reaction of photoneutron capture ^{181}Ta(n,γ)^{182}Ta, at EOB does not exceed 4% of the ^{179}Ta activity. In the nickel (see Fig. 2), apart from ^{57}Co, the ^{56}Co isotope with yield 0.53 kBq/μA·h and ^{58}Co (0.27 kBq/μA·h) are generated also.

[1] As generally adopted, n-photon source is named a γ-source having n main spectral peaks (or n bands of the closely spaced spectral lines) at possible presence of the low-intensity lines in other parts of the spectrum.

The data of Table 1 demonstrate the satisfactory agreement between the results of the experiment and simulation. Greater divergence of the results on the activity of ^{57}Ni is connected with the growth of the statistical uncertainty at measurement of low activity of this isotope after long cooling of the target.

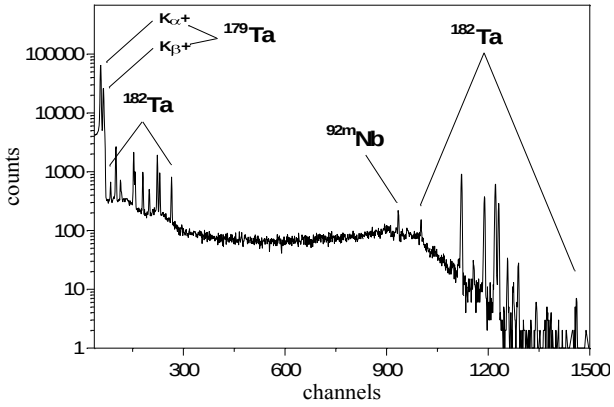


Fig. 1. γ-spectrum of activated tantalum (33 day after EOB)

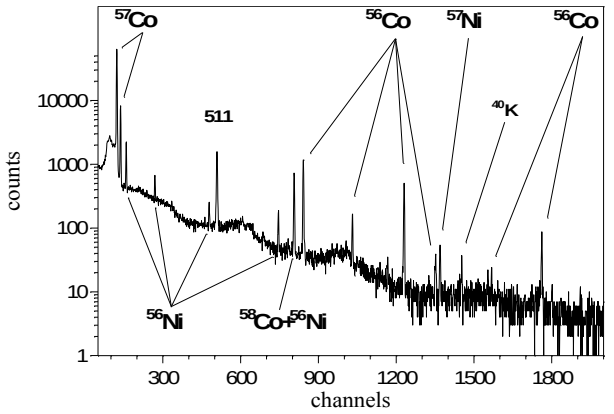


Fig. 2. γ-spectrum of activated nickel (17 day after EOB)

Table 1

The isotope yield in the experimental targets at EOB, kBq/μA·h

Isotope	^{179}Ta	^{180}Ta	^{57}Co	^{57}Ni
Simulation	1.11	$6.06 \cdot 10^3$	1.92	154
Experiment	1.08	$6.16 \cdot 10^3$	2.16	126

2.2. COMBINED GAMMA-SOURCES

In Fig. 3, the low-energy part of the spectrum of a source obtained by stacking the activated tantalum and nickel foils is shown (a detector of radiation is positioned from the tantalum side). It is seen, that the lines with photon energy 55 and 122.1 keV are prevailed. Moreover, in the low-energy spectral band, along with the K-lines of tantalum, the nearly located lines of hafnium and tungsten are identified also. The lasts are produced as a result of the decay of ^{180}Ta. At the same time, the relative intensity of the lines in the spectrum of the combined source, as compared with radiation of the separate targets, has drastically changed. So in the combined source, the intensity of the line 122.1 keV decreased by about 35%. It corresponds to the attenuation of such radiation after its passage through a layer of the tantalum 0.1 mm thick. At the same time, the intensity of the low-energy band has become practically two times greater. The growth of the X-ray yield is determined by the fluorescence of the tantalum under action of the ^{57}Co radiation.

Hereafter, we will identify the combined radiation sources by expressions like L+M*+…, where L, M… are the names of the chemical elements of materials forming a source in the order of their positioning relative to a radiation detector, when mark * denotes the presence of γ-activity at the corresponding component of the source [2].

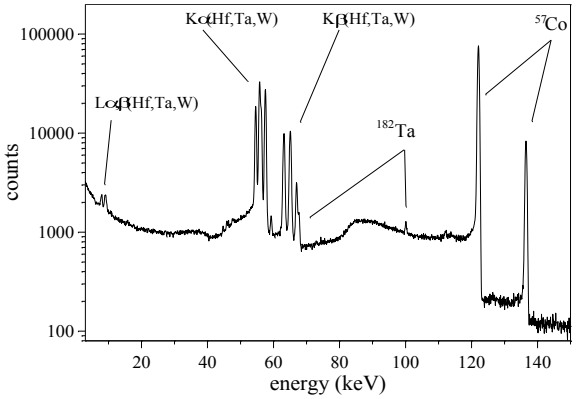


Fig. 3. Low-energy part of the spectrum of the combined ^{179}Ta+^{57}Co source

Thus the spectrum of a Ta+Ni* source, obtained by placing a cold tantalum foil 0.1 mm thick in front of the activated nickel, is demonstrated in Fig. 4. As compared with the previous case, the flux of the ^{57}Co radiation is stable, when the intensity of the 55 keV band corresponds exactly its increase in the Ta*+Ni* variant as relative to the value, observed at a separate Ta* source. At the same time, in case of the Ta+Ni* source the hafnium and tungsten lines are absent.

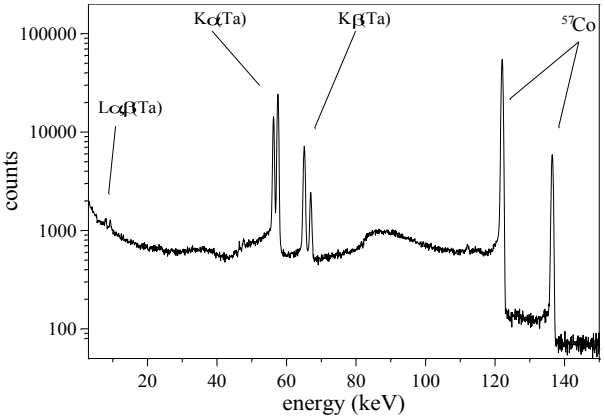


Fig. 4. Low-energy part of the spectrum of the Ta +Ni source*

In what follows, the results of measurement of the spectral line intensity of the planar sources, obtained by combining the cold and hot foils from various materials are given. As a material for the inactive components, the elementary substances of natural isotopic composition were used. All the sources were placed at a distance of 3 mm from the detector. The line intensity was determined as the number of pulses under the photopeak with due regard to the detector efficiency but neglecting the radionuclide half-life and quantum yield of the gammas. The intensity of the 122.1 keV line of Ni* was considered as 100%. Taking into account the overlapping of the peaks

from the adjacent K-lines, the averaged values of the K_α and K_β line intensity were registered. The values, obtained in such a way, are given below in the tables.

For some main lines, the quantitative estimation of their intensity was performed with the use of formulae, stated in the work [2]. IAW the terminology, offered in that work, an inactive element of a combined source being fluorescent under external γ-radiation is called *radiator* whereas a hot element of the source-*activator*. The values of the mass attenuation coefficient (Table 2) of photons in the materials under study were calculated with the use a XMuDat package [6]. Hence, the photon free range R_γ and optimum radiator thickness $d_1^{\max}(E_\gamma)$, providing the maximum yield of the fluorescence at an energy of the activating photons E_γ, were calculated. In Tables 3 and 4, the data are given on the relative intensity of the main spectral lines for the sets of the cold and hot foils 0.1 mm thick from tantalum and nickel obtained in the experiments and by simulation.

Table 2

Mass attenuation coefficient, free range and optimum thickness of radiator

Material	E_γ,keV	μ,см^2/g	R_γ,мм	$d_1^{\max}(E_\gamma)$,мм
Ni	122.1	0.31	3.65	–
	75.0	0.86	1.31	–
	55.4	1.87	0.60	–
In	122.1	0.98	1.40	0.31
	75.0	3.47	0.40	–
	59.3	6.51	0.21	–
	55.4	7.80	0.17	0.14
	24.1	12.15	0.03	–
Ta	122.1	2.65	0.23	0.17
	55.4	4.27	0.14	–
W	122.1	2.72	0.19	0.16
	59.3	3.73	0.14	–
Pb	122.1	3.43	0.26	0.27
	75.0	2.77	0.32	–

Table 3

Relative band intensity of single- and two-component sources on the basis of tantalum and nickel

Radiation line (photon energy, keV)	Source configuration											
	Ni*	Ta*	Ta*+Ni*		Ta+Ni*		2Ta+Ni*		Ni*+Ta		Ni*+3Ta	
	Exp	Exp	Exp	Calc	Exp	Calc.	Exp	Calc	Exp	Calc	Exp	Calc
Ta, K_α(55.4)	0.0	14.6	27.1	27.0	12.6	12.4	10.7	10.1	12.1	13.1	14.0	18.5
Ta, K_β(63.5)	0.0	4.9	9.1	–	4.2	–	4.0	–	4.0	–	–	–
^{57}Co(122.1)	100.0	0.0	63.7	64.3	63.9	64.3	40.6	41.2	100.0	–	100.0	–
^{57}Co(136.5)	12.5	0.0	9.2	–	9.1	–	6.3	–	12.5	–	12.7	–

Table 4

Relative band intensity of the three- and four-component sources on the basis of tantalum and nickel

Radiation line (photon energy, keV)	Source configuration							
	Ta*+Ni*+3Ta		Ta+Ni*+2Ta		Ta*+Ta+Ni*+2Ta		Ta*+2Ta+Ni*+Ta	
	Exp	Calc	Exp	Calc	Exp	Calc	Exp	Calc
Ta, K_α(55.4)	33.8	34.7	17.7	19.5	26.2	24.2	26.2	21.1
Ta, K_β(63.5)	11.6	–	6.4	–	10.6	–	10.6	–
^{57}Co(122.1)	65.2	64.3	62.8	64.3	40.6	41.2	26.1	26.5
^{57}Co(136.5)	9.0	–	8.6	–	6.2	–	6.2	–

The results given in Table 3 show, that the combinations of inactive tantalum with the hot nickel in the form Ta+Ni* or Ni*+3Ta provide the yield of the tantalum K-lines comparable with the intensity of a separate ^{179}Ta source, obtained at joint activation of tantalum and nickel, while at a Ta*+Ni*+3Ta configuration, that intensity is by 2.3 times higher. A Ta*+2Ta+Ni* combination provides the relative equality in the intensity of the both spectral bands (see Table 4).

The experimental and calculated data on characteristics of the two-photon sources manufactured by combining the active nickel and tantalum foils with the cold elements from indium, tungsten and lead are listed in Tables 5-7 (the thickness of the inactive foils in mm is specified in parentheses to the right from the symbol of the element used).

Table 5

Relative band intensity of sources with the radiator from indium

Radiation line (photon energy, keV)	Source configuration			
	In(0.23)+Ni*		In(0.23)+Ta*	
	Exp	Calc	Exp	Calc
In, K_α(24.2)	3.0	3.1	1.0	2.0
In, K_β(27.3)	0.6	–	0.2	–
Ta, K_α(55.4)	–	–	4.1	4.5
Ta, K_β(63.5)	–	–	2.3	–
^{57}Co(122.1)	84.0	85.1	–	–
^{57}Co(136.5)	11.0	–	–	–

Table 6

Relative band intensity of sources on the basis of cold tungsten and hot nickel

Radiation line (photon energy, keV)	Source configuration					
	W(0.12)+Ni*		Ni*+W(0.3)		W(0.12)+Ni*+W(1.2)	
	Exp	Calc	Exp	Calc	Exp	Calc
W, K_α(59.3)	12.7	14.9	15.2	17.5	17.7	18.9
W, K_β(67.1)	4.3	–	5.0	–	6.5	–
^{57}Co(122.1)	51.9	53.2	100.0	–	52.9	53.2
^{57}Co(136.5)	7.6	–	12.5	–	7.8	–

Table 7

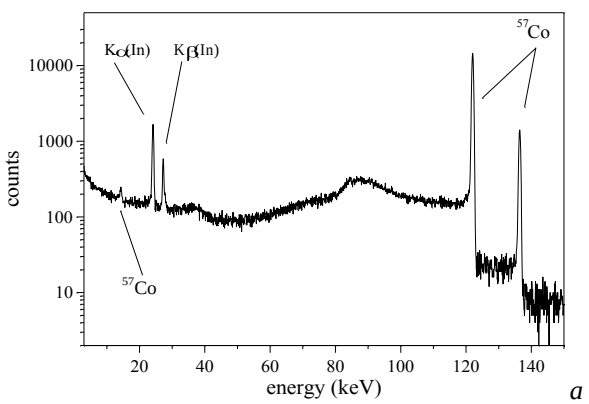
Relative band intensity of sources on the basis of lead and hot nickel

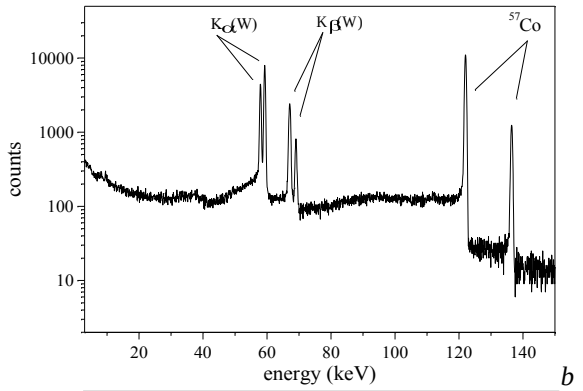
Radiation line (photon energy, keV)	Source configuration					
	Pb(0.23)+Ni*		Ni*+Pb(3)	Pb(0.23)+Ni*+Pb(3)		
	Exp	Calc	Exp	Calc	Exp	Calc
Pb, K_α(74.0)	15.3	19.7	19.0	25.6	22.7	22.6
Pb, K_β(84.9)	4.8	–	5.5	–	7.5	–
^{57}Co(122.1)	39.0	41.0	100.0	–	39.0	41.0
^{57}Co(136.5)	6.0	–	12.5	–	6.0	–

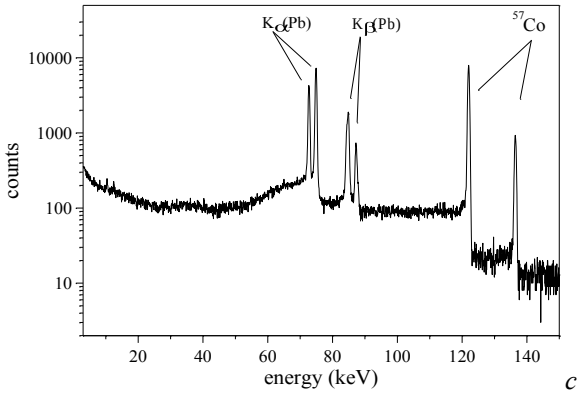
In the experiments, the use of the tungsten radiator 0.12 mm thick (that thickness is close to the optimum value) has provided the most yield of K-lines. At further growth of the radiator thickness, the intensity of that band was diminished. At excitation of X-ray in lead, the similar behavior was observed (see Table 7).

From comparison the data of Tables 3-6 it follows, that ^{57}Co induces X-ray in tantalum and lead with much greater efficiency than in indium. On the other hand, the action on the last with the ^{179}Ta radiation provides higher yield of the fluorescence. The effect can be explained in view the dependence of the photoeffect cross-section from energy of gammas. So if the last lies far from the absorption edge, $\sigma_{ph}(E_\gamma, Z) \sim E_\gamma^{5/2} \cdot Z^5$ [7]. Some disarrangement between the calculated and experimental results, observed in a number of cases, can be explained either by great thickness of a source component (when the offered analytical model is not valid) or by the growth of the statistical uncertainty at measurement of a low-intensity line.

As an instance, in Figs. 5, 6 the two- and three-photon spectra of a number of sources, obtained by means of various combinations of the activated tantalum and nickel with the cold foils from indium, tungsten and lead are demonstrated.







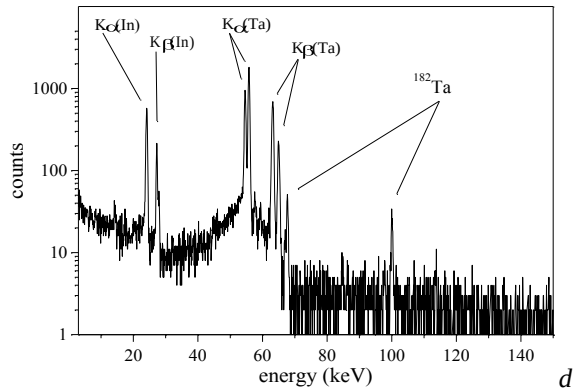


Fig. 5. Two-photon spectra: a – In(0.225)+Ni; b – W(0.12)+Ni*+W(0.6); c – Pb(0.23)+Ni*+Pb(3.0); d – In(0.225)+Ta**

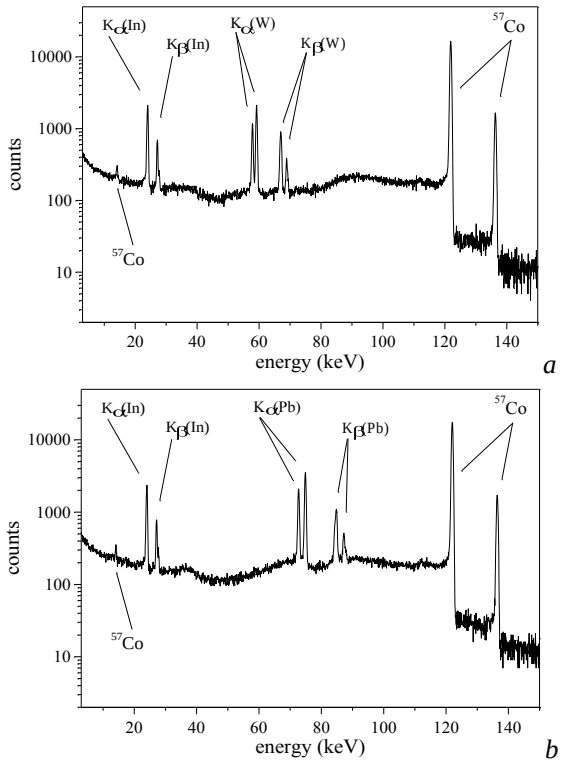


Fig. 6. Three-photon spectra: a – In(0.225)+Ni+W(0.6); b – In(0.225)+Ni*+Pb(3.0)*

CONCLUSIONS

The possibility is shown to produce the sealed planar sources on the basis of the ^{179}Ta and ^{57}Co isotopes at an electron accelerator without radiochemical procedures. With the use of the fluorescence effect, the two- and multi-photon sources with practically arbitrary size can be fabricated by stacking such sources with the cold foils from various elementary substances. The location and intensity of their spectral maximums can be controlled by selecting the radionuclide-activator of fluorescence, the material of an inactive component and its thickness as well as the order of positioning of the cold and hot elements. The half-life of the combined source is determined by the half-life of the activator.

The calculated band intensities of the combined sources on the basis of the developed analytical model are in good agreement with the experimental results.

Manufacturing of ^{57}Co planar sources with activity up to ~1 GBq by nickel irradiation with high-energy bremsstrahlung seems to be more promising in contrast to radiochemical extraction of this isotope from a photonuclear target in view of its considerable weight and consequently low specific activity.

The decrease of the hot admixtures in a ^{57}Co source produced by a photonuclear technique can be reached by cooling the target or using the nickel enriched in the ^{58}Ni isotope. In the last case, after the source exhaustion as a result of the ^{57}Co decay, it can be repeatedly activated without loss of the material typical for its reduction by chemical methods.

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ПОЛУЧЕНИЕ ПЛАНАРНЫХ МУЛЬТИФОТОННЫХ ГАММА-ИСТОЧНИКОВ ФОТОЯДЕРНЫМ МЕТОДОМ: 2. ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ

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Методом гамма-спектрометрического анализа исследованы характеристики двух- и трехфотонных источников, полученных путём комбинации неактивных фольг из индия, тантала, вольфрама и свинца с планарными γ-источниками на основе изотопов ^{57}Co и ^{179}Ta. Последние произведены путём активации фольг из никеля и тантала в поле тормозного излучения ускорителя электронов. Показана возможность регулирования числа, энергии и интенсивности спектральных полос источников с помощью выбора материала, толщины, порядка расположения и количества их компонентов. Результаты измерения интенсивности полос излучения исследованных источников удовлетворительно согласуются с расчётными данными на основе разработанной аналитической модели.

ОДЕРЖАННЯ ПЛАНАРНИХ МУЛЬТИФОТОННИХ ГАММА-ДЖЕРЕЛ ФОТОЯДЕРНИМ МЕТОДОМ: 2. ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ

М.П. Дикий, Ю.В. Ляшко, В.Л. Уваров

Методом гамма-спектрометричного аналізу досліджено характеристики двох- та трьохфотонних джерел, що одержані шляхом комбінації неактивних фольг з індію, танталу, вольфраму та свинцю з планарними γ-джерелами на основі ізотопів ^{57}Co та ^{179}Ta. Останні вироблені шляхом активації фольг з нікелю та танталу в полі гальмівного випромінювання прискорювача електронів. Показана можливість регулювання числа, енергії та інтенсивності спектральних смуг джерел за допомогою вибору матеріалу, товщини, порядку розміщення і кількості їх компонентів. Результати вимірювання інтенсивності смуг випромінювання досліджуваних джерел задовільно узгоджуються з даними розрахунків на основі розробленої аналітичної моделі.