THE RESEARCH OF X-RAY AND GAMMA RADIATION ABSORPTION BY LAYERED STRUCTURES

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It is investigated the passage of X-ray and gamma radiation through assembly consisting of layers of materials with different atomic numbers. It was experimentally measured and calculated in GEANT the spectra of radiation, passed through the assembly. Various spectra of the incident radiation (in experiments, the radiation sources ^{241}Am, ^{57}Co, ^{137}Cs, ^{60}Co), as well as combinations of materials with different atomic numbers and thicknesses were used. Coefficients of K_S and K_E that characterize the passage of particles through heterogeneous layers were defined. K_S and K_E change sign with increasing of photon energy and growth with increase of the plates thickness.

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INTRODUCTION

Search of the materials that provide effective protection against ionizing radiation remains a topical area of radiation physics [1 - 5]. Protection of nuclear power plants, reactors and tanks for spent nuclear fuel, neutron sources, electron accelerators – traditional use of biological protection [2, 4]. In nuclear medicine the protection is necessary when working with highly active radioisotopes as at the stage of pharmaceuticals preparation, as in the process of medical procedures conducting [6]. Typically, this problem is solved by "force method" – by increasing of the protective layer thickness to a value that provides an acceptable dose to personnel. However, effective protection of electronics, instruments and detectors is particularly relevant in the space industry, where criterion of weight minimizing and size protection is important.

In most practical tasks the radiation protection of nuclear facilities is a heterogeneous mixture of different environments. Also multilayer protective systems are applied in engineering of screening devices for various types of detectors, for example, their collimating systems.

The calculation of such protection by analytical methods is quite difficult because the buildup factors of heterogeneous environments depend on a large number of parameters of the task: energy of gamma radiation, thickness, material, quantity and geometry of the layers and their relative position. In works [3 - 5] the main regularities of buildup factors formation were described and a number of formulas for mathematical calculation were proposed. It is shown that the efficiency of protection against gamma radiation by a heterogeneous assembly is better in case when the light material facing to the source. However, obviously, these formulas cannot take into account the variety of practical problems of building and calculation of multilayer defenses. In such cases it is necessary to use computer simulation methods. Now for the computer simulation of radiation passage through heterogeneous media, various computer codes are widely used. In particular GEANT 3 and GEANT 4 [9] offer an adequate and comprehensive simulation of all physical processes of ionizing radiation interaction with the material, taking into account the geometry and elemental composition of protection.

The purpose of this work is the numerical description and experimental measurement of the spectral and dosimeter characteristics of the radiation passed through pairwise interchanged layers of materials with different nuclear charges *Z*, and thickness. The values of coefficients determining the noncommutativeness of the quanta passing through the heterogeneous layers were measured and calculated.

We refused to test the repeated two-layer periodic structures, as in [7, 8] it is shown that the effect of commutativity decreases, and the overall weakening tends to value in a homogeneous medium with averaged *Z*. Conversely, in the experiments and calculations we have focused on increasing of the materials thicknesses.

1. EXPERIMENTAL TECHNIQUE AND COMPUTER MODEL

There were used designed and manufactured in NSC KIPT sealed modules of two types: non-cooled silicon PIN detector and the detection system scintillator CsI(Tl) – silicon PIN photodiode [10, 11]. These modules and readout electronics showed high stability when used in nuclear physics experiments, in control device of element concentrations in medical diagnostic devices [12], spectrometry and dosimetry [13].

The energy range of incident γ-rays was 10 keV…1.33 MeV (the radiation sources ^{241}Am, ^{57}Co, ^{137}Cs, ^{60}Co). Radiation with energy of 5…150 keV for Si detector and 35…1500 keV for the system scintillator-photodiode was registered.

Between the radiation source and the detector two plates of different materials were placed, the spectra of the passed radiation while changing the order of plates were measured.

The attenuation of gamma radiation when passing through protection, consisting of alternating materials layers, depends ceteris paribus on the gamma radiation energy E_γ and the materials protection thicknesses.

Using the software package GEANT 3.21, it was simulated the assembly, consisting of a point source of γ-quanta, of light and heavy metal plates and the total absorption detector. The scheme of experiments is shown on Fig. 1.

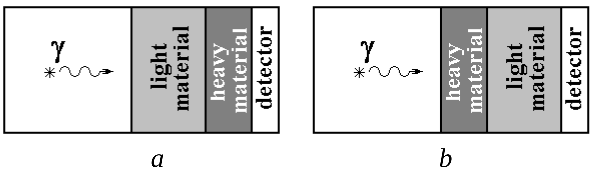


Fig. 1. Schema of computer model

The quanta from source, passing a heterogeneous target, enter the detector, which records the number of particles and their total remaining energy. It was simulated as a discrete photon energies as an energy spectra. The assembly was located in the air. The detector was close to the last plate.

On Fig. 2 it is shown a visual representation in GEANT 4 [7] of the trajectories of X-rays and gamma quanta (green line) for the system Al-Pb (a) and Pb-Al (b). The layers of material are changed places, and radiation that passes into the forward hemisphere is detected.

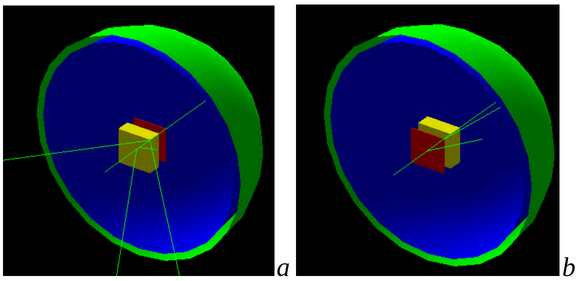


Fig. 2. Visual representation in GEANT 4 of the trajectories of X-rays and γ-quanta (green line) for the system Al-Pb (a) and Pb-Al (b). The layers of material are changed places, and radiation that passes into the forward hemisphere is detected (blue sphere-counter). Green sphere-counter registers electrons

The aim of computer simulation was to determine the radiation protection efficiency in case of the sequence of materials location: light to source and heavy to source.

2. RESULTS AND DISCUSSION

Hereinafter, the material on the left (written in text as a part of the pair), is faced to the radiation source, both in calculations and in experiments. For example, writing 1.2 mm Fe-0.3 mm Pb means the arrangement of objects in the following way: radiation source – first foil 1.2 mm Fe – second foil 0.3 mm Pb – Si or CsI detector (in experiment) or counter quanta (in calculations).

Let, S_{LH} is a count of quanta $N\gamma$ recorded by the detector, and E_{LH}, MeV – total energy $N_\gamma(E_\gamma)\cdot E_\gamma$, in case of location "Source → light material (L) → heavy material (H) → detector" and S_{HL}, E_{HL} – in case of location "Source → heavy material (H) → light material (L) →detector". In the experiment and calculations the various sizes, possessing noncommutative feature, are compared. Let us introduce the coefficients of the differences in the passage K_S, K_E:

$$K_S = (S_{\mathrm{HL}} / S_{\mathrm{LH}} - 1)\cdot 100\%, \qquad (1)$$

$$K_E = (E_{\mathrm{HL}} / E_{\mathrm{LH}} - 1)\cdot 100\%. \qquad (2)$$

If the coefficients are greater than zero, then the protection efficiency light material – heavy material (LH) above. If less than zero, the protection efficiency of HL above.

2.1. COMPUTER SIMULATION RESULTS

Using the software package GEANT 3.21, computer simulation for studying the γ-radiation passage through a combination of tungsten and aluminum foils, in analogy to [7, 8], was carried out. The simulation results are shown on Fig. 3.

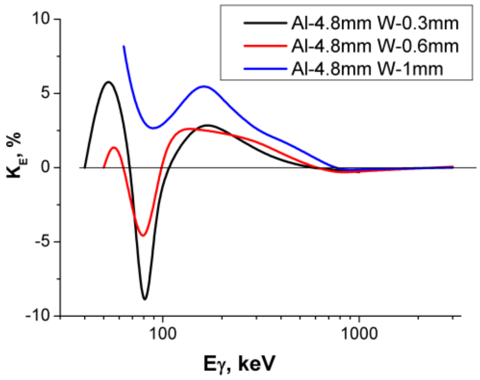


Fig. 3. The change of K_E depending on the thickness of tungsten and the energy of incident radiation

For thicknesses of Al-4.8 mm and W-0.3 mm in the energy range of incident radiation from 50 to 400 keV (with exception of 70…100 keV) $K_S > 0$ and $K_E > 0$ for 1…6%, that shows a better protection in case of materials location of light to source.

At the energy range 70…100 keV the opposite effect (noncommutativeness changes sign) is occur. It is connected with generation of characteristic X-ray (CXR) in tungsten. K-absorption edge for tungsten is 69.524 keV. By increasing the thickness of tungsten up to 0.6 mm, the influence of CXR on the commutatively value decreases, and while increasing up to 1 mm, the influence of CXR disappears.

Also with the help of the software package GEANT 3.21 the passage of γ-radiation through a combination of lead and aluminum foils was studied. The scheme of experiment is shown on Fig. 1, where the light material is taken as aluminum, and heavy as lead.

The results of computer simulation for different materials thicknesses and energies of incident radiation are presented on Fig. 4,a,b.

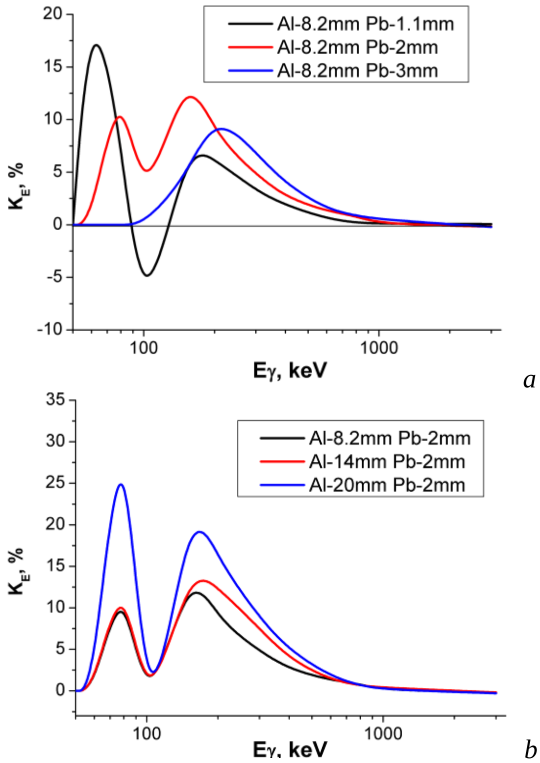


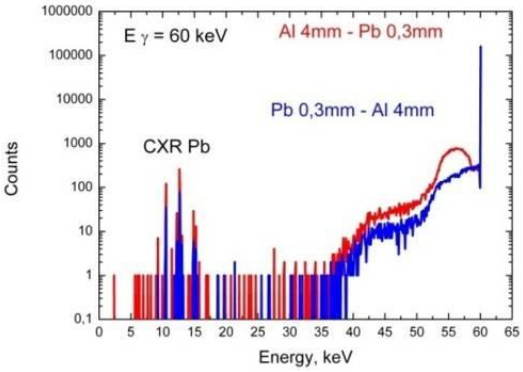
Fig. 4. The change of K_E depending on lead and aluminum thicknesses and energy of the incident radiation

For these calculations the effect of commutativeness sign changing by generating of lead CXR (K absorption edge 88.006 keV) is also occurred.

The presented data of computer simulation of gamma radiation passage through heterogeneous protection system show that multi-layer protection is more efficient in case when the light material facing to the source, as theoretically predicted. The effect can reach 5…25% depending on the energy of incident radiation and combinations of thicknesses of protective materials.

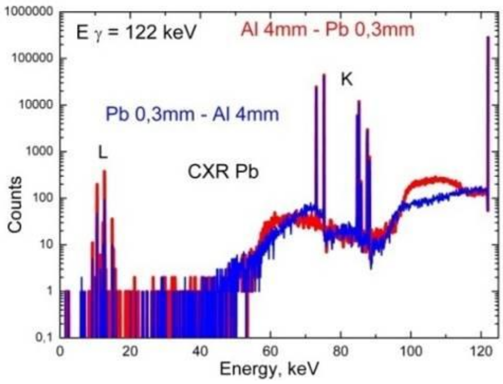
However, at energies of incident radiation close to the energy of K absorption edge for heavy material the opposite effect with a change of commutativity sign can be occurred, and it is more significant for thin plates.

Typical results of calculations in GEANT 4 are presented on Fig. 5,a-c.



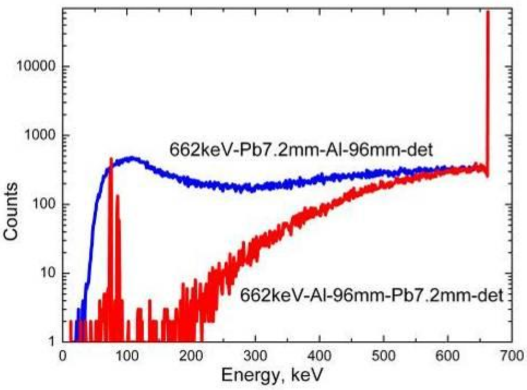
a

E_γ = 60 keV



b

E_γ = 122 keV



c

E_γ = 662 keV

Fig. 5. The calculated energy distributions of quanta, depending on the energy of incident radiation for a pair of Pb-Al

Some numerical values K_S and K_E are given in Table 1. Note the change of noncommutativeness sign and its growth with increasing of the plates thickness at a fixed value of the quanta energy.

Table 1

The numerical values K_S and K_E, %

E_γ, keV	Plates combination, mm	K_S, %	K_E, %
60	Pb 0.3-Al 4	-12.8	-11.83
122	Pb 0.3-Fe 3	-13.71	-7.9
122	Pb 0.6-Fe 6	-22.6	-16.6
122	Pb 0.9-Fe 9	-34.8	-23.22
122	Pb 0.3-Al 4	-5.9	-5.15
490	Pb 0.3-Al 4	0.43	3.07
662	Al 4-Pb 0.3	0.2	0.1
662	Al 8-Pb 0.6	0.9	0.4
662	Al 24-Pb 1.8	6.4	3
662	Al 48-Pb 3.6	13.5	6.81
662	Al 96-Pb 7.2	77.1	32.1
662	Al 120-Pb 9	101.5	43
662	Al 172-Pb 13	156.3	67.14
2 000	Al 4-Pb 0.3	0.18	0.04
2 000	Al 96-Pb 7.2	8.48	1.67
2 000	Al 116-Pb-8.6	26.83	5.14
2 000	Al 126-Pb 9.4	28.76	5.92
2 000	Al 140-Pb 10.4	29.36	5.83
2 000	Al 160-Pb 11.9	30.61	6.42
3 000	Pb 7.2-Al 96	6.2	0.
3 000	Al 160-Pb 11.9	19.49	1.55
5 000	Al 96-Pb 7.2	3.9	-0.8
5 000	Al 160-Pb 11.9	11.08	-1.3
100 000	Al 160-Pb 11.9	1.54	-1.27
100 000	Al 200-Pb 20	6.1	1.1
200 000	Al 200-Pb 20	0.47	9.3

In Table 2 the calculations for K_S, and K_E and E_γ = 662 keV are given, and the quanta percentage N_{662}/N_0 passed a couple of plates without interaction is presented. The thickness of the lead plate is constant, and the thickness of Al is increased.

There is an increase of noncommutativeness effect with increasing of Al thickness, which correlates with the decrease of N_{662}/N_0. Accordingly, a greater proportion of quanta dissipated, that causes the increase of noncommutativeness.

Table 2

The numerical values of K_S, K_E, N_{662}/N_0

Plates combination, mm	K_S, %	K_E, %	N_{662}/N_0
Pb 12-Al 6	4.6	2.5	0.216
Pb 12-Al 12	10.46	5.84	0.192
Pb 12-Al 24	21.87	11.1	0.15
Pb 12-Al 48	47.64	23.06	0.092
Pb 12-Al 96	96.05	44.6	0.035
Pb 12-Al 120	112.6	49.1	0.022
Pb 12-Al 160	141.2	59.3	0.01

The calculations of gamma-rays passage through the layers of materials were carried out and K_S and K_E for the quanta spectrum of $\sim 1/E_\gamma$ were counted. On Figs. 6, 7 the calculated spectra of the incident quanta and quanta passed through a couple of plates are shown.

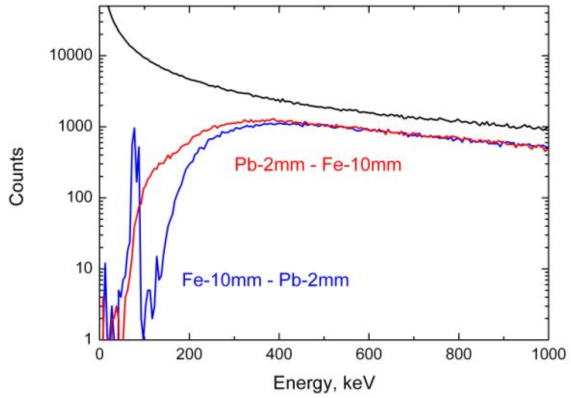


Fig. 6. Calculated energy distributions of passed gamma-ray for pairs Pb-Fe, and the spectrum of incident quanta ~1/E_γ (0…1 MeV)

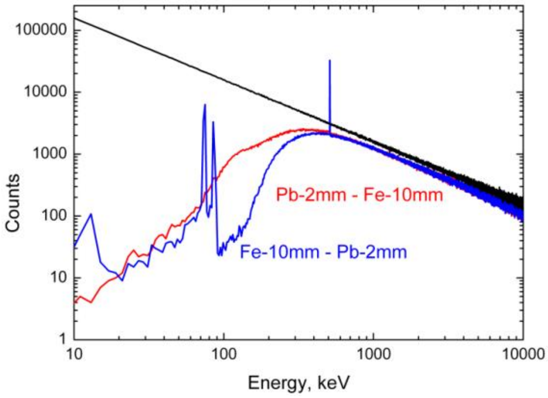


Fig. 7. Calculated energy distributions of passed gamma-ray for pairs Pb-Fe, and the spectrum of incident quanta ~1/E_γ (0…10 MeV)

The numerical values of K_S, K_E for gamma-quanta spectrum ~1/E_γ are shown in Table 3.

Table 3

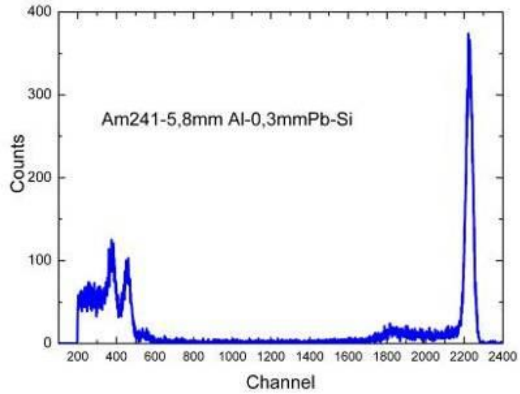
The numerical values of K_S, K_E for the quanta spectrum ~1/E_γ

Plates combination, mm	K_S, %	K_E, %	~1/E_γ, MeV
Pb 2-Fe 10	11.4	5.86	0…1
Pb 2-Fe 10	6.32	0.95	0…5
Pb 2-Fe 10	5.5	0.25	0…10
Pb 10-Fe 40	8.6	3.6	0…100
Pb 20-Fe 80	10.76	3.0	0…100
Pb 30-Fe 100	5.56	7.52	0…100

2.2. EXPERIMENTAL RESULTS

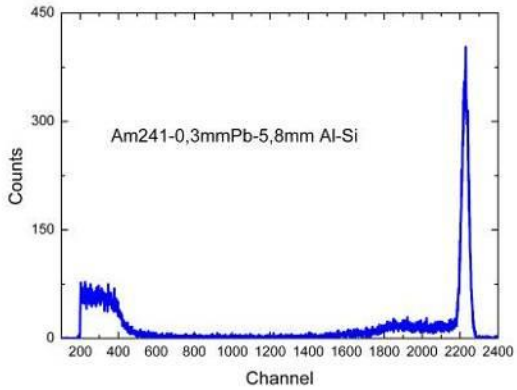
Radiation sources ^{241}Am, ^{57}Co, ^{137}Cs, ^{60}Co were used, the energy range for gamma-rays was 0.06…1.33 MeV. Experimental spectra of radiation passed through a plate pair were measured and K_S value was evaluated.

Note that within the experiment precision the peaks of total absorption in the calculations and in the experiment are equal. On Fig. 8 it is shown the experimental energy spectra of quanta for the radiation source ^{241}Am and a pair Pb-Al, measured by Si-detector. In the left part of the spectrum in case of location pairs Al-Pb by solid material to the detector appears L triplet of Pb CXR (see Fig. 8,a). In this experiment it is significantly influence the lead CXR on the K_S value. Moreover, the K_S value changes sign.



a

Al 5.8 mm - Pb 0.3 mm



b

Pb 0.3 mm - Al 5.8 mm

Fig. 8. Experimental energy distributions of quanta for radiation source ^{241}Am and the pair Pb-Al measured by Si-detector

On Fig. 9 it is shown the experimental energy spectra of quanta for the radiation source ^{241}Am and a pair Pb-Fe, measured by the CsI-detector.

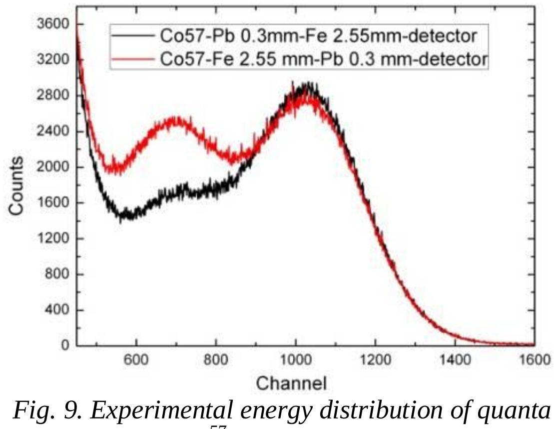
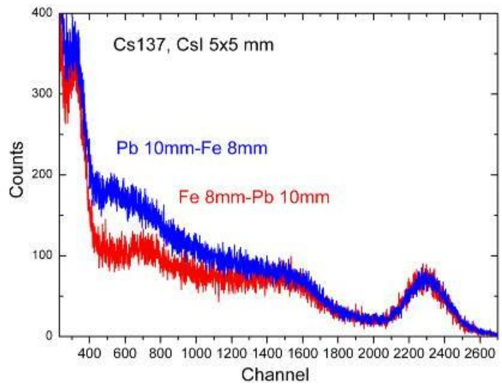


Fig. 9. Experimental energy distribution of quanta for radiation source ^{57}Co and the pair Pb-Fe measured by CsI-detector

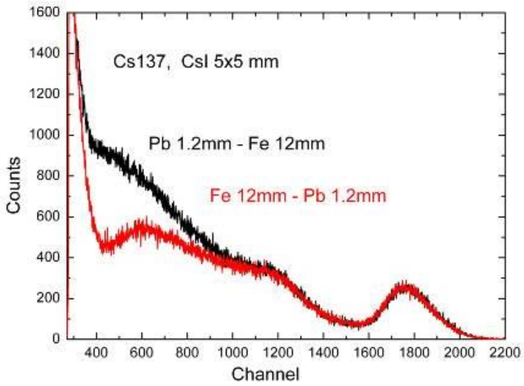
For pair Pb 0.3 mm and Fe 2.55 mm and the energy E_γ =122 keV we have $K_S = (S_{HL}/S_{LH} -1)\cdot 100\% = -10.5\%$. In this experiment it is significantly influence of lead CXR on K_S value, and there is a difference – additional peak in the left part of the spectrum (channels 600…800).

On Fig. 10 it is shown the experimental energy spectra of quanta for the radiation source ^{137}Cs and a pair Pb-Fe, measured by CsI detector. In these experiments, Compton scattering of quanta on K_S value is essentially, and there is a distinction on the left part of the spectra.



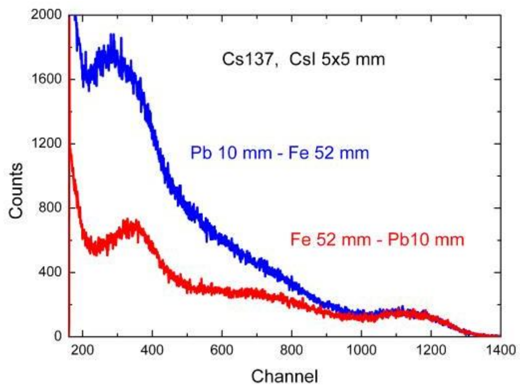
a

Pb 10 mm - Fe 8 mm



b

Pb 1.2 mm - Fe 12 mm

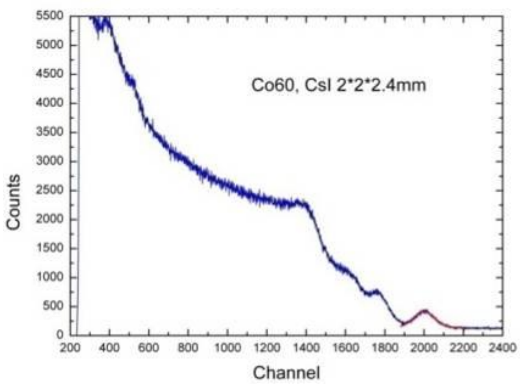


c

Pb 10 mm - Fe 52 mm

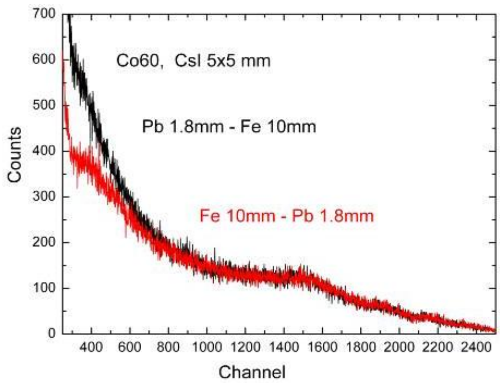
Fig. 10. Experimental energy distribution of quanta for radiation source ^{137}Cs and pairs Pb-Fe, measured by CsI-detector

On Fig. 11 it is shown the experimental energy spectra of quanta for radiation source ^{60}Co and a pair of Pb-Fe, measured by the CsI-detector. The experimental results are shown in Table 4.



a

Without plates



b

Pb 1.8 mm - Fe 10 mm

Fig. 11. Experimental energy distribution of quanta for radiation source ^{60}Co and the pair of Pb-Fe, measured by the CsI-detector

Table 4

Experimental values K_S

Radiation source	Plates combination, mm	K_S,%
^{241}Am	1 Cu - 0.3 Pb	-0.5
^{241}Am	1.2 Fe - 0.3 Pb	-6.28
^{241}Am	2 Fe - 0.3 Pb	-9.5
^{241}Am	4 Al - 0.3 Pb	-3.8
^{241}Am	5.8 Al - 0.3 Pb	-7.3
Co57	0.3 Pb - Fe 2.55	-10.5
^{137}Cs	0.3 Pb - 1 Cu	0.7
^{137}Cs	1.2 Pb - 12 Fe	25.4
^{137}Cs	10 Pb - 8 Fe	29.9
^{137}Cs	10 Pb - 52 Fe	113.7
^{137}Cs	40 Pb - 52 Fe	49.8
^{60}Co	1.8 Pb - Fe 10	20.0

As experiment showed a sign of noncommutativeness is changed with increasing of photon energy and the plate thickness. This coincides with the data of calculations in GEANT 4 and GEANT 3.

CONCLUSIONS

The passage of X-ray and gamma radiation through assembly consisting of layers of materials with different atomic numbers was investigated. It was experimentally measured and calculated in GEANT the spectra of radiation, passed through the assembly. The various spectra of incident radiation (in experiments, the radiation sources ^{241}Am, ^{57}Co, ^{137}Cs, ^{60}Co), as well as combinations of materials with different atomic numbers and thicknesses were used.

Coefficients K_S and K_E that characterize the passage of particles through heterogeneous layers were defined. K_S and K_E change sign with increasing of photon energy and growth with increase of the plates thickness.

The physical causes of the observed commutatively were determined. It occurs only via secondary processes: Compton scattering, photoelectric effect, electron-positron pairs production. Thus, the effect size growthes with the thickness increas.

The data of computer simulation of the gamma radiation passage through heterogeneous protection system show that multi-layer protection, usually effective in case of arrangement of a light material to the radiation source.

At the incident X-ray radiation energies close to the energy of K-, L-absorption edge for heavy material the noncommutativeness sign is negative and the inverse effect is observed, so in such situation more effective protection is in case of a heavy material location to the radiation source. This effect is most significant for thin foils (~1 mm).

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ИССЛЕДОВАНИЕ ПОГЛОЩЕНИЯ РЕНТГЕНОВСКОГО И ГАММА-ИЗЛУЧЕНИЙ СЛОИСТЫМИ СТРУКТУРАМИ

А.С. Деев, А.А. Мазилов, А.В. Мазилов, Н.И. Маслов, М.Ю. Шулика

Исследуется прохождение рентгеновского и гамма-излучений через сборки, состоящие из слоёв материалов с различными атомными номерами. Экспериментально измерены и рассчитаны в GEANT спектры излучения, прошедшего через сборку. Использовались различные спектры падающего излучения (в экспериментах источники излучения ^{241}Am, ^{57}Co, ^{137}Cs, ^{60}Co), а также комбинации материалов с различными атомными номерами и толщинами. Определены коэффициенты K_S и K_E, характеризующие прохождение частиц через гетерогенные слои. K_S и K_E меняют знак с увеличением энергии квантов и растут с увеличением толщины пластин.

ДОСЛІДЖЕННЯ ПОГЛИНАННЯ РЕНТГЕНІВСЬКОГО І ГАММА-ВИПРОМІНЮВАНЬ ШАРУВАТИМИ СТРУКТУРАМИ

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Досліджується проходження рентгенівського і гамма-випромінювань через зборки, що складаються із шарів матеріалів з різними атомними номерами. Експериментально виміряні і розраховані в GEANT спектри випромінювання, що пройшло через зборку. Використовувалися різні спектри падаючого випромінювання (в експериментах джерела випромінювання ^{241}Am, ^{57}Co, ^{137}Cs, ^{60}Co), а також комбінації матеріалів з різними атомними номерами й товщинами. Визначено коефіцієнти K_S і K_E, що характеризують проходження часток через гетерогенні шари. K_S і K_E міняють знак зі збільшенням енергії квантів і ростуть зі збільшенням товщини пластин.