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Laminated material for gamma radiation shielding

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The efficiency of a radiation shielding structure consisting of a set of alternating layers of light and heavy metals is shown to be enhanced when the layered structure is turned to a radiation source by the light metal layer. The protection efficiency is maximal at the single-period structure scheme (one light metal layer and one heavy one). The validity of the predicted regularities is confirmed by experimental results obtained using W and Al as the layered structure materials. Dependence of radiation absorption efficiency on orientation of layers relative to the source was observed also for thin three-layer W–Mo–Ti structure.

Показано, что эффективность защиты, состоящей из набора чередующихся слоев легкого и тяжелого металлов, выше в случае, когда слоистая структура обращена к источнику излучения слоем легкого металла. Эффективность защиты максимальна при однопериодной схеме структуры (один слой легкого металла и один — тяжелого). Справедливость предсказанных закономерностей подтверждена результатами экспериментов с использованием W и Al в качестве материалов слоистой структуры. Зависимость эффективности поглощения излучения от ориентации слоев относительно источника наблюдалась также для тонкой трехслойной структуры W–Mo–Ti.

Traditionally, homogeneous materials on the base of elements with high atomic numbers (heavy metals, steels, concrete, etc.) are used to make radiation-shielding structures. However, the size thereof (including weight, cost, and other important characteristics) as determined by provision criteria of designed attenuation level of primary fluxes γ-radiation limit the practical use possibility such structures. This functional limitation of protecting structures made of traditional homogeneous materials may be surmounted by insertion of heterogeneous materials into their composition. The use of multiple scattering and backscattering of photons on boundaries of different structure-phase components of heterogeneous material is supposed.

In this connection, of interest is the manufacturing of spatial structures containing separate restricted volumes of two or more homogeneous substances, where the reflecting characteristics of one substance are higher while the absorbing characteristics are lower than those of another substance. Joining of substances with low atomic number (highly reflecting) and with high atomic number (highly absorbing) in one heterogeneous structure provides the conditions for multiple reflection of photons from interface of these substances and return of the photons into the volumes filled with highly absorbing substance not leaving the boundaries of the structure as a whole. Such structure has higher protecting characteristics in comparison with homogeneous substances being its constituents. The scattering mechanisms at atomic level inherent in homogeneous substances are complemented in heterogeneous materials by macrostructural mechanisms. As an example of such structure, the heterogeneous structure of layered type, where each pair of the neighbouring layers consists of different homogeneous materials, reflecting and absorbing, could be considered.

Analytical description of such a structure [1] testifies that its total transmission coefficient will be minimum when minimal transmission coefficients for absorbing components are in combination with maximal reflection coefficients for reflecting components. This agrees with the known criterion for optimal material selection for multilayer structures according to maximal difference in reflection coefficients of neighboring layers [2]. This work is aimed at analytical and experimental study of γ-radiation absorption by laminar heterostructures.

The attenuation law of irradiation intensity (dose, dose rate or flux density) by homogeneous protection in a narrow beam geometry for single-directed source may be described as

$$S = S_0 \cdot e^{-\mu d}, \quad (1)$$

where S_0 and S are the measurable values of irradiation intensity without and with shielding, respectively; d, the shield thickness; μ, the linear attenuation coefficient. When solving the problems of shielding, one has to consider a broad beam where both the primary, non-scattered, and multiply scattered photons should be taken into account.

Photons multiply scattered into the medium are taken into account by introduction of accumulation factor B [3] into the law of irradiation attenuation in narrow beam geometry, this factor characterizes the ratio of detector reading in broad beam geometry to that in narrow beam one. Attenuation of γ radiation on passing through the shield composed of m layers of protecting materials occurs according to the law:

$$S = S_0 \cdot \exp\left(\sum_{i=1}^{m} b_i\right) \cdot B(E_\gamma, b_i), \quad (2)$$

where $b_i \equiv \mu_i \cdot d_i$ is a dimensionless quantity characterizing the i-th component of the shield with the thickness d_i; μ_i, linear coefficient of radiation attenuation in the i-th shield material determined by the total interaction cross-section of γ radiation with atom of the protecting material; B, accumulation factor depending, other conditions being the same, on γ radiation energy E_γ and the protecting material thickness b_i.

For multilayer shield, the accumulation factor depends on the arrangement of protecting layers, namely [3–6]:

$$B = \sum_{n=1}^{m} B_n\left(\sum_{i=1}^{n} b_i\right) - \sum_{n=2}^{m} B_n\left(\sum_{i=1}^{n-1} b_i\right) \quad , \quad (3)$$

where the layers are numbered starting from the source side. So, $n = 1$ refers to first layer from the source, $n = m$, for the last; $B_n\left(\sum_{n}^{m} b_i\right)$ is the accumulation factor in homogeneous medium for material of n-th layer at a thickness equal to the total thickness of all layers up to n, or the total thickness up to $(n-1)$-th layer.

It is important to emphasize what follows. The summation in (3) is made starting from $n = 1$, that is from the first protecting layer faced to the source and further in order of increasing layer numbers. That is, the accumulation factor of a multilayer shield depends on the arrangement order of layers. So, the degree of equality (3) completion may be used as a measure of the protection efficiency.

Let a case be considered when the shield consists of two materials only (for example, W and Al) with corresponding accumulation factors B_{W} and B_{Al}. Let C to be a constant thickness of shield; b, the total thickness of one of materials (e.g., tungsten). Then the total thickness of other material is equal $C - b$ (Fig. 1). Write N for number of periods or number of layer pairs in the shield and consider the accumulation factors for two shield modifications, namely, (i) the heavy material (B^*_N) and (ii) the light material (B_{*N}) layer faced to the source.

It follows from (2) that

$$S^*_N = S_0 \cdot e^{-c} \cdot B^*_N = KB^*_N; \quad (4)$$
$$S_{*N} = S_0 \cdot e^{-c} \cdot B_{*N} = KB_{*N};$$
$$S^*_N - S_{*N} = K(B^*_N - B_{*N}),$$

where K is a constant independant of number of periods N. So, knowing the dependence of accumulation factor B_N on the number of periods N, we can judge the efficiency degree of a multilayer shield.

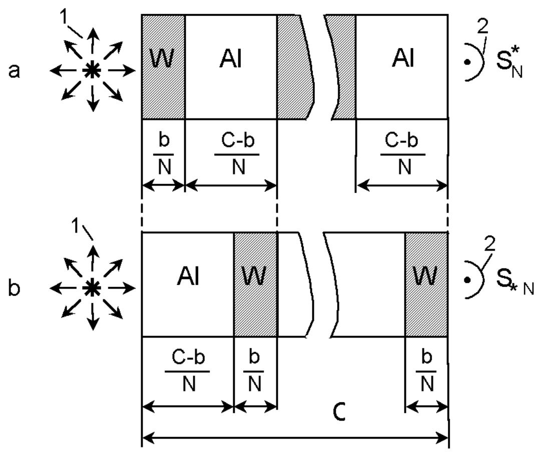

Fig. 1. Scheme of experiment with N-periodic shield: *1*, of gamma-radiation source; *2*, detector recording the radiation intensity S_N.

Applying (3) for $N \geq 2$, we get

$$B^*_N = B_{\mathrm{Al}}(C) - f\left(\frac{b}{N}\right) + \sum_{n=1}^{N-1}\left[f\left(\frac{nC}{N}\right) - f\left(\frac{nC+b}{N}\right)\right], \quad (5.1)$$

$$B_{*N} = B_{\mathrm{W}}(C) + f(C - \frac{nC}{N}) - \sum_{n=1}^{N-1}\left[f\left(\frac{nC}{N}\right) - f\left(\frac{nC-b}{N}\right)\right], \quad (5.2)$$

$$B^*_N - B_{*N} = f(C) - f\left(\frac{b}{N}\right) - f(C - \frac{b}{N}) + \sum_{n+1}^{N-1}\left[2f\left(\frac{nC}{N}\right) - f\left(\frac{nC+b}{N}\right) - f\left(\frac{nC-b}{N}\right)\right]. \quad (5.3)$$

Here the introduced function $f(x) = B_{\mathrm{Al}}(x) - B_{\mathrm{W}}(x) > 0$, where x is the material thickness, has the obvious properties:

$f(x) \to 0$ at $x \to 0$, because $B_{\mathrm{Al}}(x) \to 1$ and $B_{\mathrm{W}}(x) \to 1$ at $x \to 0$ and $f(x + a) > f$ at $a > 0$ (see, for instance, values of accumulation factors in [5]).

In the particular case at $N = 1$ (bilayered modification), we have:

$$B^*_I = B_{\mathrm{Al}}(C) - f(b), \quad (5.4)$$

$$B_{*I} = B_{\mathrm{W}}(C) + f(C - b), \quad (5.5)$$

$$B^*_I - B_{*I} = f(C) - f(b) - f(C - b). \quad (5.6)$$

Consideration of functions 5.1–5.6 shows that at any values of total thickness b of heavy material, that is, within the limits $0 < b < C$, the following relationships are satisfied:

(i) $B^*_{N+1} < B^*_N$, that is, in the case when the heavy material of the shield is faced to the radiation source, the accumulation factor B^* and thus the measured value S^* at the outer shield side decreases with the increasing number of layers:

$$S^*_{N+1} < S^*_N \;\; or \;\; K^*_{N+1} > K^*_N. \quad (6.1)$$

Here $K_N = S_0/S_N$ is ratio of γ radiation attenuation in the shielding material.

(ii) $B_{*N+1} > B_{*N}$, that is, in the case when the light material of the shield is faced to the radiation source, the accumulation factor B^* and thus the measured value S^* increase with the increasing number of layers:

$$S^*_{N+1} > S_{*N} \;\; or \;\; K_{*N+1} < K_{*N} \quad (6.2)$$

(iii) $B^*_N > B_{*N}$, that is, in the case when the heavy material of the shield is faced to the radiation source, the accumulation factor and thus the measured value S^* is always higher than when the light material is faced to the source:

$$S^*_N > S_{*N} \;\; or \;\; K^*_N < K_{*N}. \quad (6.3)$$

Thus, for any number of layers the shielding efficiency is higher when the light material is faced to the radiation source. (As it is shown in [4], for multiperiod shield cosisting of two or more different materials, the accumulation factor does not exceed the maximum and is not lower than the minimum accumulation factor values of homogeneous materials, taken over the total thickness of multiperiodic shield in the free path lengths).

$$B^*_N - B_{*N} > B^*_{N+1} - B_{*N+1} \to 0 \;\; at \;\; N \to \infty$$

$$S^*_N - S_{*N} > S^*_{N+1} - S_{*N+1} \to 0 \; at \;\; N \to \infty. \quad (6.4)$$

Inequalities in (6.4) follow from (2) and (3) and the limit equal to zero means the transition to the homogeneous mixture of heavy and light materials.

It is important to note what follows. In [4, 5] the formula (3) is stated to be applicable for energies from 1 to 10 MeV. Restriction of the top energy limit is explained by the fact that at $E_\gamma > 10$ MeV, the formation of pairs is definitive interaction kind of gamma radiation with sub-

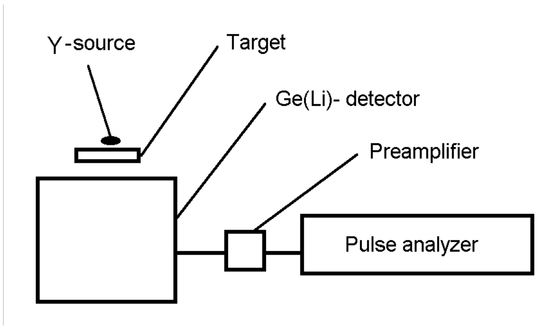

Fig. 2. Diagram of experimental setup.

stances (gamma quanta interact not with electrons of atoms of protecting material, but with Coulomb field of their nuclei). At energies $E_\gamma < 1$ MeV, the cross-section of photoelectric interaction having the resonance character contributes to the cross-section of gamma radiation interaction with the target atoms together with cross-section of Compton scattering having the smooth character of the dependence on E_γ. Therefore, for energies, lying between resonances of photoelectric interaction, the ratio (3) will be also valid.

To check the relationships (6.1–6.4), the experiment was performed with examination of a shield composed of two materials (W and Al) and combined in six modifications: single-periodic (one W layer and one Al layer), two-, three-, four, six- and twelve-periodic. The total thickness of each material and, consequently, the total shield thickness was constant (0.3 mm thick W and 4.8 mm thick Al). A fragment of spent nuclear fuel (SNF) was used as the radiation source with minimum registerable γ-quanta energy of 7 keV. The measurements was carried out using a SEG-50P spectrometer with DRG5-2 detector in open geometry (the beam was not collimated). Energy interval from 10 to 840 keV was studied. The experiment scheme is shown in Fig. 2.

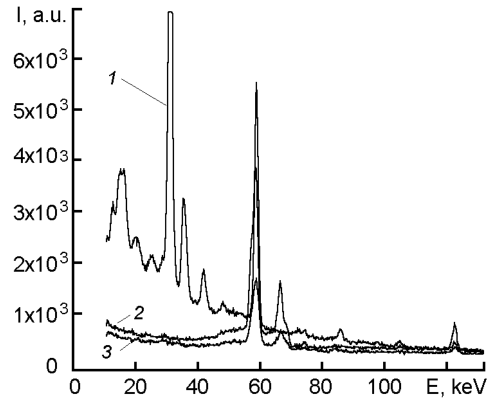

Fig. 3. Low energy (to 130 keV) part of measured spectra: *1*, spectrum without target, *2*, spectrum after passing through two-layered (W + Al) foil target faced to the source by tungsten layer; *3* — the same with aluminum faced to the source.

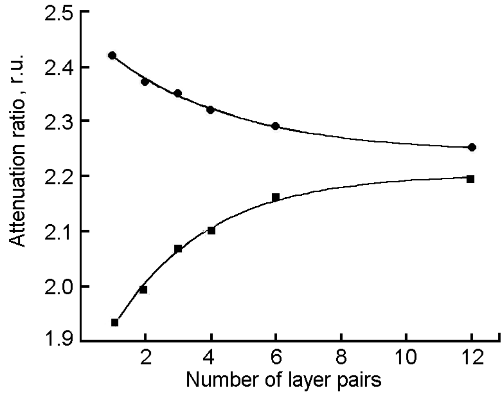

Fig. 4. Dependences of radiation attenuation ratio on number of layer pairs with aluminum (upper curve) and tungsten (lower curve) faced to the source.

Fig. 3 shows the low-energy (10–130 keV) part of measured spectra: spectrum without target (*1*), spectrum after passing through a target composed of one W layer and one Al layer with tungsten faced to the source (*2*) and the same with aluminum faced to the source (*3*). In this Figure, the effect described above is more pronounced. Fig. 4 shows the dependence of attenuation ratio (in relative units) of photon radiation on the number of layer pairs (number of periods) with aluminum (upper curve) and tungsten (lower curve) faced to the source. It can be seen that the effect of attenuation is more pronounced with aluminum faced to the source.

Similar measurements were carried out with a three-layered W–Mo–Ti composition. The samples were prepared by subsequent deposition of molybdenum and titanium layers (100 μm thick each) on 100 μm thick tungsten foil using the vacuum-arc method [7]. The spectra typical of such a structure are shown in Fig. 5. It is seen that even for such thin targets, a rather clear difference in spectra obtained at two different orientations of target is observed against the background of insignificant absorption.

Consideration of results obtained shows that absorbing properties of multiperiod target in the range of photon energies from 50 to 350 keV is obviously higher when

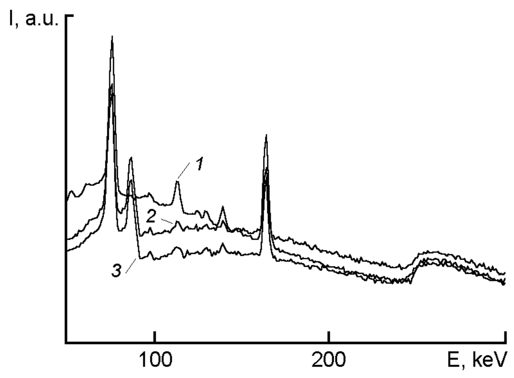

Fig. 5. Low energy (50–350 keV) part of measured apparatus spectra for three-layered (Ti–Mo–W) target. *1*, spectrum without target; *2*, spectrum after passing through the target faced to the source by tungsten layer; *3* — the same with titanium faced to the source.

lighter metal is faced to the source than at inverse orientation of layers with respect to the radiation source. This effect is less pronounced at higher energies within the investigated range. The maximum deviation of protective properties from those typical of homogeneous mixture of materials is observed in the case of one-period target (in experiment, the bilayer target).

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Шаруватий матеріал для захисту від гамма-випромінювання

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Показано, що ефективність захисту, що складається з набору переміжних шарів легкого та важкого металів, є вищою у випадку, коли шарувата структура обернена до джерела випромінювання шаром легкого металу. Ефективність захисту є максимальною при одноперіодній схемі структури (один шар легкого металу та один важкого). Справедливість прогнозованих закономірностей підтверджено результатами експериментів з застосуванням W та Al як матеріалів шаруватої структури. Залежність ефективності поглинання випромінювання від орієнтації шарів відносно джерела спостерігалася також для тонкої тришарової структури W–Mo–Ti.