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Transport of Neutrons and γ Quanta through a Highly Filled Polymer Composite

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Abstract—The transport of neutrons and γ quanta of various energies through a polymer composite based on tungsten-filled track membranes is studied. Expressions describing the attenuation coefficients of γ quanta and neutrons in the developed polymer composite are obtained. The change in the intensity of beams of γ quanta and neutrons when passing through a periodic layered structure consisting of polymer composite layers with tungsten and pure tungsten depending on the number of layers is investigated.

Keywords: neutron transport, polymer composite, radiation protection, γ quanta, track membranes

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INTRODUCTION

The widespread use of ionizing radiation in industry, medicine, and scientific research leaves unsolved the urgent problem of protecting personnel working at various enterprises that use radiation technologies. This problem leads to the need to develop new shields for radiation protection. Selection of the composition of the radiation shield depends on many factors, such as energy, duration, and type of ionizing radiation. For example, in order to protect against X-rays and γ-rays, shields filled with materials with a high atomic number and high density (lead, bismuth, tungsten, etc.) are used [1–3]. Cadmium and boron-containing shields are used against slow (thermal) neutrons [4, 5]. For protection from radiation in space (electrons and protons), it is promising to use polymer composites, especially based on polyimide [6–8].

Recently, the development of radiation shields based on polymers has become relevant. The addition of various fillers makes it possible to obtain polymer composites with given functional properties, including high radiation-protection characteristics [9, 10]. There are various methods that allow the filler to be evenly distributed in the polymer matrix [11]. Polymer materials based on polyimide are widely used in modern spacecraft (SC). The combination of high strength characteristics retained even after exposure to space radiation, high and low temperatures, and ultraviolet (UV) irradiation makes it possible to consider polyimide as a promising material for creating elements of space equipment with improved energy-mass characteristics [12, 13]. Polyimides are used to create various thermal control coatings, elements of screen-vacuum thermal insulation, sun-protection devices, etc. [14].

Previously, the authors developed a method for the synthesis of polymer composites based on polymer track (nuclear) membranes, which are filled with nanofillers, in which agglomeration of the filler is completely eliminated [15]. Track (nuclear) membranes are thin polymer films with many through nanoholes (tracks) [16].

It should be noted that polyimide itself is a good shielding material against neutrons of a wide energy spectrum, but on the other hand it barely protects against γ radiation. In this article, we investigate whether neutrons and γ radiation pass through a tungsten-filled polymer composite developed on the basis of track membranes. Polyimide track (nuclear) membranes are used as the track membranes.

ATTENUATION COEFFICIENTS OF γ QUANTA AND NEUTRONS IN A POLYMER TRACK MEMBRANE

A polymer composite based on track membranes filled with tungsten was developed (Table 1). Polyimide track (nuclear) membranes with a thickness of 25 μm and with a pore diameter of about 200 nm were used as track membranes. The total porosity of the membrane was 70%. A 0.06-μm-thick tungsten metal was sputtered onto one side of the membrane. The pores of the track membrane were filled with tungsten, and the composite density was 13.9 g/cm^3.

Table 1. Elemental chemical composition of the polyimide track membrane filled with metallic tungsten

Atomic composition, wt %				
C	N	O	H	W
2.10	0.24	0.67	0.09	96.9

Let us study the γ-radiation transmission through the developed composite. We will take into account that γ radiation attenuates due to the photoeffect, the Compton effect, and the effect of electron-positron pair formation. For the calculations, we used well-known formulas describing the cross sections of these processes in a homogeneous material [17].

The expression describing the cross sections of the photoeffect process on an atom has the following form:

$$\sigma_f = 4\pi r_e^2\alpha^4 Z^5 G_f(E), \tag{1}$$

$$G_f(E) = \frac{(2+\varepsilon)^{3/2}}{\varepsilon^{7/2}}\left(\frac{4}{3} + (1+\varepsilon)\frac{\varepsilon-1}{\varepsilon+2}\right.$$
$$\left.\times\left(1 - \frac{1}{2(\varepsilon+1)\sqrt{\varepsilon(2+\varepsilon)}}\ln\left(\frac{1+\varepsilon+\sqrt{\varepsilon(2+\varepsilon)}}{1+\varepsilon-\sqrt{\varepsilon(2+\varepsilon)}}\right)\right)\right), \tag{2}$$

where $\varepsilon = E/m_e c^2$, E is the energy of γ quanta, $m_e c^2 = 0.511$ MeV is the electron rest energy, $r_e = e^2/m_e c^2 = 2.8\times10^{-13}$ cm is the classical electron radius, and $\alpha = 1/137$ is the fine structure constant. The attenuation coefficient of γ quanta for homogeneous matter with the density ρ due to the photoeffect is determined by the following expression: $\mu_f = \sigma_f N_A \frac{\rho}{A}$, where $N_A = 6\times10^{23}\,\frac{1}{\text{mole}}$ is Avogadro's number, and A is the atomic mass.

Since the composite material under study consists of atoms of several elements, the formula for the attenuation coefficient of the γ-quantum flux due to the photoeffect is as follows:

$$\mu_f = 4\pi r_e^2\alpha^4 N_A\left(\rho_C\frac{Z_C^5}{A_C} + \rho_N\frac{Z_N^5}{A_N}\right.$$
$$\left. + \rho_O\frac{Z_O^5}{A_O} + \rho_H\frac{Z_H^5}{A_H} + \rho_W\frac{Z_W^5}{A_W}\right)G_f(E). \tag{3}$$

The expression describing the cross sections of the process of Compton scattering at an electron is as follows:

$$\sigma_C = 2\pi r_e^2\left[\frac{1+\varepsilon}{\varepsilon^2}\left(\frac{2(1+\varepsilon)}{1+2\varepsilon} - \frac{\ln(1+2\varepsilon)}{\varepsilon}\right)\right.$$
$$\left. + \frac{\ln(1+2\varepsilon)}{2\varepsilon} - \frac{1+3\varepsilon}{(1+2\varepsilon)^2}\right]. \tag{4}$$

The attenuation coefficient of the γ-quantum flux due to the Compton effect passing through the investigated composite material:

$$\mu_C = N_A\left(\rho_C\frac{Z_C}{A_C} + \rho_N\frac{Z_N}{A_N} + \rho_O\frac{Z_O}{A_O}\right.$$
$$\left. + \rho_H\frac{Z_H}{A_H} + \rho_W\frac{Z_W}{A_W}\right)\sigma_C. \tag{5}$$

In order to estimate the contribution of the electron-positron pair formation process at energies of γ quanta in the region of their energies, $2m_e c^2 < E < 137 m_e c^2 Z^{-1/3}$, formula (4) was used:

$$\sigma_P = r_e^2\alpha Z(Z+1)\left[\frac{28}{9}\ln(2\varepsilon) - \frac{218}{27}\right]. \tag{6}$$

The attenuation coefficient of the γ-quantum flux due to the formation of electron-positron pairs for the composite material was obtained:

$$\mu_P = r_e^2\alpha N_A\left(\rho_C\frac{Z_C(Z_C+1)}{A_C} + \rho_N\frac{Z_N(Z_N+1)}{A_N}\right.$$
$$+ \rho_O\frac{Z_O(Z_O+1)}{A_O}$$
$$\left. + \rho_H\frac{Z_H(Z_H+1)}{A_H} + \rho_W\frac{Z_W(Z_W+1)}{A_W}\right)$$
$$\times\left[\frac{28}{9}\ln(2\varepsilon) - \frac{218}{27}\right]. \tag{7}$$

The total attenuation coefficient of γ-quanta in the studied materials consists of the sum of attenuation coefficients from each process: $\mu = \mu_f + \mu_C + \mu_P$.

Using expressions (3), (5), and (7), which describe the attenuation coefficients of the γ-quantum beam due to the photoeffect, the Compton effect, and the effect of electron-positron pair formation, numerical calculations for the developed polymer composite were performed in this work. Calculations are shown for the most interesting values of γ-quantum energies from the point of view of radiation protection in space $0.5\text{ MeV} \le E \le 5\text{ MeV}$. Figure 1 presents curves showing the dependence of the total attenuation coefficient $\mu = \mu_f + \mu_C + \mu_P$ on the energy of γ quanta passing through the polymer composite as well as curves describing the contribution of different attenuation coefficients. Figure 2 shows the curves describing the total attenuation coefficients of γ quanta in the polymer composite and tungsten W as a function of energy, from which it follows that the difference between them decreases as the γ-quantum energy increases.

Let us investigate the attenuation of γ-quantum intensity when passing through a periodic layered structure consisting of N-layers in the tungsten polymer composite. The expression describing the intensity of γ-quantum beams which passed N layers is

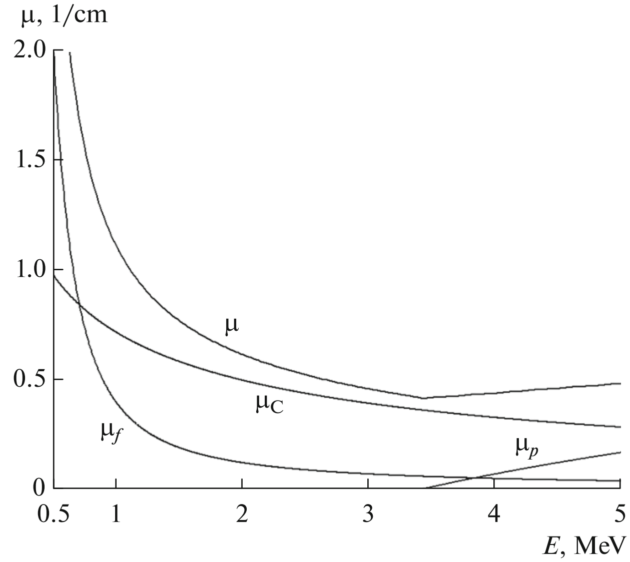

Fig. 1. Contribution of different attenuation coefficients of γ quanta in a polymer composite based on a track membrane to the total attenuation coefficient μ.

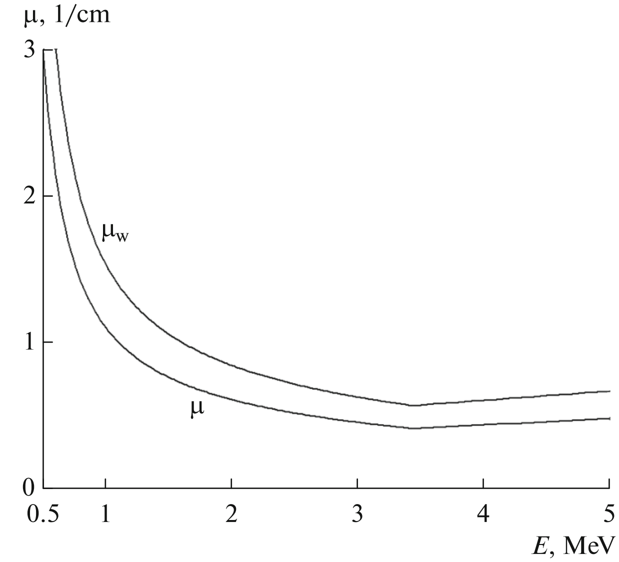

Fig. 2. Comparison of the γ-quantum attenuation coefficient in the polymer composite and in pure tungsten W.

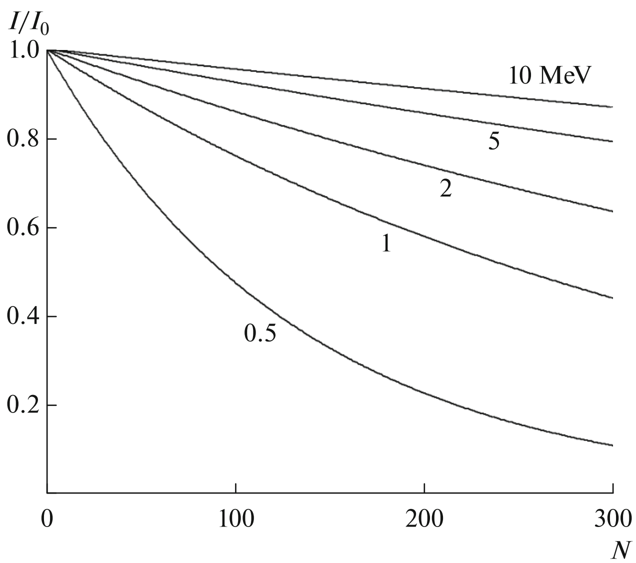

Fig. 3. Attenuation of the γ-quantum beam intensity as a function of the number of layers: tungsten polymer composite.

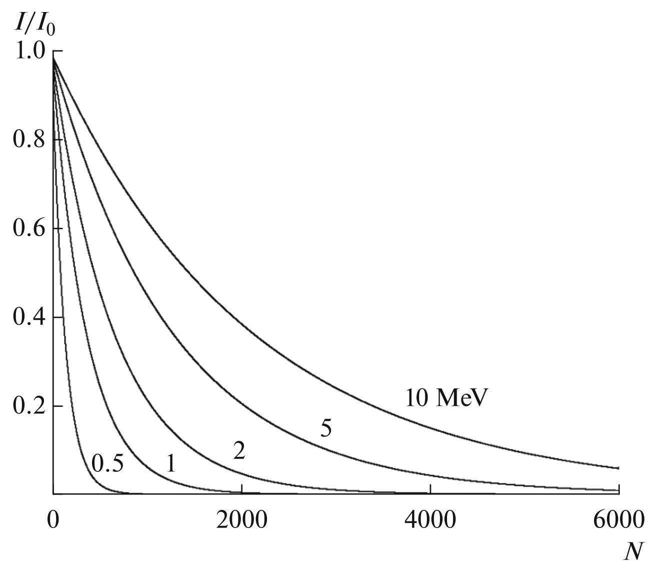

Fig. 4. Same as Fig. 3, but for a larger number of layers: tungsten polymer composite.

defined by the equation: $I = I_0 e^{-N(\mu L + \mu_W L_W)}$, where $L = 25$ μm is the thickness of the polymer composite, $L_W = 25$ μm is the thickness of the tungsten, and μ_W is the attenuation coefficient of γ quanta in tungsten. I_0 is the initial intensity of the γ-quantum beam. Figure 3 shows the curves describing the relative change in the intensity of the γ-quantum beam as a function of the number of layers N for different γ-quantum energies. It follows from the figure that for $N \sim 300$ the intensity of the γ-quantum beam with the energy of 0.5 MeV attenuates by about 90%. Figure 4 shows the curves similar to Fig. 3, but for a larger number of N layers. From Fig. 4, it follows that 90% attenuation of the γ-quantum intensity at an energy of 5 MeV will be for the number of layers $N \sim 3000$ and at 10 MeV, for $N \sim 5000$.

Let us consider the process of neutrons passing through the developed polymer composite. An expres-

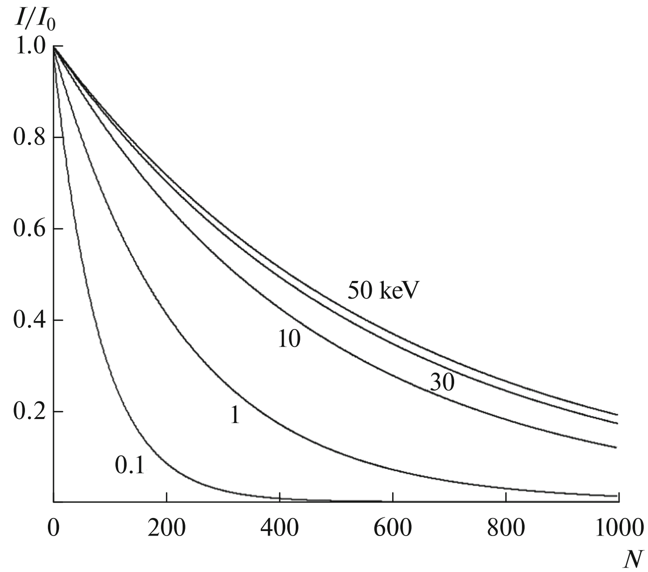

Fig. 5. Attenuation of the neutron-beam intensity as a function of the number of layers: tungsten polymer composite.

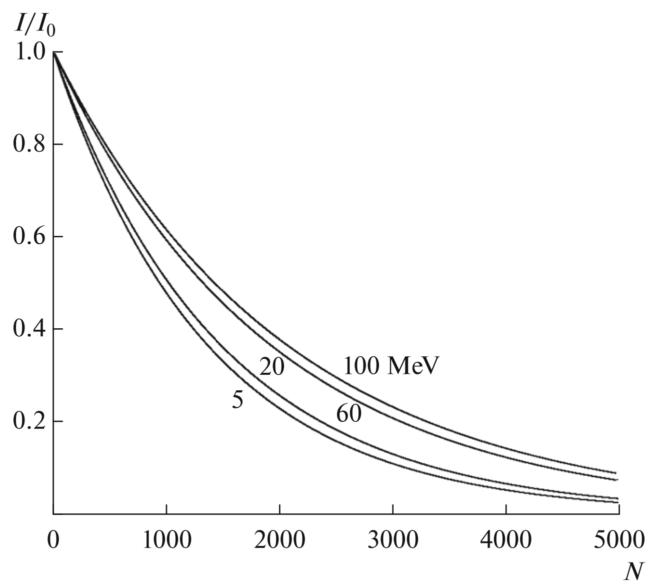

Fig. 6. Same as Fig. 4, but for a higher neutron energy.

sion describing the neutron-beam attenuation coefficient in the composite material under consideration was obtained:

$$\mu_n = N_A \times \left(\rho_C \frac{\sigma_C}{A_C} + \rho_N \frac{\sigma_N}{A_N} + \rho_O \frac{\sigma_O}{A_O} + \rho_H \frac{\sigma_H}{A_H} + \rho_W \frac{\sigma_W}{A_W}\right), \quad (8)$$

where σ_C, σ_N, σ_O, σ_H, σ_W are the total cross sections of the interaction of neutrons with atoms of the corresponding materials; for calculations, their numerical values for a specific neutron energy were taken from the corresponding tables. The expression describing the intensity of neutron beams which passed N layers of the tungsten polymer composite is defined by the following expression: $I = I_0 e^{-N(\mu_n L + \mu_{nW} L_W)}$, where μ_{nW} is the neutron attenuation coefficient in pure tungsten. Figure 5 shows the curves describing the relative change in the neutron-beam intensity as a function of the number of layers N for neutrons of low energies 0.1–50 keV. It follows from Fig. 5 that for $N \sim 1000$ the intensity of the neutron beam with an energy of 50 keV attenuates by about 80%. Figure 6 shows curves similar to Fig. 5 but for a larger number of layers N. It follows from Fig. 6 that the attenuation of the neutron intensity by 90% for the neutron energy 100 MeV will be for $N \sim 5000$.

Therefore, for $N \sim 5000$, the designed layered structure will protect biological objects by 90% from neutrons at 100 MeV and γ quanta at 10 MeV. It should be noted that for lower energies of γ quanta and neutrons protection will be greater.

CONCLUSIONS

A theoretical study of the transport of neutrons and γ quanta of various energies through the developed polymer composite based on track membranes filled with tungsten was carried out. Expressions describing the attenuation coefficients of γ quanta and neutrons in the developed polymer composite were obtained. The change in the intensity of beams of γ quanta and neutrons when passing through a periodic layered structure, i.e., tungsten polymer composite, depending on the number of layers, was investigated. The efficiency of the developed layered structure (tungsten polymer composite) is shown even for the number of layers $N \sim 5000$ for the radiation protection of biological objects from fast neutrons (up to 100 MeV) and γ quanta (up to 10 MeV) in outer space.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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