Anisotropy of the Absorption of the Photon Ionizing Radiation by $YAlO_3$: Mn Dosimetric Detector

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Abstract—**The dependence of the absorption of photon radiation on the spatial orientation of the $YAlO_3$:Mn cube-shape dosimetric detector is investigated. It is shown that at high enough values of the edges length and/or the attenuation coefficient the relative difference of the doses absorbed at different spatial orientations can reach the value about 0.73. Taking into account the energy dependence of the attenuation coefficient of $YAlO_3$:Mn, it is shown that the measurement error not higher than 5% can be ensured in the photon energy range above 0.4 MeV for the sensitive element of dimensions between 1 and 10 mm.**

Index Terms—**radiation dosimetry; angular dependence, gamma radiation; phosphors; yttrium-aluminium perovskite**

I. Introduction

As it is known, the thermo- (TL) and optically stimulated luminescence (OSL) methods of passive dosimetry allow to determine the integral dose of ionizing radiation absorbed during certain time interval [1, 2]. The different solid-state materials, particularly, oxides, fluorides, sulfates, borates are used for construction of such detectors. Their sensitive element usually has got the form of the plate, so, if the radiation has got the predominant direction of propagation, the energy absorbed by the detector depends on the spatial orientation of the detector plate relative to radiation flow direction. This peculiarity causes the additional dose measurement error known as an angular or directional dependence of dose value [3-5] which, in general, depends on the irradiation source properties (shape, dimensions, energy etc.) as well as detector (shape, dimensions and attenuation coefficient of the material). This error rises with increasing of absorption ability, i.e. with increasing of effective atomic number Z of detector's compound. The possibility of usage of high Z detector for estimation of energy range of unknown radiation source [6,7] inspired us to explore a possible practical approach for compromise search between angular dependence of the radiation energy absorption resulting in dose assessment error and advantage of high Z dosimetric phosphor like $YAlO_3$:Mn which competitive properties were demonstrated both in TL and OSL dosimetry [8-11].

The obvious solution to avoid an angular dependence in absorbed dose measurement is to use a detector of spherical shape (such approach was used for example in [12]) but its fabrication in the case of routine passive dosimetry is much more complicate. Much simpler technologically is to make detector in the form of cube which in a certain approximation is closer to sphere than to plate. The objective of this paper consists in estimation of the possible values of the measurement error for different dimensions of the sensitive element of the cube-shaped detector in the wide range of the energy of photon radiation. All calculations of our paper were carried out for $YAlO_3$:Mn crystal phosphorus in the field of uniform photon flow.

II. The Method of Calculation

The following model is used for calculation of the absorbed dose at different orientations of the detector. The edge of the cube-shaped dosimetric detector is equal to $2a$ = 1…10 mm that covers the typical values of its linear dimensions. The source of the radiation (SR) is modeled as a flat rectangle (the radiation surface), each its point radiates photons along its normal. For calculation, this surface is divided into squares (elementary sources) with a side of $10^{-3}a$ that is enough to obtain high precision of the calculation. Each elementary source is characterized by the same value of the radiation intensity I_0. The directions of exposure of the detector are changed by rotation of the radiation surface (Fig. 1). Because all volume of the detector should be irradiated at all possible orientations of this surface, its linear dimensions were equal to the length of spatial diagonal of the cube that is equal to $2\sqrt{3}a$. At that the cube-shaped crystal is completely projected inside the radiation surface for all possible orientations.

Firstly the radiation surface lies in XY coordinate plane. If (x_e; y_e; 0) are the coordinates of the certain elementary source and the angles θ and ϕ determined the rotation of the SR (see Fig. 1), the coordinates of the elementary source (x_0; y_0; z_0) after rotation are given by:

$$\begin{aligned} x_0 &= x_e \cos\theta\cos\varphi - y_e \sin\varphi, \\ y_0 &= x_e \cos\theta\sin\varphi + y_e \cos\varphi, \\ z_0 &= -x_e \sin\theta. \end{aligned} \quad (1)$$

The radiation propagates along the normal of the radiation surface $\vec{p} = (p_1; p_2; p_3) = (\sin\theta\cos\varphi; \sin\theta\sin\varphi; \cos\theta)$ or, in other words, along the straight line described by the canonic equation

$$\frac{x - x_0}{p_1} = \frac{y - y_0}{p_2} = \frac{z - z_0}{p_3}. \quad (2)$$

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Two points of cross-section of this line with the faces of the cube are determined by sequential substitution of x, y, z in (2) by the values of $x = \pm a$, $y = \pm a$, $z = \pm a$ under the condition $|x| \le a$, $|y| \le a$, $|z| \le a$. If (x_1; y_1; z_1) and (x_2; y_2; z_2) are the coordinates of the points of the cross-section, the path of the ionized radiation in the sensitive element is equal to $L = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$ and the absorbed intensity of the radiation is $I = I_0 - I_0 \exp(-\mu L) = I_0(1 - \exp(-\mu L))$, where μ is the attenuation coefficient of $YAlO_3$:Mn crystal.

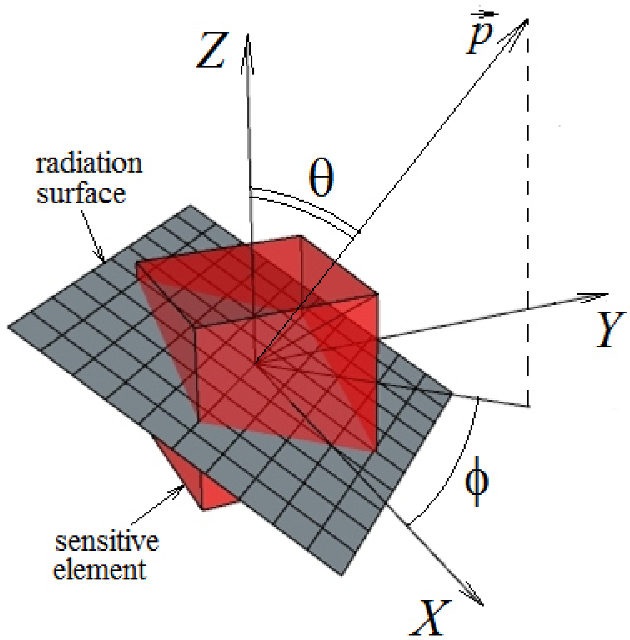

Figure 1. The sensitive element of the detector and the radiation surface.

The dose absorbed in the sensitive element during the time t can be calculated by summarizing of the contributions of all elementary sources:

$$D = \frac{E_{abs}}{m} = \frac{t}{m}\sum_{i=1}^{N} I_i = \frac{I_0 t S}{m}\sum_{i=1}^{N} \delta_i \left(1 - \exp(-\mu L_i)\right), \quad (3)$$

where E_{abs} is the absorbed energy, m is the mass of the sensitive element, S is the area of the elementary source, δ_i is equal to 1 if the radiation from the i^{th} elementary source falls on the sensitive element, otherwise δ_i is equal to 0.

The anisotropy of the spatial distribution of the absorption was characterized by the absorption anisotropy coefficient, i.e. by the relative difference of the maximal D_{max} and minimal D_{min} doses obtained at different spatial orientations of the radiation surface:

$$\eta = \frac{D_{max} - D_{min}}{D_{min}}. \quad (4)$$

The value of the attenuation coefficient μ depends on the energy of photons. Such a dependence for the case of $YAlO_3$:Mn crystal of dimensions 3×3×1 mm^3 was determined [6] by Monte-Carlo simulation in the range of 0.001 … 20 MeV (Fig. 2). It should be noted that the presented dependence accounts for scattered radiation build up and is true specifically for the considered geometry (detector size and incidence angle). For other detector sizes and orientations in the radiation field contribution of the scattered radiation will differ, so the straightforward application of the above dependence can be treated as a sort of simplified approximation. Even further simplification may be based, yet undesired, on the utilization of the narrow beam linear attenuation coefficient [13], which accounts only non-scattered radiation (kerma approximation).

III. Results and Discussion

The typical 3D dependencies of the absorbed dose (in arbitrary units) on the direction of radiation propagation are shown in Fig. 3 for the sensitive element with the linear dimension of $2a$ = 10 mm. These dependencies are constructed by lying off the segments with the length equal to the absorbed dose in the directions of the radiation propagation.

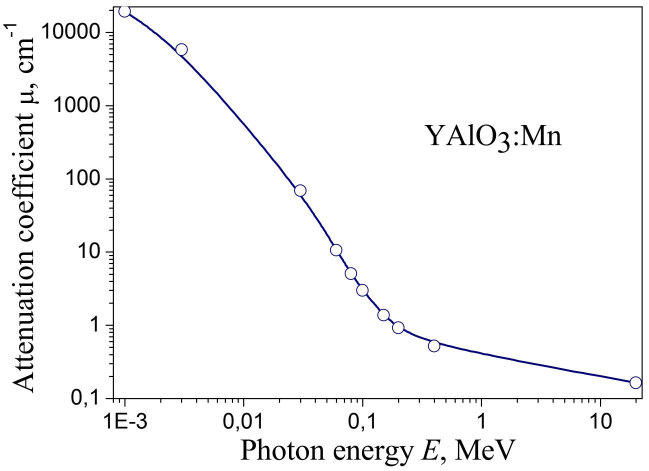

Figure 2. The dependence of the linear attenuation coefficient of $YAlO_3$:Mn on the energy of photons: points represent calculation results and curve is B-spline fitting [9].

It should be noted that the forms of the these dependencies at the values of attenuation coefficients higher than 10 cm^{-1} are visually the same to the one shown in Fig. 3,*f*.

As it is seen from Fig. 3, at high enough energies and, correspondingly, low attenuation coefficients the absorption is practically isotropic, whereas at lower energies the anisotropy of absorption becomes essential. Such a peculiarity is directly followed from (3). Indeed, at low values of the attenuation coefficient $\exp(-\mu L_i) \approx 1 - \mu L_i$ and (3) comes to

$$D = \frac{E_{abs}}{m} = \frac{t}{m}\sum_{i=1}^{N} \delta_i I_i = \frac{I_0 t \mu S}{m}\sum_{i=1}^{N} \delta_i L_i . \quad (5)$$

If the number of the elementary sources tends to infinity, the value $S\sum_{i=1}^{N} \delta_i L_i$ tends to the crystal volume V, the absorbed dose $D = \frac{I_0 t \mu V}{m}$ do not depend on the orientation of the sensitive element and the relative difference η is equal to zero.

On the other hand, at high enough attenuation coefficient $\exp(-\mu L_i) \approx 0$ and

$$D = \frac{I_0 tS}{m}\sum_{i=1}^{N}\delta_i = \frac{I_0 tS}{m} n_{el}\,, \qquad (6)$$

where n_{el} is the number of the elementary sources which radiation falls on the surface of the sensitive element. This value is obviously proportional to the area of the sensitive element projection of the surface of irradiation. The minimal value of this area is equal to the area of the cube face $4a^2$, and the maximal one – to the area of the projection obtained in the case when the radiation propagates along the space diagonal of the cube. In the last case the projection is the regular hexagon with the area of $4\sqrt{3}a^2$, so the corresponding value of the relative difference η is equal to $\sqrt{3}-1\approx 0.73$. For the intermediate values of the attenuation coefficient μ the relative difference is within the range of 0 … 0.73.

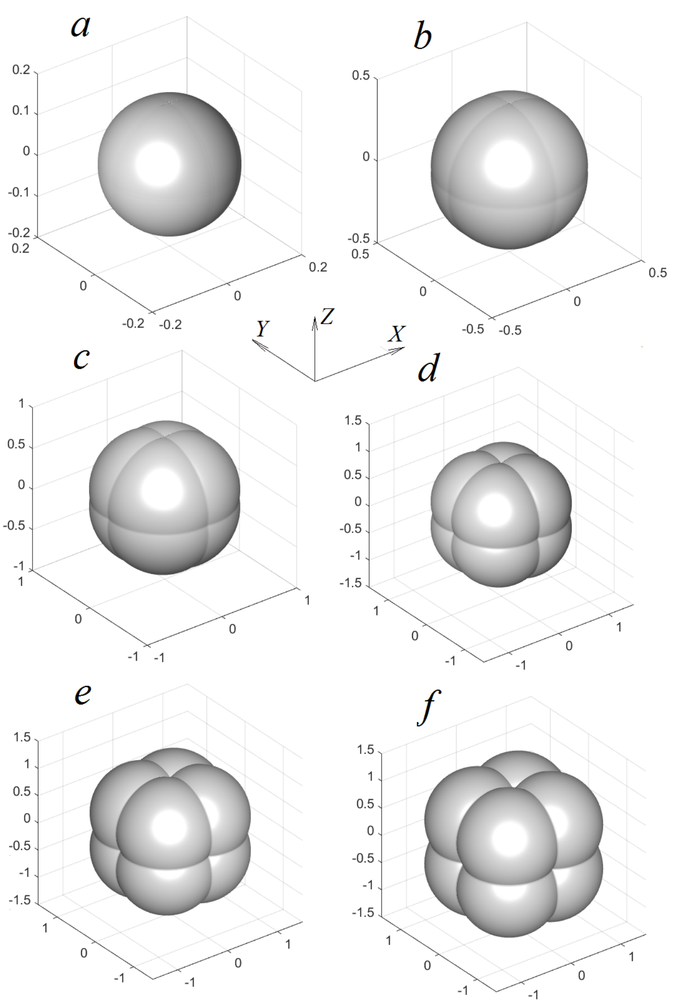

Figure 3. The dependencies of absorbed dose (arbitrary units) of γ radiation of the different energies; *a*: E = 20 MeV (μ = 0.16 cm^{-1}), *b*: E = 0.4 MeV (μ = 0.52 cm^{-1}), *c*: E = 0.15 MeV (μ = 1.38 cm^{-1}), *d*: E = 0.1 MeV (μ = 3.0 cm^{-1}), *e*: E = 0.08 MeV (μ = 5.1 cm^{-1}), *a*: E = 0.06 MeV (μ = 10.7 cm^{-1}).

The 3D dependencies of the absorbed dose obtained for other dimensions of the sensitive element are similar to the ones shown in Fig. 3, however, at the same value of the attenuation coefficient, the anisotropy of the absorption increase with increasing of the sensitive element sizes. It is seen from the dependencies of the relative difference η on the energy of the photon at the different values of the edge length 2*a* (Fig. 4). As it is also seen from this figure, the main changes of the relative difference η are observed in the energy range from 0.01 to 1 MeV, whereas outside this interval the relative difference of absorption is practically unchanged.

Increasing of the relative difference of absorbed doses η for the detectors of the larger dimensions is quite obvious from the fact that increasing of the sensitive element volume leads to increasing of the absorption, so it is equivalent to increasing of the attenuation coefficient.

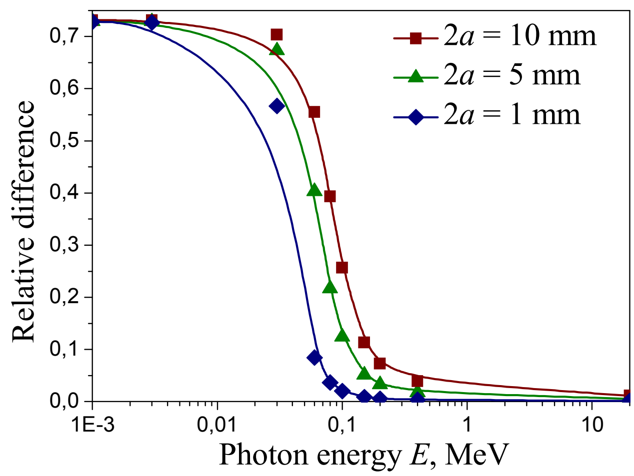

Figure 4. The dependence of the relative difference of absorbed doses on the energy of photons: points represent calculation results and curves are B-splines.

It is essential that the relative difference η becomes significant at the low energies of photons. Taking into account the energy dependence of the attenuation coefficient of $YAlO_3$:Mn, one can conclude that the measurement error not higher than 5% can be ensured at the photon energies of 0.4 MeV and higher if the sensitive element linear dimensions are about 1 … 10 mm. Further increasing of the precision of the measurements requires decreasing of the crystal size. However, this way of anisotropy decreasing is limited, because such decreasing simultaneously leads to decreasing of the absorbed dose that, in turn, increases the measurement error. Other possible variants of decreasing of the absorption anisotropy influence on the measurements error consist in using of the detectors of less anisotropic forms or the combined detectors that contain few crystals with different spatial orientations. Further refinement of the proposed approach should include Monte Carlo calculations for precise account of the build up effect of scattered photons.

IV. Conclusions

The dependencies of the absorbed dose of photon radiation on the spatial orientation of the $YAlO_3$:Mn cube-shape dosimetric detector is evaluated. Generally, the absorption of the ionizing radiation is the highest when it propagates along the spatial diagonals of the sensitive element, and the lowest if it propagates perpendicularly to its faces. The relative difference of the absorbed dose increases with increasing of the attenuation coefficient and/or the linear dimensions of the sensitive element. At high enough values of the edges length and/or the attenuation coefficient the relative difference η saturates on the value about 0.73. The measurement error not higher than 5% can be ensured if the photon energy is above 0.4 MeV for the detector's dimensions within 1…10 mm. Decreasing of the error at the lower photon energies requires further decreasing of detector dimensions.

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