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# Light collection simulation in the scintillation detectors of short-range radiation

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The light collection has been simulated in of the short-range radiation detectors based on CsI:Tl crystals. For detection of the X-ray and gamma-radiation in the energy range from 5.9 to 60 keV, it was found that the surface matting causes a decreased light collection coefficient. The decreased scatter of the light collection coefficients for the different surface parts was observed. The radial distributions practically coincide in this energy range both in case of polished and matted surfaces due to the same light collection conditions. This is due to an insignificant difference in the radiation penetration depth for various energies (3–300 μm). The use of the scintillation efficiency dependence on the scintillation depth coordinate in the simulation allowed to approach the simulation results to the experimental energy dependences of the specific light output. This made it possible also to study the reflector influence on the character of the energy dependence of the relative specific light output.

Проведено моделирование светособирания в детекторах короткопробежного излучения на основе кристаллов CsI:Tl. Для случаев регистрации рентгеновского и гамма-излучения в диапазоне энергий от 5.9 до 60 кэВ найдено, что матирование поверхности приводит к уменьшению коэффициента светособирания. При этом для разных участков поверхности наблюдалось уменьшение разброса коэффициентов светособирания. В этом диапазоне энергий радиальные распределения практически совпадают как в случае полированной, так и матированной поверхности из-за одинаковых условий светособирания, поскольку определяются небольшим различием глубины проникновения излучения разных энергий (3–300 мкм). Использование в моделировании зависимости сцинтилляционной эффективности от координаты места вспышки по глубине позволило приблизить результаты моделирования к экспериментальным зависимостям изменения удельного светового выхода от энергии. Также это дало возможность исследовать влияние отражателя на характер зависимости относительного удельного светового выхода от энергии.

## 1. Introduction

The light collection simulation is one of the main tools for the prediction of the characteristics of the scintillation detectors. Numerous programs which allow successfully simulate the light collection in the volume scintillators have been developed recently [1–6]. The simulation versions are known for the light collection simulation in the short-range radiation detectors being heterogeneous structures with significant light scattering. The light collection simulation in such systems is carried out as for homogeneous scintillator but specific scattering properties of the volume are taken into account [7, 8]. The simulation in heterogeneous columnar structure of the scintillation screens is performed under account for the X-ray radiation penetration depth and the presence of the interfaces in the medium [9]. The light collection in X-ray detectors with NaI:Tl and CsI:Na single crystals has been simulated depending on the detector design, the reflector types and scintillator surface treatment [10].

The known light collection simulation versions in the short-range radiation detectors do not take into account a number of well-known peculiarities that are observed in experiment. The short-range radiation detectors are thin (millimeters or several hundreds of micrometers); that is why the surface effects are of a great importance in the scintillator response generation. The changes of scintillation efficiency in the near-surface layers as compared to the values for bulk scintillator play a significant role in the scintillator response formation. The significance of the light collection in the formation of the short-range radiation detector response remains under discussion. A substantial role in the change of the specific light output as the radiation energy function is assigned to the light collection [11]. It is shown [12] that the the light collection coefficients must be calculated to understand the nature of the light output non-proportionality in the low energy range of 5.9–60 keV.

The goal of this study is to evaluate the light collection role in the change of specific light output as a function of the radiation energy for the short-range radiation detectors. CsI:Tl inorganic scintillation crystals were selected as objects for our investigations and simulations. These objects were the simplest among the alkali halide scintillators. Unlike CsI:Na or NaI:Tl scintillators, those are nonhygroscopic and provide simpler conditions for comparative analysis of the experimental and calculated data.

## 2. The scintillator model and simulation principles

The scintillation detector was simulated as an optical system consisting of a set of the shells (scintillator, output glass), each having a disk shape. The flat surfaces of the disks were in direct contact. Different parts of each shell surface possibly could be in contact with a medium having different characteristics (air, immersion) and reflectors (without any reflector, absorber, specular reflector, diffuse reflector). Optical characteristics of the materials and reflectors were taken into account as corresponding light absorption and refraction coefficients and those of reflectors, as reflection factors, respectively. Monte-Carlo simulations were used to build the light ray traces from the scintillation generation points. The points of the scintillation emission in the scintillator through the surface and depth were selected under account for the distance from the source and radiation penetrability, respectively. The light ray direction was defined by the isotropic random vector. This vector was simulated by the statistical sampling of the polar angle cosine and of the azimuth angle cosine and sine (using Neumann algorithm) followed by the transformation thereof into the direction cosines in the Cartesian rectangular coordinates [13]. The shell intersection points and the sequence thereof were determined using standard [14, 15] or modified algorithms. The exponential character of the light attenuation was taken into account during the statistical sampling of the light absorption in the optical medium. The reflection probability from the reflector surface was determined using the reflection coefficients for the specular or diffuse surface.

The reflection or refraction at the optical medium boundaries were taken into account after determination of the reflection coefficient at the boundary. The reflection coefficient and the angle of reflection (refraction) were calculated by the Fresnel formula. The refractive indices at the medium boundary and the incidence angle on the interfaces were taken into account during the calculations. The interface can be smooth or rough formed of the micro-facets [14–16]. It should be noted that the simulation programs describe the micro-facet orientation distributions using different approaches (the diffuse reflection model [2], the effective reflectivity model [3], striated model [4]). Generally, the micro-facet orientation distribution on the surface is specified by relative parameters (roughness [4], effective reflectivity [3], normal distribution with the specified dispersion [2]). The relative parameters reduce the prediction possibility of the scintillator characteristics basing of the performed simulation. Thus, it is not quite clear how to realize in the real scintillators the optimum micro-facet distributions obtained under the simulation.

The micro-facet distribution obtained in [17] proceeding from experimental study of the reflectance distribution functions of the surfaces treated by abrasives with various grain size has been used in this work. The application of this surface model allows to link the predicted characteristics with the particular conditions of the surface treatment. This result was confirmed experimentally for ∅30 mm×2 mm CsI:Tl reflector-free scintillators with different surface treatment (F600, F400, F320, F230 abrasives with average grain size of 14 μm, 21 μm, 33 μm and 56 μm, respectively). The whole sample volume was excited uniformly by 662 keV gamma-radiation from a $^{137}$Cs source to reduce the influence of the scintillation efficiency change of the surface layer for different treatment types.

In the simulation, the trajectory of each scintillation ray was tracked from the emission point to the exit from the detector output window or to the absorption in the detector volume or in the reflector. The light collection coefficient was obtained as a ratio of the number of the light rays passed through the detector output window to the number of the emitted rays from all scintillations. The specific light output was calculated as a ratio of the number of detected rays to the energy absorbed in the scintillator. The dependences of the light collection coefficients and the specific light output under different conditions of the light collection and scintillation excitation were studied. The simulation results were compared with the experimental results reported previously by co-authors of this work [12, 17].

## 3. The simulation results and discussion

The radial dependences of the light collection coefficient at the of the short-range X-ray and gamma-radiation detection in the energy range 5.9 to 60 keV have been studied. The local excitation of the surface parts with the 2 mm spot diameter was simulated for ∅30 mm×2 mm CsI:Tl scintillator. The depth exponential scintillation distributions with the linear absorption coefficients of 3043 cm$^{-1}$, 203 cm$^{-1}$, 100 cm$^{-1}$ and 36 cm$^{-1}$ for the photon energy of 5.9 keV, 17 keV, 22.4 keV and 59.6 keV, respectively, were taken into account in the simulation. The crystal surface layer is excited under the short-range radiation absorption. For comparison sake, simulation was performed for 662 keV $\gamma$ quanta, when the whole scintillator volume is excited. The simulation was carried out for the polished and ground radiation input surface of the scintillator. Other surfaces were polished. The face and lateral reflectors were absent. The distribution of the micro-facet normals for the ground surface corresponded to treatment by the F230 abrasive. The results are shown in Fig. 1.

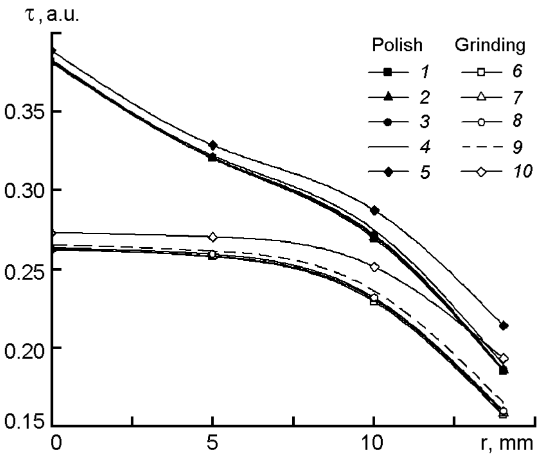

Fig. 1. Radial dependences of light collection coefficient (τ) for the 5.9 keV (*1*, *6* curves), 17 keV (*2*, *7*), 22.4 keV (*3*, *8*), 60 keV (*4*, *9*) and 662 keV (*5*, *10*) photons for ground and polished radiation input surface of a ∅30 mm×2 mm CsI:Tl scintillator.

The surface matting decreases the light collection coefficient τ, especially for the central part of the crystal and at the same time equalizes the radial dependence of τ for all energy values. The strongest equalizing of the light collection coefficient is obtained when detecting of the 662 keV $\gamma$ radiation. This radiation ensures the uniform scintillation distribution through the depth of the specified scintillator. At lower radiation energies, the radial distribution coincide practically both in case of polished and ground surface. This means that the light collection conditions remain the same in the 5.9 to 60 keV energy range due to insignificant change of the light collection coefficient while the radiation penetration depth changes from 3 to 300 μm.

The obtained results are confirmed by the more detailed simulation (using the emitted scintillation coordinates) of the axial and radial dependences (Fig. 2). The difference of these distributions from the previous ones is due to the depth and surface part integration of the light collection coefficients in the first simulation variant and the absence of such integration during point-by-point simulation. The weak radial dependence of the light collection coefficient for the 5.9 to 60 keV energy range allows to predict the absence of the energy dependence for both the light collection co-

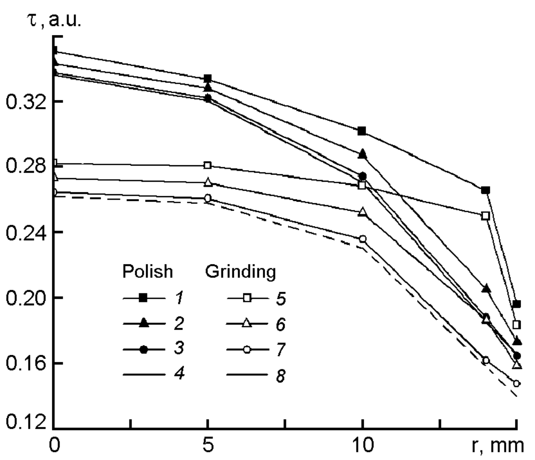

Fig. 2. Radial dependences of light collection coefficient (τ) for ground and polished radiation input surface of a ∅30 mm×2 mm CsI:Tl scintillator. At different scintillation emission height (0.2 mm – *(1,5* curves), 1 mm *(2, 6)*, 1.8 mm (*3, 7*), 1.9 mm (*4, 8*)) over the light output scintillator window.

efficient and the relative specific light output when simulating the irradiation of the whole scintillator surface.

The simulation results of the specific light output change with energy confirm this prediction (Fig. 3, upper curve). The simulation was performed for ∅25 mm×4 mm CsI:Tl samples with diffuse face and lateral reflectors where a significant deviation of the specific light output (~20 %) for the 5.9 keV energy from its value for the 60 keV energy is observed [12]. It is impossible to explain the experimental dependence only by the change of the light collection conditions. In [18], dependence of the relative light output vs. the scintillation depth is proposed in the form:

$$L/L_0 = 1 - \exp(-\lambda \cdot x), \qquad (1)$$

where $L$ is the light output at a distance $x$ from the surface; $L_0$, that in the scintillator volume; λ, the surface layer parameter. The formula (1) is used to describe the influence of the dead layer value on the scintillation efficiency in the form [19]:

$$\eta = 1 - \exp(-x/d_0), \qquad (2)$$

where η is the relative scintillation efficiency; $x$, the scintillation depth; $d_0$, the dead layer parameter. The formula (2) provides a good agreement with experiment for CsI:Tl scintillators at $d_0$ = 0.4 μm.

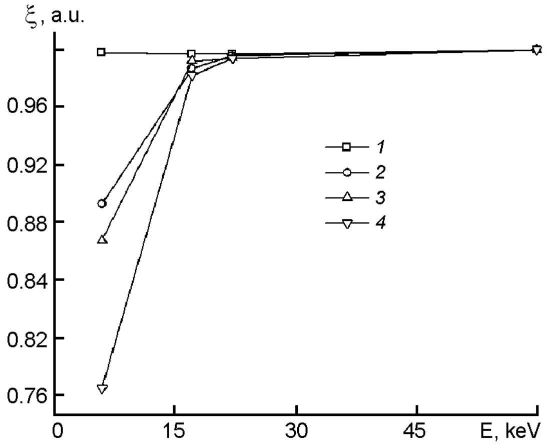

Fig. 3. The change of relative specific light output (ξ) vs the radiant energy ($E$) for a polished ∅25 mm×4 mm CsI:Tl sample with diffuse lateral and face reflectors (tetratex) for different values of the dead layer parameter $d_0$ under irradiation of the whole radiation input surface of the scintillator: *1* – $d_0$=0 *2* – $d_0$=0,4 μm; *3* – $d_0$=,5 0μm; *4* – $d_0$=1 μm;

When simulating the changes in the relative specific light output as a function of the energy, the relation (2) is included in the simulation conditions. The simulation results are presented in Fig. 3 (three lower curves). Significant changes of the relative specific light output which approach the experimental values [12] at $d_0$ > 0.4 μmm are observed. The role of light collection in the change of the relative specific light output is studied experimentally in [12] using various reflective coatings. We attempted to reproduce those experimental conditions in the simulation. The light collection for ∅25 mm×4 mm CsI:Tl samples was simulated initially without reflector and then with different face reflectors at the same lateral reflector (Teflon ring). The reflection coefficients for the reflectors were selected in such a way that the relations of the light outputs for the 60 keV energy without reflector and with a specified reflector correspond to the experimental ones. The dependences obtained during simulation of the relative specific light output vs. the energy without reflector and with Mylar, Tyvek and Tetratex face reflectors are shown in Fig. 4a. In this case, the scintillation efficiency was constant over the whole scintillator volume.

The changes of the light output $C$ and specific light output $\Delta_{5.9\ldots60}$ and $\Delta_{17\ldots60}$ for

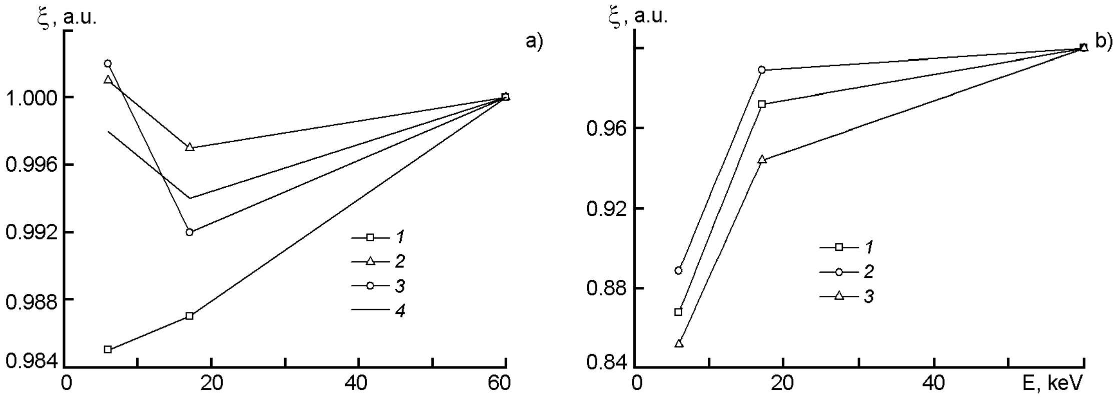

Fig. 4. Dependences of relative specific light output (ξ) on the radiant energy (*E*) for polished ∅25 mm×4 mm CsI:Tl samples without reflector and with Mylar (*2*), Tyvek (*3*a) and Tetratex (*4*a, *3*b) reflectors in case of: a) lack of the dead layer, $d_0 = 0$; b) existence of the dead layer, $d_0 = 0.4$ μm.

the 5.9 keV and 17 keV energy, respectively, are compared in Table with the specific light output for the 60 keV energy obtained by simulation (this work) and experimentally [12]. It is seen from Table and Fig. 4a that the calculated relative specific light outputs $\Delta_{5.9...60}$ and $\Delta_{17...60}$ are almost the same for all reflector types. The changes are by order of magnitude smaller in comparison with experiment [12]. At the same time, the quantitative dependence of the light output *C* on the reflector material is very similar in the simulation and in the experiment. It is possible to achieve the changes of the relative specific light output approaching the experimental ones in the absolute magnitude but opposite in sign when a dead layer of $d_0 = 0.4$ μm is included in the simulation conditions (Fig. 4b). Such a simulation result is quite predictable assuming the proposed form of the scintillation efficiency dependence on the depth (formula (2)).

It is very hard to explain the contradictions between the simulations and experimental results [12]. On the one hand, the existence of a dead layer in CsI:Tl and the estimation of its thickness was reported in [19]. From this point of view, it is difficult to suppose that the dead layer is absent in the CsI:Tl samples used in [12]. A significant decrease (~11 %) of the relative specific light output for 5.9 keV energy is observed for the reflector-free ∅25 mm×4 mm CsI:Tl sample (Table). This evidences the dead layer presence. Moreover, a discrepancy in the experimental results is observed in [12]. The significant decrease (~20 %) of the specific light output for 5.9 keV energy is found when constructing the specific light output dependence on the energy for ∅25 mm×4 mm CsI:Tl sample (with low activator concentration) with diffuse reflector (Tetratex). When the same sample in the similar wrapping with diffuse reflector (Tetratex) is used to study the reflector influence, a substantial increase (~9 %) of the relative specific light output for 5.9 keV energy is observed. Such a wide variation of the specific light output (~29 %) cannot be explained by change of the light collection conditions, because they are practically the same in these two cases. On the other hand, the light collection model used here does

Table. The change of the light output *C* and the specific light output $\Delta_{5.9...60}$ and $\Delta_{17...60}$ for ∅25 mm×4 mm CsI:Tl crystals with various reflectors obtained in the simulation and in the experiment [12]

| Reflector | *C*, rel.un. | | $\Delta_{5.9...60}$, % | | $\Delta_{17...60}$, % | |
|---|---|---|---|---|---|---|
| | Calculat. | Exper. [12] | Calculat. | Exper. [12] | Calculat. | Exper. [12] |
| Absent | 1.00 | 10.2 | −1.5 | −11 | −1.3 | +8 |
| Mylar | 1.46 | 14.8 | +0.1 | 0 | −0.3 | +6 |
| Tyvek | 1.47 | 14.9 | +0.3 | +7 | −0.3 | +6 |
| Tetratex | 1.93 | 19.7 | −0.2 | +9 | −0.6 | +5 |

not take into account a number of factors that effect the light collection in real conditions. For example, the change of the scintillator luminescence spectrum excited by the soft radiation of different energy and dependence of the reflector reflection coefficients on the wavelength. The model does not also take into account the change of the scintillation duration vs. the radiation energy, as well as the changes in the optical characteristics of the near-surface layers (transparency, scattering centers, refractive index) for the different surface treatment conditions.

## *4. Conclusions*

The radial dependences of the light collection coefficient at the detection of the X-ray and $\gamma$ radiation in the 5.9 to 60 keV energy range have been obtained when simulating the light collection in the CsI:Tl detectors with various treatment of the radiation input surface. The surface matting results in a decreased light collection coefficient for the indicated energy values, especially for the central part of the scintillator. Meanwhile, the dispersion of the light collection coefficients for the different surface parts decreases. The maximum equalizing of the light collection coefficient has been obtained for the detection of the penetrating $\gamma$ radiation which gives the uniform depth distribution of the scintillations in the specified scintillator. The radial distributions are practically coincided for lower radiation energies both in case of polished and ground surfaces. This is due to almost the same light collection conditions for the 5.9 to 60 keV energy range and appropriate change of the radiation penetration depth from 3 to 300 μm.

The weak radial dependence of the light collection coefficient results in the constant relative specific light output in the 5.9 to 60 keV energy range when the irradiation of the whole scintillator surfaceis simulated. This disagrees with existing experimental results. Taking into account the dead layer as a dependence of the scintillation efficiency on the depth approaches the simulation results to the experimental dependence of the relative specific light output change on the energy. When studying the reflector influence on the energy dependence type of the relative specific light output, insignificant changes in this dependence on the reflector type have been also obtained. These changes increase when the scintillation efficiency dependence on the scintillation depth coordinate is taken into account. The simulation results obtained in this particular case are inconsistent with experimental data and at the present time there is no reasonable explanation for this difference.

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# Моделювання світлозбору у сцинтиляційних детекторах короткопробіжного випромінювання

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Проведено моделювання світлозбору у детекторах короткопробіжного випромінювання на основі кристалів CsI:Tl. Для випадків реєстрації слабопроникаючого рентгенівського і гамма-випромінювання у діапазоні енергій від 5.9 до 60 кеВ знайдено, що матування поверхні приводить до зменшення коефіцієнта світлозбору. При цьому для різних ділянок поверхні спостерігалося зменшення розкиду коефіцієнтів світлозбору. У цьому діапазоні енергій радіальні розподіли практично співпадають як у разі полірованої, так і матованої поверхні із-за однакових умов світлозбору, оскільки визначаються невеликою відмінністю глибини проникнення випромінювання різних енергій (3–300 мкм). Використання у моделюванні залежності сцинтиляційної ефективності від координати місця спалаху за глибиною дозволило наблизити результати моделювання до експериментальних залежностей зміни питомого світлового виходу від енергії. Також це дало можливість досліджувати вплив відбивача на характер залежності відносного питомого світлового виходу від енергії.