

Light collection peculiarities in X-ray scintillation detectors

T.E.Gorbacheva, V.A.Tarasov, Yu.T.Vidayj, A.A.Ananenko, V.P.Gavrylyuk

Institute for Scintillation Materials, STC "Institute for Single Crystals", National Academy of Sciences of Ukraine, 60 Lenin Ave., 61001 Kharkiv, Ukraine

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The X-ray energy that can be detected using NaI(Tl) scintillators is rather low (5 to 60 keV), thus, it is especially important to achieve the maximum light collection. In this work, the factors favoring enhanced light collection in such detectors have been studied. To that end, the light collection process has been simulated and studied in experiments using various technology and design features of the detector manufacturing. The experimental results have been shown to confirm the calculation data obtained using the simulation.

Энергия регистрируемого рентгеновского излучения детекторами на основе NaI(Tl) невелика (5–60 кэВ), поэтому задача получения максимального светового выхода особенно важна. В работе исследовались факторы, способствующие увеличению светособирания в таких детекторах. Для этого проведено моделирование процесса светособирания и экспериментальное исследование при различных технологических и конструкционных особенностях изготовления таких детекторов. Показано, что экспериментальные результаты подтверждают данные расчета, проведенного с помощью моделирования.

Detectors on the basis of thin NaI(Tl) single crystals [1, 2] are used most often in X-ray diffraction apparatus and in X-ray spectral analysis. The scintillation performance of such detectors are known to depend on numerous factors; mainly on the quality of single crystal and reflectors as well as on the detector design. Taking into account that the energy of radiation monitored by such detectors is rather low (5 to 60 keV), the problem of maximum light collection is especially important. If the scintillator is selected properly, the light yield depends on the detector surface treatment and design of the detector accounting for the reflectors used. In this work, the influence of these factors on the light collection parameter τ being in proportion to light output V [3, 4] has been studied. To that end, the light collection in the detector has been first calculated, then the scintillation characteristics have been studied in experiment depending on several parameters accepted for the detector model calculation.

The light collection process in the specified detectors was simulated using the Monte-Carlo method based on the CFlash 1.3 algorithm. The following factors were considered in the calculation:

— density distribution of scintillation flashes in the crystal volume calculated under account for penetration of the radiation being monitored;

— light absorption in the crystal volume;

— relative refractive index at the media boundaries;

— light scattering indicatrice on the rough crystal and reflector surfaces with/without optical contact (OC);

— presence of a gap between the input crystal surface and reflecting coating.

Factors not considered in calculation:

— light dispersion at its propagation within the crystal;

— spectral characteristics of radioluminescence and sensitivity of the photodetector;

— light ray propagation from the scintillator through immersion lubricant into the photodetector.

Light propagation in a NaI(Tl) crystal was simulated with the refractive index 1.85 and transparency $\mu = 0.005$ cm^{-1}. The crystal had the cylinder shape of 20 mm diameter and 2 mm thickness (Fig. 1). The irradiation geometry corresponded to infinitely distant source situated on the cylinder axis in such a manner that one of the cylinder butts was the input surface for radiation, while another one, the output surface. The refractive index jump at the transfer from the scintillator to the glass is 1.85/1.5. A thin disk which diameter corresponds to crystal diameter was used as the mirror reflecting coating. The reflection index was assumed to be equal 0.9.

Microscopic examination of scintillation crystal surface after lapping and polishing had shown that the surface is covered by scratches (grooves) varying in depth and direction. To simplify mathematical model of such surface, the scratches can be assumed to have cylindrical shape and a constant depth comparative to the radius. The parameter K is the fraction of the surface occupied by grooves. Then the absolutely smooth surface has $K = 0$ and for the most rough surface, $K = 1$. By varying the parameter K in the range (0–1), the surface of any roughness can be described (of course in the range of application of this particular model). First, we have calculated the light collection coefficients in dependence on the roughness degree of the input and output surfaces. The lateral reflector with $P_{ref} = 0.9$, and a reflector situated 0.001 cm above the input surface were assumed. The calculation results are shown in Table 1.

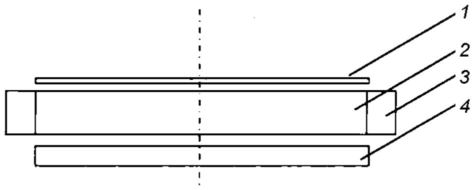

Fig. 1. The Sketch of the detector design; *1*, reflector; *2*, crystal; *3*, side reflector; *4*, optical glass.

It can be seen from the Table that light collection coefficient increases with output surface roughness. The peak losses of light are observed at weak roughness of the input and output surfaces. At a substantial roughness of input surface, a considerable fraction of light gets out towards the upper reflector and its presence provides a high light collection coefficient. The light collection coefficient in X-ray detectors in presence and absence of side and upper reflectors, and at matted butt surface of the crystal adjacent to PM was calculated using the above model.

The calculation results for the case of presence or absence of an optical contact (OC) between the crystal and target window are given in Table 2 where τ_1 is the light collection coefficient without reflectors; τ_2, the same with reflectors; τ_3, the same with reflectors and matted surface. It follows

Table 1. Calculated dependency of light collection, light losses and amount of light which goes toward the top reflector on roughness of entry and exit facets of scintillation crystal.

Calculation parameters	The roughness degree, K			
	Input $K = 0.01$ Output $K = 0.01$	Input K = 0.3 Output $K = 0.3$	Input K = 0.01 Output $K = 0.3$	Input $K = 0.3$ Output $K = 0.01$
Light collection coefficient, a.u	0.699	0.893	0.892	0.817
Light losses, a.u.	0.301	0.107	0.108	0.183
Amount of output to the top reflector side, %	14	18	9	27

Table 2. Calculated dependency of light collection on presence of optical contact between crystal and exit window of the detector.

Presence of optical contact	Light collection coefficient		
	τ_1	τ_2	τ_3
OC	0.56	0.84	0.97
Without OC	0.23	0.56	0.71

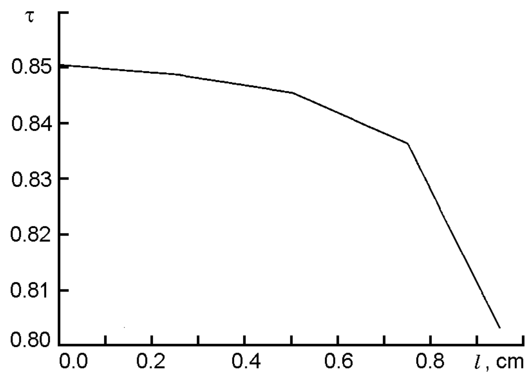

Fig. 2. Dependence of light collection coefficient (τ) on the distance (*l*) between the flash site and center crystal.

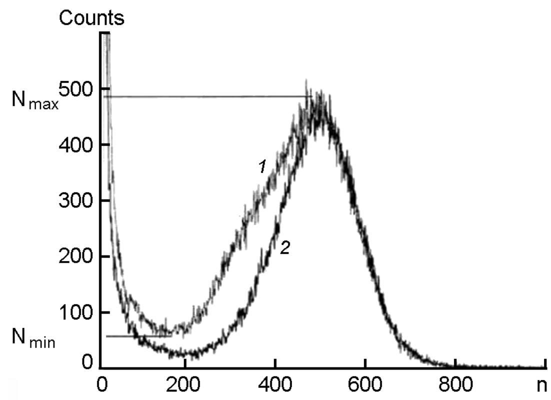

Fig. 3. Pulse height spectra of detectors No.1 (*1*) and No.2 (*2*) at detection of radiation from ^{55}Fe (E = 5.9 keV).

from those data that even in the presence of side and upper reflectors which reduce essentially the light losses in the detector, the light collection coefficient does not exceed 84 %. The matting of a butt surface results in enhanced light collection coefficient, and an especially essential contribution from this effect in case of the OC absence (the increase by a factor about 1.3).

The light collection coefficient was determined as a function of the distance between the flash site and the crystal center. The roughness degree of the input and output surface was assumed to be 0.1, the reflector being located at the height of 0.001 cm, the lateral surface being in OC with the reflector. Fig. 2 presents the dependence of light collection coefficient on the distance (*l*) between the flash site and the crystal center. A substantial deterioration of τ is seen near the crystal edge. The dependence of light collection coefficient on *l* was found at the roughness degree of the input and output surface 0.1. The calculation results are given in Table 3. The light collection coefficient decreases insignificantly (8 %) at a considerable increase of the gap between the reflector and the crystal input surface. Absolute light loss amounts about 40 % in this case.

Dependence of light collection coefficient vs. the crystal side surface treatment and properties of the side reflector was calculated, too. The following parameters for calculation were accepted: the distance from the reflector to the crystal input 0.001 cm; the input and output crystal surfaces roughness degree 0.2. It follows from the calculation that absence of optical contact between the side reflector and crystal increases the light collection coefficient by 4–5 %. No dependence of τ on the roughness degree (whether the side coating reflection is mirror-like or diffuse) is revealed.

The light output and energy resolution of the detectors at ionizing radiation detection were studied in experiment. It is known that the physical light output is determined as $V = \eta \cdot \tau$, where η is the conversion efficiency of a scintillator; τ, the light collection coefficient. Hence, at a given scintillator, the light output is in proportion to τ. The energy resolution is connected with the light output homogeneity over the detector. Table 4 shows results of the energy resolution (*R*) and a light output (*V*) measurements for a detector coupled with a FEU-35 PM under excitation with X-rays from ^{55}Fe radionuclide as a func-

Table 3. Calculated dependency of light collection and light losses on the gap between top reflector and scintillation crystal.

Calculation parameters	Gap width (*l*), cm			
	0.001	0	0.1	0.2
Light collection coefficient	0.834	0.8	0.785	0.763
Light losses	0.166	0	0.215	0.237

Table 4. Experimental dependency of energy resolution and light output on the gap between top reflector and scintillation crystal

Scintillation parameters	The gap between the crystal and the upper reflector, mm				
	2	1	0.5	0 (without OC)	0 (with OC)
Energy resolution, %	41.0	40.5	42.0	40.8	46.0
Light yield, a.u.	1.0	1.1	0.9	1.1	0.7

Table 5. Experimental dependency of energy resolution and light output on the treatment of top surface of scintillation crystal

Scintillation parameters	Surface treatment			
	Polishing		Grinding	
	OC	without OC	OC	without OC
Light yield, a.u.	1.0	1.1	1.2	1.5
Energy resolution, %	49.0	48.5	42.0	40.0

Table 6. Experimental scintillation characteristics with different treatment of entrance surface of scintillation crystal.

Reflector	R, %	V, a.u.
Beryllium disk	47	0.92
Aluminized film	44	1.001
Aluminum film deposited on the crystal	55	0.64

Table 7. 14.Experimental scintillation characteristics obtained with different top reflectors.

Detector No.	Light yield, a.u	R, %	Peak/valley, a.u
1	1	46	15.0
2	1.4	38	21.0

tion of distance between the crystal and upper reflector. A Teflon plug was used as the side reflector. It follows from the Table that the light output and energy resolution of the detectors are essentially independent of the distance between the crystal and reflector within the range studied until their mechanical touch under condition of OC absence between them. In the presence of OC between the crystal and the upper reflector, the scintillation characteristics are deteriorated essentially.

The measured light output and the energy resolution of detectors with polished and ground surfaces near the PM are given in Table 5 for the cases of presence or absence of OC between the crystal and the detector output window. It is seen that the grinding of the crystal lower surface allows to increase the light output by a factor exceeding 1.2 times and to improve the energy resolution absolute value by 6–8% on the average.

The peak-to-valley ratio, i.e. the ratio of number of pulses in the maximum of amplitude spectrum N_{max} to that in minimum N_{min} (Fig. 3) is a parameter of importance for of X-ray and soft gamma radiation detectors: $p/v = N_{max}/N_{min}$. This parameter depends on light yield homogeneity over a scintillation crystal surface. The model calculation shows that this can be achieved by roughing of the crystal upper surface. In Fig. 3, the amplitude spectra of two detectors are presented at recording radiation from ^{55}Fe with E = 5.9 keV. In the detector No.1, the crystal input surface is polished by a standard means, while in No.2 one, ground by means of Al_2O_3 powder with grain size of 0.5 μm. As for the rest, the detectors are made similarly using the standard procedure. The scintillation performances of the detectors are given in Table 6. Hence, such grinding of the surface oriented towards the origin provides increase of peak/valley parameter by 40 % and improvement of R absolute value by 8 %.

The character of light propagation in the crystal at various irradiated area values was studied. A series of lead diaphragms with 9 mm, 16 mm, 20 mm orifice diameters was used in the experiment. The Al film deposited onto the crystal and Dakron disposed on the crystal were used as reflectors for No.1 and No.2 crystals, respectively. The dependence of the energy resolu-

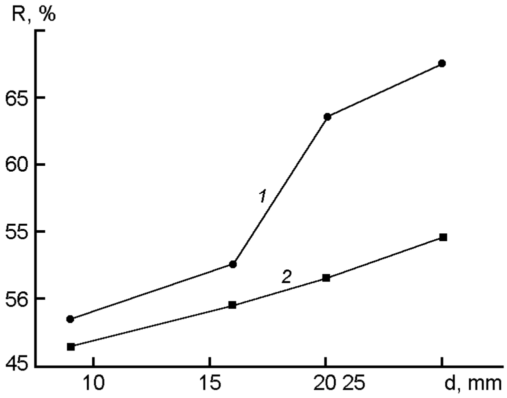

Fig. 4. Dependences of energy resolution on irradiated area diameter for X-ray detectors №1 (*1*) and №2 (*2*) at $E = 5.9$ keV X-rays

tion on the irradiated area diameter at monitoring X-rays with $E = 5.9$ keV is shown in Fig. 4. A sharp improvement of the resolution with decrease of the orifice diameter through which the crystal is irradiated for the detector (No.1) with deposited mirror is obviously related to the fact that the light in such detectors is concentrated on the crystal edges where it is partially absorbed. For the detector No.2, a smaller amount of light is absorbed in a crystal due to total internal reflection and the light gets PM at such reflector arrangement.

Influence of the upper reflector type on scintillation parameters of detectors was studied. As the reflectors, used were: 1) beryllium disk, 2) aluminized Dakron film glued to beryllium disk, 3) aluminium film deposited onto the crystal. The average values of the energy resolution and a light output are presented in Table 7 at detection of radiation from ^{55}Fe ($E = 5.9$ keV) for several groups of detectors with the NaI(Tl) crystal size of ∅20 mm × 2 mm. It follows from Table 7 that the use of aluminized Dakron film or beryllium input window as reflector results in a significant improvement of detector scintillation performance in comparison with detectors where deposited aluminium film is used as the reflector. This fact is related to improvement of light collection conditions in the presence of an air gap between the crystal and reflector.

In conclusion, the experimental results confirm the data obtained by means of model calculations. To obtain the optimum scintillation parameters, the detectors should have a mirror-like upper reflector and a diffuse side reflector. The upper reflector should be arranged the distance no more than 0.5 mm from the crystal input surface and should not have optical contact with that surface. It is desirable to matte the scintillator surfaces that form the radiation input and light output. In this case, such diffuse reflection provides more light to get the PM. Aluminum deposition on the crystal input surface gives worsened results as compared to the reflector arranged at some distance from the crystal surface. Improvement of scintillation performance is observed at a reliable optical contact between lower crystal face and glass of the container. Increase of the irradiated crystal surface by a factor of 5 results in the resolution drop by 30 % for crystal of 25 mm diameter.

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Особливості світлозбору у детекторах рентгенівського випромінювання

Т.Є.Горбачова, В.О.Тарасов, Ю.Т.Видай, А.О.Ананенко, В.П.Гаврилюк

Енергія рентгенівського випромінювання, що реєструється детекторами на основі NaI(Tl), незначна (5–60 кеВ), тому одержання максимального світлового виходу є особливо важливим. У роботі досліджувалися фактори, які сприяють збільшенню світлозбору у таких детекторах. Для цього проведено моделювання процесу світлозбору та експериментальне дослідження при різних технологічних і конструкційних особливостях виготовлення таких детекторів. Виявлено, що експериментальні результати підтверджують дані розрахунку, проведеного з використанням моделювання.