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Unidimensional position sensitive detector

A.V.Gektin, V.P.Gavrylyuk, D.I.Zosim, V.L.Yankelevich

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

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It has been shown that a predetermined distribution of the light yield along the length of scintillator can be achieved by treatment of the side surface of CsI(Tl) crystal. A principle and of manufacturing a position sensitive detector have been considered. The dependence of the detector position resolution on its size has been studied.

Показано, что предопределенное распределение светового выхода вдоль длины сцинтиллятора может быть достигнуто обработкой боковых поверхностей кристалла CsI(Tl). Приведены принцип и метод получения позиционно-чувствительного детектора. Изучена полученная зависимость позиционного разрешения детектора таких размеров.

As a rule, distribution of the light yield along the scintillator length is not uniform. The main reason of this effect is the difference in the efficiency of light collection. Due to this fact long length crystals require special surface treatment intended for leveling the light yield along the scintillator length. Such treatment includes applying some roughness on to surface of a scintillator. A rough surface has different reflective properties as against a polished one. The theory of roughening up the scintillator surface to modify light collection and scintillator performance can be found in [1, 2]. The scattering indicatrix of a rough surface has maximum in the direction of the mirror reflection, but only 75 % of the total intensity of scattered light reflects to this direction in fact [3]. So the change of the light collection by the surface treatment allows to modify distribution of the scintillator light output. In [4] for instance, such a method was utilized to reduce edge effects in a scintillation camera.

The grade of the surface roughness, dimension and location of the site to grind can be calculated beforehand by the methods of mathematical simulation of the light collection in the detector [5].

The light yield leveling by the surface treatment was applied to long length CsI(Tl) scintillators for electromagnetic calorimeter BELLE (KEK) [6], for example. It allowed to achieve light nonuniformity less than 7 % along 300 mm length of a crystal. Such approach was also used for the BaBar CsI(Tl) scintillator treatment to unify the light output to 6 % [7]. Statistics and reliability of this treatment were confirmed on more than 6624 CsI(Tl) scintillators for BELLE calorimeter [6] and for BaBar ones [7].

It is clear that leveling the light output distribution along the crystal could be done in the opposite direction, i.e. to make nonuniform distribution too. In this work we will show how to use such treatment to make a position sensitive scintillation bar. Fig. 1 describes schematically the principle of position sensitivity of long length scintillator and conditions to be fulfilled to achieve such a property. Showed is a typical irregular light output distribution along the length of a scintillator the lateral size of which is small as compared to its length ($20\times20\times400$ mm^3 for the reference scintillator) and the side surface is ground rough. The inset shows characteristic pulse height spectrum yielded by the scintillator when irradiated by a ^{22}Na collimated source.

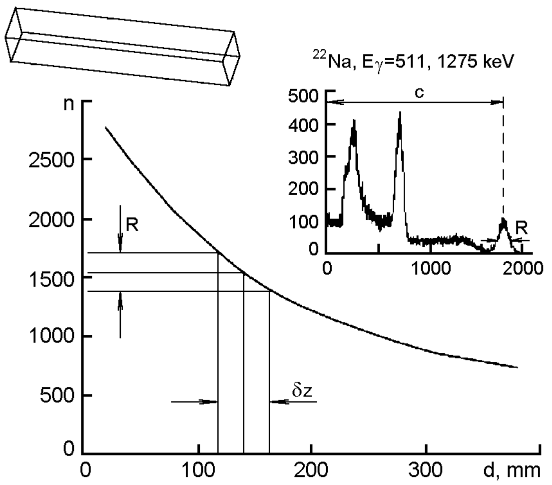

Fig. 1. On the principle of position sensitivity of a long length detector. Side surface of the detector is ground rough, so light yield is sloping considerably. Accuracy of position determination δz is defined by light yield c, pulse height resolution R and slope of the curve at the point of interaction.

The side surface is made rough so that the light yield distribution has a tilt. Under these conditions the position of the collimated source of ionizing particles z can be determined by the measured value of the light yield c. The accuracy δz of the source position is defined by the value of pulse height resolution (PHR) of the detector R and the tilt α of distribution $c(z)$ in the point of measurement:

$$\mathrm{tg}\alpha = \lim_{\Delta z \to 0} \frac{\Delta c}{\Delta z}, \quad \delta z = c\frac{R}{\mathrm{tg}\alpha}. \qquad (1)$$

Thus, a long length detector possesses positional sensitivity in one direction. To achieve better position sensitivity one needs to improve light yield and energy resolution of a detector, preserving $c(z)$ distribution as steep as possible.

These requirements are somewhat contradictory. Accordingly, this paper is focused on the study how the transversal size/length ratio of CsI(Tl) scintillator influences its position sensitivity. We tried to determine the optimal dimensions of a detector allowing to achieve the best position resolution.

CsI(Tl) scintillators in the form of a parallelepiped 20×30×400 mm^3 were taken as a base of the detector. After preliminary treatment of the side surface the crystal was enveloped in a layer of Tyvek reflective coating. One of the ends was left free for coupling with a photomultiplier tube (PMT). PMT utilized was R609 which is sensitive to the spectral range of CsI(Tl) emission band $\lambda = 650$ nm. There was air gap between free end of the detector and PMT.

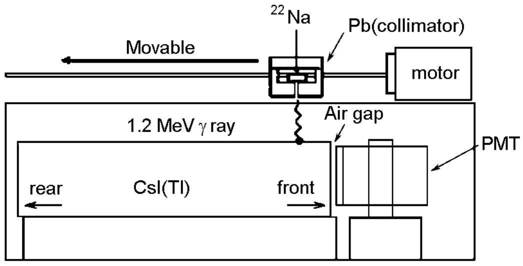

Fig. 2. A diagram of the scanner used for measuring light yield and pulse height resolution. Collimated source of radiation was moved along axis of 400 mm length scintillator. Light is collected on photomultiplier tube placed on the readout face through air gap.

Light yield distribution was measured with a help of the set-up schematically shown in Fig. 2. The luminescence was excited by a collimated ^{22}Na source, E_γ = 1275 keV, 511 keV. Diameter of the collimator hole was 2 to 5 mm.

Several measurements of the detectors' pulse height resolution were made using γ-quanta source collimated to a smaller diameter of the beam in order to estimate shift contribution to the value of position resolution. For example, narrowing collimator hole to 1 mm was acknowledged to lead to a better energy resolution: 3 % under irradiation by E_γ = 1275 keV. Comparison with the value obtained when the beam was collimated to 5 mm showed that changes energy resolution only, not light yield or its distribution. Thus, the width of the collimating hole 5 mm chosen for the experiment is justified enough since the accumulation rate increases along with the beam broadening, contribution of background events to the photoelectric peak decreases, so accuracy of the measurement improves.

Characteristic pulse height spectrum yielded by detectors is shown in Fig. 1. Since ^{22}Na has two lines, both can be used to determine light yield and PHR. The photoelectric peaks from the two energies were approximated by a Gaussian. For each point along the length of a sample determined were the position of the approximating curve (light yield) and its width on half-height (PHR). Typical energy resolution achieved was 5 and 10 % to the two ener-

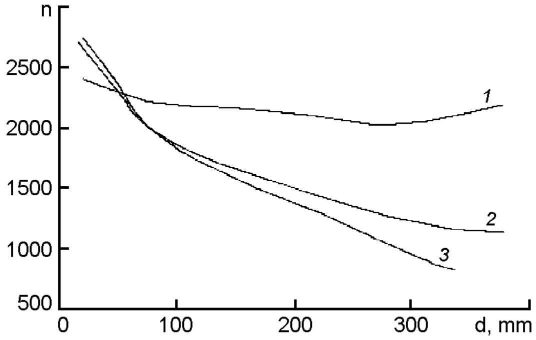

Fig. 3. Purposeful variation of the slope of the light yield distribution curve. *1* — side surface of the scintillator is polished; *2* — side surface is rough; *3* — side surface is rough, coating on the far end of the scintillator has been darkened.

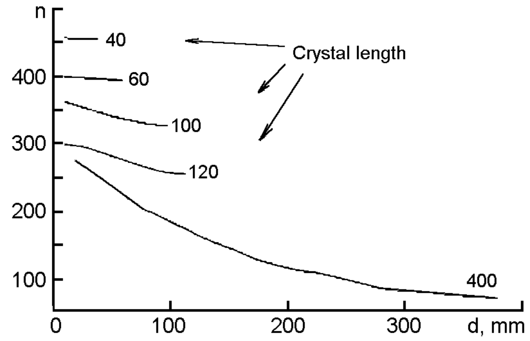

Fig. 4. Light yield distribution in scintillators of different lengths. Reflective properties of the detector surface, its coating and parameters of signal amplification are kept unchanged, so comparison can be made. If detector shortens, average light yield becomes higher, the curve levels.

gies, correspondingly. The values obtained by approximating 1275 keV line were taken to represent properties of a sample, the ones yielded by 511 keV line were used to control correctness of the measurement.

The γ-quanta source was moved along the detector axis with a step 20 mm. The measurements were repeated in each point to obtain light yield distribution over the whole length of a detector. The initial detectors with a polished side surface had approximately uniform light yield distribution over the length (Fig. 3, curve 1). The distribution $c(z)$ becomes more steep if all the lateral surface has been made rough (Fig. 3, curve 2). If in addition cover on the far end has been rendered black, the curve becomes more linear (Fig. 3, curve 3).

The tilt α is determined by the roughness grade (grain size of the grinding abrasive material) and reflective efficiency of the detector envelope, so one can find a compromise between slope of the curve and too bad PHR. The values presented in Fig. 3 are absolute, so mutual comparison can be made. Note, that light yield from far sections of the scintillator drops when side surface is rendered rough. But light yield from sections adjacent to readout end improves simultaneously, so the slope of the curve gains. This circumstance is favorable from the point of view defined by (1).

It has been found that the difference in the ultimate values of light yield and behavior of its distribution over the length of the detector can be controlled in a wide range by varying degree of the side surface roughness. The biggest tilt of the function $c(z)$ is observed for the detector with the highest degree of the side surface roughness. Such an experimental conclusion complies with a theoretical one [8, 9]. Detector possessing big tilt of the light yield distribution has better spatial resolution according to (1). However, energy resolution at the low light yield regions worsens together with the increase of the tilt $c(z)$. Therefore, one should find a balance between these two factors to choose the optimal tilt of the light yield distribution. Characteristic value of pulse height resolution measured in the central part of the detector worsens from 5 to 9 % when the light yield tilt increases. This drop is bound to a total light yield drop among other causes.

A series of measurements were carried out on one and the same sample each in order to determine the effect of the scintillator dimensions on the light yield distribution. Since prototypes utilized possessed a high transparency (which did not exceeded 0.005 cm^{-1}) only the ratio of length to cross section is important [1, 2]. Cross section was fixed at 20×30 mm^2. Such a dimension is sufficient to effective recording $E_\gamma = 1275$ keV events. The initial length of the scintillator was 400 mm. Lateral surface of the crystals and the end opposite to PMT were enveloped in a layer of Tyvek reflector. The scintillator was sequentially shortened with a step of 20 mm, the light yield distribution was measured at each length correspondingly. Parameters of pulse amplification and state of the remaining surface of the sample were preserved the same to perform comparison of average light yield. The one of obtained light yield-

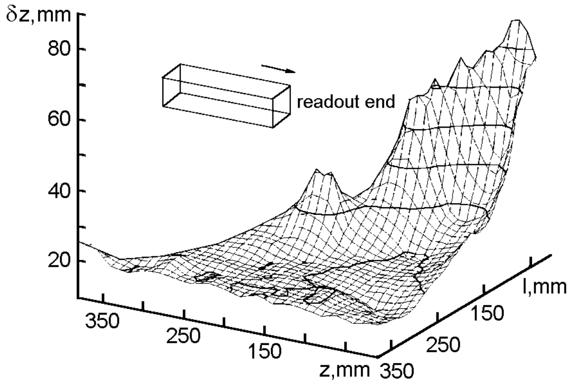

Fig. 5. Position resolution of detectors of different lengths obtained in accordance with (*1*).

vs-scintillator length curves sets is shown in Fig. 4.

The drop in the light yield when collimated source moved away from PMT is explained by line geometry of the detector which causes exponential attenuation of the scintillation light along the length [8]. As scintillator length l shortens and its shape becomes cubic, the distribution $c(z)$ becomes leveled, the average value of the light yield increases. The light reflected by the far end of parallelepiped gets mostly lost if latter is long. While far end becomes nearer to readout end total light increases. A shorter detector has a lower slope of the function $c(z)$ but a better pulse height resolution. Since these two factors have an effect on position resolution in an opposite way (1), the function of two variables $\delta z(z,I)$ may have a local minimum. The position resolution value for detectors of different length has been calculated according to (1). The obtained behavior of the position resolution $\delta z(z,I)$ dependence on the detector length and position of the collimated source are given in Fig. 5.

It is seen that position resolution remains more or less constant over the whole volume of the detector when its length varies in the range of 200 to 380 mm.

Consequently, the factors of the light yield increase and leveling over the detector length are changed synchronously as the latter becomes no shorter than 200 mm. Equation (1) should be rewritten in such a form to elucidate physical sense of this phenomenon:

$$\delta z = \frac{R}{(\ln c)_z}. \tag{2}$$

Since pulse height resolution (the numerator in (2)) varies insignificantly in the mentioned length range, the derivative of the light yield logarithm remains constant. It means that the light attenuates exponentially as its source is moved away from readout end. Worsening of the position resolution for the detectors shorter than 200 mm points to the deviation of distribution $c(z)$ from the exponential nature. The main reason of such deviation is the closeness of the opposite end of the scintillator. The far end reflects light which is summed up with a direct light onto PMT and distorts the distribution. This distortion leads to a more flat light yield distribution. Improving PHR does not recompense it.

The contribution of experimental errors was estimated primarily by comparison values of PHR and light yield from the two energy lines. Furthermore, light yield was measured repeatedly after re-enveloping scintillators. Up to 3–5 repetitions were performed, reliability of light yield values is proven to be in a range 1 %. Since in (1) utilized is the tilt averaged over adjacent points, such deviations do not lead to significant error.

The spatial resolution function was obtained using a collimated γ-quanta source. However its shape can change a little when registering single quanta, not collimated flow from radiation source. Let us consider the cause and effect of such a change.

Total pulse height resolution of a detector is formed as a result of the action of some processes having statistical nature. Each of these processes can be characterized by corresponding contribution into total PHR: R_{int} — the intrinsic resolution of the detector, remains constant for all the detectors utilized in the experiment. R_{ph} — measure of the full absorption peak broadening due to the statistical variations of the number of photoelectrons knocked out of the photocathode, depends on the quality of photomultiplier and light yield value; the absolute value of the latter was sufficient enough for the condition $R_{ph} < R_{int}$ to be fulfilled in the experiment. At the same time one can use photodiodes for signal registration, so R_{ph} will be even lower. This leaves the last cause which bound to light efficiency nonuniformity: R_τ is the spread in the pulse related to the fact that the scintillation flashes emerge in final volume over which the light collection efficiency may vary essentially. Total pulse height resolution of the detector can be written as follows:

$$R^2 = R_{int}^2 + R_{ph}^2 + R_\tau^2. \tag{3}$$

The value of the last term depends on the type of registered particles. Since the gradient $c(z)$ was high in the detectors utilized in the experiment it should be expected that R_τ in the performed experiment was set too high as compared to the case when registered would be particles which interact in a small volume of scintillator. It is obvious that PHR of the detector would deteriorate to dozens percents when registering isotropic radiation originating from 4π solid angle.

One can expect the position resolution to improve at registering single quanta. Amount of the improvement is dependent on the size of volume luminous under quanta impact.

The defined optimal range of cross section/length ratio was found to be 1:10 and lesser. But total size of a detector is restricted to utilize it in position measurement. The light propagating from far end attenuates in $\exp(-l{\cdot}K) = 0.82$ times for scintillators used to obtain the data. As a scintillator becomes bigger, contribution of non-transparency grows and nature of $\delta z(z,l)$ dependency alters. So, large scintillator must possess high transparency to validate the ratio defined.

It must be noted also that position resolution can be improved and useful length extended by combining signals from two photoreceivers applied to opposite ends of the detector (see Fig. 6 for the corresponding light yield dependencies).

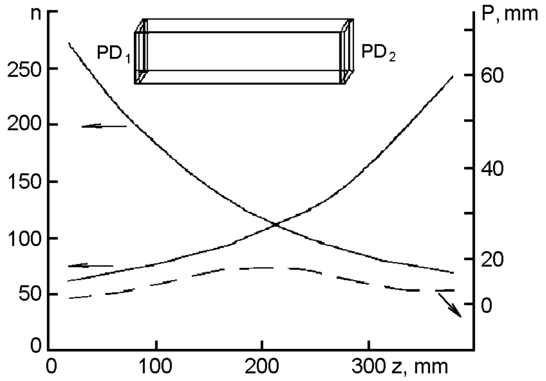

Fig. 6. Improvement of position sensitivity by combining signals from two photodiodes applied to opposite ends of the scintillator.

It has been shown that scintillators based on highly transparent CsI(Tl) scintillation crystals can be used for position sensitive measurements. Manufacturing position sensitive detector requires special treatment of the scintillator surface. It is important to obtain considerable slope of light response while keeping pulse height resolution as minimal as possible (4 to 6 %).

An unidimensional position sensitive detector was produced by special surface treatment of 20×30×400 mm^3 CsI(Tl) scintillator. Position resolution about 15 mm was obtained when detecting γ-quanta from ^{22}Na ($E_\gamma = 1275$ keV, $R = 4$ to 8 %). The value does not worsen while the bar is chopped down to 200 mm length.

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Довгомірний позиційно чутливий детектор

О.В.Гектін, В.П.Гаврилюк, Д.І.Зосим, В.Л.Янкелевич

Показано, що наперед визначений розподіл світлового виходу вздовж сцинтилятора може бути досягнутий обробкою бічних поверхонь кристала CsI(Tl). Наведені принцип та метод отримання позиційно-чутливого детектора. Вивчено отриману залежність позиційного розділення детектора таких розмірів.