Large area scintillation detector for dosimetric stand with improved light collection

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Abstract. In order to improve scintillation light collection from a thin plastic scintillator, the shape of a light reflector, and a new concept of extraction scintillation light trapped inside the scintillator were investigated. The trapped scintillation light is extracted from the scintillator by cutting the scintillator into two pieces with the edges machined at an angle of 45° and polished. Considerable improvement of detection efficiency can be achieved when the extracted and the escape scintillation light are collected together. Prototype of such a scintillation probe was constructed and investigated.

Key words: large area scintillator • light collection • radioactive contamination

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Introduction

A tendency can be observed to use scintillation detectors instead of using proportional counters as beta radiation detectors for measurement of radioactive contamination of hands and feet in dosimetric gates [4–6, 8]. To measure contamination of hands and feet, a large area thin plastic scintillator coupled optically with a photomultiplier tube (PMT) is used. This device acts as a detector of radioactive contamination. The main problem when using thin large area scintillation detector is collection of scintillation light, and uniformity of detection efficiency across the whole area of the scintillator. Two schemes of light collection from plastic scintillator are in use.

In one of the scheme a PMT is placed below and at some distance from the scintillator. The PMT collects scintillation light from the scintillator. To improve light collection and ensure better signal to noise ratio a light reflector is added. In this version only scintillation light that escapes from the scintillator can be collected.

In the other scheme, a wave shifter is coupled to the edges of the scintillator that shifts scintillation light wavelength from 420 to 490 nm and then the wave shifter is coupled directly or by means of a light guide to the PMT [7]. In this version scintillation light, that is trapped inside the scintillator due to total internal reflection, is collected.

Investigations were carried out how to improve light collection of the previous version in which scintillation light that escapes from the scintillator is collected. Results of the investigations of such a probe are given in the paper.

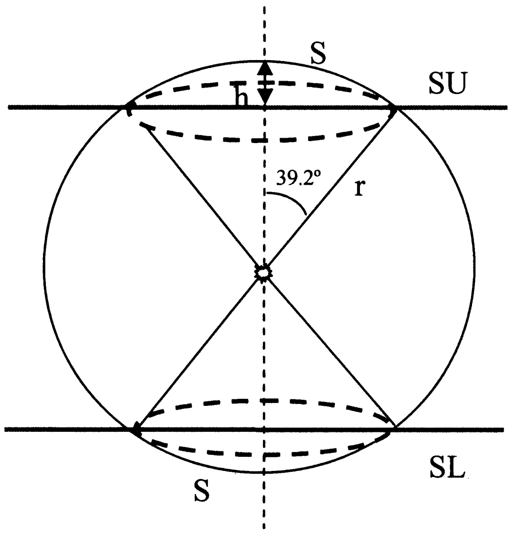

Fig. 1. Scintillation light originating in point 0 can escape from the scintillator in a cone limited by total reflection angle 39.2° (refractive index 1.58). 0 – origin of scintillation; r – radius; S – cap surface; h – height of cap; SU – scintillator upper plane; SL – scintillator lower plane.

Light collection

Light photons from scintillation originating inside a scintillator in point 0 can escape from the scintillator only within the cone limited by total reflection angle, as shown in Fig. 1. Refractive index of a plastic scintillator EJ-212 [2] used in the scintillation detector is 1.58 and the corresponding total internal reflection angle is 39.2°. The ratio of scintillation light escaping from the scintillator to the total scintillation light is equal to the ratio of the area of two caps S to the area of total sphere surface of radius r. Noting that the area of the cap cross-section is $S = 2\pi rh$, and $h = [1 - \cos(39.2°)]\,r$, it can be found that the light escaping from the scintillator is a 0.225 fraction of the total scintillation light. This also means that the $1 - 0.225 = 0.775$ fraction of the total scintillation light is trapped inside the scintillator. In a scintillation probe employing plastic scintillator and PMT at some distance from the scintillator, not more than the 0.225 fraction of scintillation light can be collected.

Light output of plastic scintillator for beta radiation is 1 photon/100 eV (66% of anthracene) [2]. Light output for alpha radiation is approximately 10 times lower than for beta radiation. Scintillation intensity and amplitude of pulses at the output of PMT of alpha radiation are low and comparable with noise pulses. To overcome low light output for alpha radiation and to ensure good discrimination of alpha scintillations pulses from the noise, a thin plastic foil, < 0.1 mm covered with a thin, semitransparent layer of ZnS(Ag) phosphor is placed on top of the plastic scintillator, as shown in Fig. 2.

Light trapped inside the thin plastic scintillator can be extracted from it, if the light can be guided inside the plastic scintillator in some manner. Schemas on how to control the flow of light and how to improve light collection are shown in Figs. 2 and 3. The plastic scintillator 1 mm thick is cut into two equal parts. The cut line is fixed over a photocathode of the PMT. The edges of

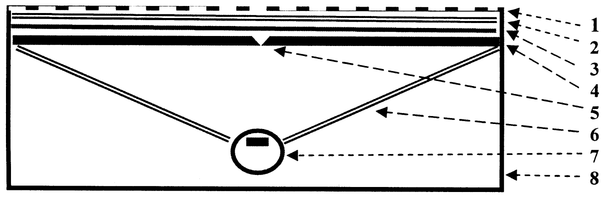

Fig. 2. Layout of the scintillation probe. 1 – protection grid; 2 – three layers of aluminized foil; 3 – ZnS(Ag) phosphor on a thin plastic foil; 4 – plastic scintillator 250 × 125 × 1 mm³; 5 – intersection of plastic scintillator; 6 – light reflector; 7 – side window PMT; 8 – light tight housing.

the cut are then machined at an angle of 45° and are polished. A light photon running in the direction 1–0 hits the cut at the angle of 45° in respect to the normal line 0–3, is reflected in the direction 0–2, and enters the area of PMT photocathode. Due to reflections from lower or upper scintillation plane, light photons hitting the cut edges at angles different from 45°, are reflected in the direction of PMT or in the direction of ZnS(Ag) layer at different angles, and then eventually reflected from the ZnS(Ag) layer back in the direction of PMT. Trapped scintillation light is extracted in this way from the scintillator and is registered by the PMT together with the escape light. All other edges of the scintillator are painted with EJ-510 [2] reflector paint for plastics. Due to this paint, light photons incident on these edges are reflected back also in the direction of scintillator cut.

Scintillation light produced inside plastic scintillator escapes from it within a cone limited by the total reflection angle. If irradiated fragment lays far away from the PMT, the scintillation light cannot be detected. To collect scintillation light a light reflector is placed to direct the light to the photocathode. The reflector has a shape of an upside down pyramid with top cut off. The base of the reflector has dimensions 23.5 × 11 cm and matches active area of the plastic scintillator. The cut off top has dimensions 27 × 30 mm embracing the R3788 PMT window with a photocathode 24 × 8 mm [3]. The inside walls of the reflector are lined with a reflecting aluminum foil.

To secure good light tightness of the measuring window, there are three layers of an aluminized polyester foil EJ-590 placed on top of the scintillators; each layer being 2 μm thick [2]. According to the data given by producer, two layers of the aluminized foil strip by approximately 1 MeV energy from alpha radiation and 20 keV from beta radiation. Above the aluminized foils, there is a steel grid, 12 × 12 mm, wire diameter 1.5 mm is fixed to protect the delicate window against mechanical breakdown. The scintillation probe is equipped with a controlled, high voltage power supply,

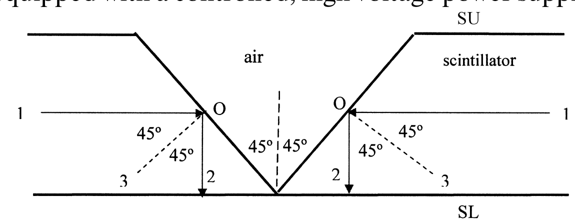

Fig. 3. The path of internal reflection of scintillation light inside the scintillator. 0–1 – incident light at 45° cut scintillator edge; 0–2 – reflected light; 3–0 – normal line; SU – scintillator upper plane; SL – scintillator lower plane.

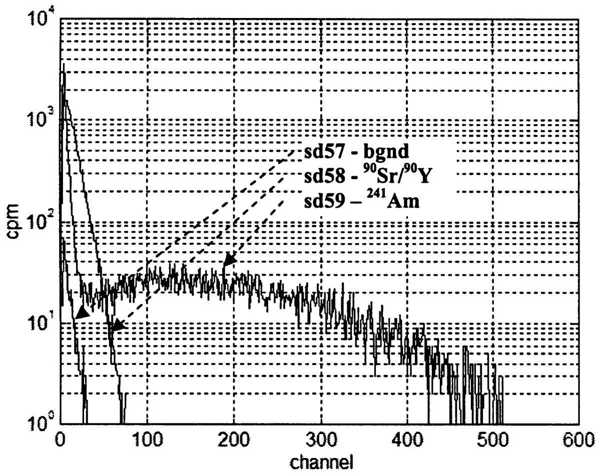

Fig. 4. Differential spectra of background, $^{90}Sr/^{90}Y$ and ^{241}Am measured with a Genie 2000 multichannel analyzer.

a pulse amplifier, a pulse discriminator, and is powered from 5 V dc.

The mechanical layout of the probe is shown in Fig. 2.

Results of measurements

Differential spectra of background, alpha and beta radiation are shown in Fig. 4, illustrating what kind of spectra are to be registered and processed. Differential spectra of $^{90}Sr/^{90}Y$ beta radiation and ^{241}Am alpha radiation were measured when the central point of the probe was irradiated (sources placed on the protection grid). It can be seen from Fig. 4 that the large part of the $^{90}Sr/^{90}Y$ spectrum registered by the plastic scintillator coincide with the noise spectrum, while the ^{241}Am spectrum that is registered by ZnS(Ag) phosphor differs distinctly from the noise.

A light reflector plays an important role in collecting scintillation light in a probe operating on the principle of collection of scintillation escape light. Preliminary investigations aimed at improving scintillation light collection were thus focused on the shape of light reflector. Detection efficiency uniformity is defined as the norm [10] concerning contamination monitors as the ratio of maximum to minimum detection efficiency (max/min), measured with a small area radiation source. The max/min ratio across the whole probe surface should not exceed 2. To determine the effectiveness of the light reflector, detection efficiency and the max/min ratio were measured. It was found that the light reflector in the form of a parabola around the PMT is less effective than the reflector in the pyramid form. The pyramid form reflector equipped with a standard finish, and lined with an aluminum foil reflecting incident light was then investigated. Standard finish reflector was zinc galvanized, with silver matt color scattering incident light.

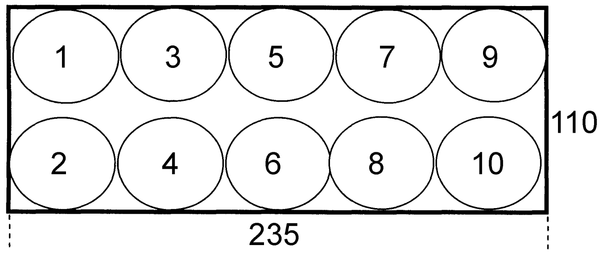

Fig. 5. Placement of measured positions of scintillation probe. Dimensions of active area of the scintillator are given in mm.

Beta radiation source $^{90}Sr/^{90}Y$, of active diameter 36 mm and an external diameter of 50 mm, was used for the investigations. The probe was irradiated in ten positions lying in two rows as shown in Fig. 5, and a count rate was measured at the output of a pulse discriminator for each position. The count rate was corrected for background, a detection efficiency was computed for each position, and then the average detection efficiency η and the max/min ratio were calculated. All measurements were carried out at the same gain of measuring channel (constant PMT high voltage). The results of these measurements are given in Table 1. It can be seen from Table 1 that the detection efficiency is higher by 17%, and the max/min ratio is lower for the reflector lined with aluminum foil in comparison to the reflector with standard finish. Such a light reflector is used for further investigations.

To investigate improvement of light collection when the plastic scintillator was cut into two parts and the cut edges were machined at the angle 45°, as shown in Fig. 3, detection efficiency was measured when: 1) scintillator was not cut; 2) scintillator was cut and fixed in a standard configuration as shown in Fig. 2; 3) when the 45° cuts of the scintillator edges were reversed, i.e. the reflected light (0–2, Fig. 3) was directed to the scintillator upper (SU) plane. As in the previous case, the probe was irradiated with the $^{90}Sr/^{90}Y$ source in ten positions. Based on count rate measurements corrected for background, detection efficiency was calculated for each measuring position, and mean value of the detection efficiency and max/min ratio was computed. All measurements were carried out at a constant gain of the measuring channel. The background count rate was 10–12 cps, the signal count rate after background correction varied in the range 80–400 cps, the background counting time = 5 min, and the signal counting time = 1 min. Results of the investigations are given in Table 2.

Based on the data in Table 2, the following observations can be made. The scintillator, cut at an angle of 45° in standard configuration ensures an increase of the mean total detection efficiency by 56% with respect to the not cut scintillator. Simultaneously, the max/min ratio is approximately 2 times lower than in the case of not cut scintillator. Reversed configuration of the scintillator ensures more than 40% increase of the total

Table 1. Light reflector arrangement

Background (cps)	η (cps/Bq)	Max/min	Scintillator cutting	Light reflector
10	0.212	2.2	Yes	Standard finish
10	0.248	1.9	Yes	Foil lined

Table 2. Plastic scintillator configuration and ZnS(Ag) phosphor

Parameter	Plastic scintillator			Source
	Not cut	Cut – standard configuration	Cut – reverse configuration	
Mean detection efficiency, positions 1÷4, (cps/Bq)	0.13	0.222	0.189	
Mean detection efficiency, positions 5÷8, (cps/Bq)	0.227	0.300	0.285	
Mean detection efficiency, positions 1÷10, (cps/Bq)	0.158	0.248	0.224	$^{90}Sr/^{90}Y$
Max/min ratio for single readings diameter 36 mm	4.00	1.90	2.40	
MAX/MIN ratio for reading size approx. 100 × 110 mm	1.75	1.35	1.50	
Mean detection efficiency, positions 1÷4, (cps/Bq)	–	0.304	–	
Mean detection efficiency, positions 5÷8, (cps/Bq)	–	0.356	–	
Mean detection efficiency, positions 1÷10, (cps/Bq)	–	0.324	–	^{241}Am
Max/min ratio for single readings diameter 49 mm	–	1.46	–	
MAX/MIN ratio for reading size approx. 100 × 110 mm	–	1.17	–	

mean detection efficiency with respect to the not cut scintillator. This means that the scintillation light that is primarily directed from the scintillator in the direction to ZnS(Ag) layer is quite well backscattered from the ZnS(Ag) layer in the direction to PMT.

To imitate calibration with large area calibration sources 10 × 10 cm², mean detection efficiencies for measuring positions 1÷4 and 5÷8 were computed and are given in Table 2. It can be considered with acceptable approximation that such mean detection efficiency is equal to the detection efficiency that can be achieved with a source 10 × 10 cm². The MAX/MIN ratio is the ratio of these two groups (1÷4 and 5÷8) and indicates that at a distance of 10 cm the detection efficiency varies by a factor = 1.35 and this is the highest possible variation across the entire probe area.

When checking responses of detection system to irradiation, a large area radiation source is recommended. This area should cover the whole active measuring surface, if such a source is available, [10], but smaller sources are acceptable as well. In the Technical Bulletin of US Department of Agriculture [1] contamination limits are given in activity units per 100 cm² area. Commonly used sources for calibration are the sources with dimensions 10 × 10 cm².

For measurement of alpha nuclide contamination, a semitransparent layer of ZnS(Ag) phosphor deposited on a thin plastic foil is placed above the plastic scintillator. Attenuation of $^{90}Sr/^{90}Y$ radiation by the ZnS(Ag) layer together with a plastic foil on which it is deposited decreases the count rate by approximately 1%.

Detection efficiency and uniformity of detection efficiency for alpha radiation were measured with an ^{241}Am source, the active diameter being 49 mm. The probe was irradiated in ten positions as shown in Fig. 5. The count rate was measured and corrected for background, and the detection efficiency was computed for each measured position. The mean total detection efficiency was computed (measured positions 1÷10), as well as the mean detection efficiency for measured positions 1÷4 and 5÷8 and the max/min ratio. The results of measurements and computations are given in Table 2. Detection efficiencies given in table include attenuation of beta and alpha radiation by the protection grid (transparency for alpha and beta radiation of protection grid is equal to 0.77).

A minimum detectable activity (MDA), which is an essential parameter characterizing any detection system for radioactive contamination is computed from the relation [10]

$$\mathrm{MDA} = 3.29k\sqrt{n_b\left(\frac{1}{t_b} + \frac{1}{t_s}\right)} \quad (\mathrm{Bq/cm^2})$$

$$k = (\eta\, p)^{-1}\ (\mathrm{Bq/cm^2})/\mathrm{cps} \text{ – calibration coefficient}$$

where: η (cps/Bq) – average detection efficiency; p (cm²) – probe measuring area; n_b (cps) – background count rate; t_b (s) – background counting time; t_s (s) – signal counting time.

For background n_b = 12 cps, background counting time t_b = 60 s, signal counting time t_s = 10 s, the average detection efficiency η = 0.248 cps/Bq for beta radiation, p = 23.5 × 11 = 258.5 cm², MDA = 0.0607 Bq/cm², and the corresponding calibration coefficient k = 0.0156 (Bq/cm²)/cps for beta radiation. For alpha radiation, the detection efficiency is η = 0.324 cps/Bq, MDA = 0.0465 Bq/cm² and the corresponding calibration coefficient k = 0.0119 (Bq/cm²)/cps.

Recommended permissible limits of surface contamination in laboratories are 10 Bq/cm² for $^{90}Sr/^{90}Y$ and 0.1 Bq/cm² for ^{241}Am [9]. It can be noted that the described scintillation probe is able to measure and easily detect whether the permissible level of contamination is not exceeded.

If only a contamination of alpha nuclides is to be measured, the MDA can still be improved. It can be done by an increase of pulse discrimination level that is accompanied by a simultaneous decrease of background count rate.

Measurements of alpha detection efficiency at elevated discrimination level, in a manner described earlier resulted in: background count rate n_b = 1 cps, average detection efficiency η = 0.221 cps/Bq, ratio max/min = 1.87, ratio MAX/MIN = 1.09. The corresponding k = 0.0175 and the MDA = 0.0197 Bq/cm².

Comments and conclusions

To improve light collection of scintillation, the trapped light from internal total reflection is extracted from the scintillator. This light is detected by a PMT together with escape light. To enable light extraction, a 1 mm thick scintillator is cut into two pieces and the edges are machined at 45° and polished. Detection efficiency achieved in such a manner is 56% higher, and uniformity of the detection efficiency is two times better for beta contamination. The plastic scintillator is used for beta contamination.

To detect contamination by the ^{241}Am (alpha) nuclide, semitransparent layer of ZnS(Ag) phosphor deposited on a thin plastic foil is placed on top of the plastic scintillator.

A light reflector in the form of an inverted pyramid with the cut off top is used in the probe to enhance light collection. Lining the reflector with a reflecting aluminum foil, improves the detection efficiency by 17%.

MDA of ^{90}Sr/^{90}Y (beta) contamination is MDA = 0.0607 Bq/cm^2, and of ^{241}Am (alpha) contamination MDA = 0.0465 Bq/cm^2. Both at a background level of 12 cps.

If only alpha contamination is to be measured, the MDA for alpha contamination can be improved by increasing pulse discrimination level (decrease of background count rate). At a background equal to 1 cps, the MDA = 0.0197 Bq/cm^2 for ^{241}Am contamination.

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