Evaluating Determination Limits for Scintillation Signal Considering Cherenkov Radiation in 3D-Printed Light Guides

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1. Introduction

In the detection of scintillation signals, one of the dark pulses to consider is Cherenkov radiation. Cherenkov radiation occurs when charged particles travel faster than the speed of light in a dielectric medium, emitting a faint, bluish light as a result. Generally, the amount of Cherenkov radiation produced in the light guide during scintillation signal detection is minimal and thus does not have a dominant effect on the overall signal. However, when detecting extremely weak scintillation signals, the dark pulse caused by Cherenkov radiation can be of comparable size to the net scintillation signal, potentially leading to measurement errors [1].

In this study, Cherenkov light signals were obtained for each length of the light guide. And the minimum net scintillation signal required to distinguish them from Cherenkov light signals was determined by calculating determination limit formula mentioned by Currie [2]. Drawing from these results, three analytical regions for signals considering Cherenkov and background signals were established.

This study aims to analyze the relationship between light guide length and Cherenkov radiation to enhance the accuracy of scintillation detectors, particularly in detecting very weak scintillation signals.

2. Methods and Results

2.1 Fabrication of Light Guide using 3D printing

The 3D-printed light guide was fabricated using an SLA-based 3D printer (Form 3, Formlabs) and a transparent resin (Clear V4, Formlabs). The light guide is in the shape of a truncated cone, with a top diameter of 9 mm, a bottom diameter of 15 mm, and a height varying from 1 mm to 5 mm in 1 mm increments, resulting in a total of five different light guides. Additionally, to increase the number of photons reaching the PMT, the sides of the light guide were coated with reflective paint (EJ-510, Eljen Technology). The fabricated light guides are shown in Figure 1.

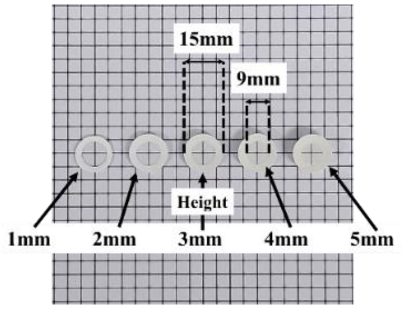

Fig. 1. 3D-printed light guide with reflective paint on the side.

2.2 Evaluating Cherenkov Light Signals

The Cherenkov light signal of each 3D-printed light guide was evaluated using the experimental setup shown in Figure 2. Each light guide was connected to a PMT (H10721-110, Hamamatsu), and Cherenkov light signals were generated in the light guide by a ^{137}Cs gamma source (9.45 μCi). Background measurements and Cherenkov light signal measurements for each light guide were conducted three times, with each measurement taking 20 minutes.

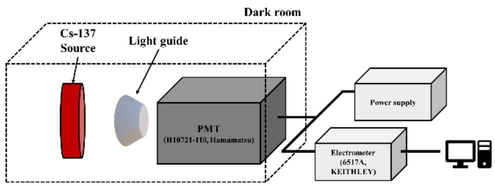

Fig. 2. Schematic of the experimental setup for measurement of Cherenkov light signal.

The Cherenkov light signal was obtained by subtracting the background signal from the measurements with the light guide in place. As shown in Figure 3, the Cherenkov light signal decreases as the length of the light guide decreases. Also, the Cherenkov light signal constitutes approximately 30% of the total signal. However, in cases where the light guide length is too short, such as 1mm or 2mm, the relative error for the Cherenkov light signal is 15.1% and 10.1%, respectively. Therefore, it is recommended to use light guides of at least 3mm in length for more accurate and efficient measurements. The resulting Cherenkov light signals and total signals are summarized in Table 1.

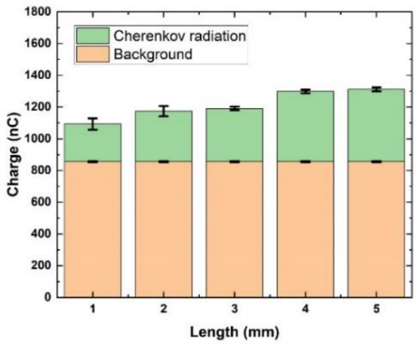

Fig. 3. Comparison of Cherenkov and background signals across different light guide length.

Table I: Cherenkov light signal and total signal values across different light guide length

Length [mm]	Cherenkov light signal [nC]	Total signal [nC]	Cherenkov ratio [%]
1	236.94 ± 35.72	1093.19 ± 35.70	21.67%
2	317.42 ± 32.38	1173.67 ± 32.35	27.05%
3	334.89 ± 10.60	1191.14 ± 10.53	28.12%
4	442.58 ± 11.35	1298.83 ± 11.28	34.08%
5	455.85 ± 12.33	1312.10 ± 12.27	34.74%

2.3 Calculation of the Determination Limit for Net Scintillation Signals

To calculate the minimum net scintillation signals required to distinguish them from Cherenkov light signals, the critical level(L_C), detection limit(L_D) and determination limit(L_Q) formulas were used [2]. Each formula is presented in Equation (1), (2) and (3) respectively,

$$(1)\ \ L_C = k_\alpha \sigma_0$$

$$(2)\ \ L_D = L_C + \frac{k_\beta}{2}\left\{1 + \left(1 + \frac{4L_C}{k_\beta^2} + \frac{4L_C^2}{k\alpha^2 k_\beta^2}\right)^{\frac{1}{2}}\right\}$$

$$(3)\ \ L_Q = \frac{k_Q}{2}\left\{1 + \left(1 + \frac{4\sigma_0^2}{k_Q^2}\right)^{\frac{1}{2}}\right\}$$

where k_α and k_β are Z-value of the standardized normal distribution corresponding to probability levels, 1 - α and 1 - β. Here, α represents the probability of a Type I error, which occurs when concluding that a substance is present when it is not, while β represents the probability of a Type II error, which occurs when probability of failing to detect the substance when it is present. In this study, the values of α and β were assumed to be 0.05, resulting in k_α and k_β values of 1.645. And σ_0 represents the standard deviation of the total signal of Table I.

Equation (3) represents L_Q, determination limit, which refers to the minimum level of quantification necessary to ensure that the analytical results meet the desired measurement accuracy and can be used for subsequent purposes. The k_Q represents the reciprocal of the standard deviation of L_Q. The calculated values of L_Q corresponding to different light guide lengths are summarized in Table II. In this study, k_Q was assumed to be 20 (σ_Q=0.05), which is more conservative than the value of 10 (σ_Q =0.1) used by Currie [2].

Table II: Determination Limit for net scintillation signals and total signals

Length [mm]	Calculated minimum net scintillation signal, L_Q [nC]	Required Total signal [nC]
1	941.51	2034.70 ± 59.08
2	877.29	2050.96 ± 54.51
3	490.41	1681.56 ± 26.69
4	501.56	1800.39 ± 27.50
5	516.51	1828.61 ± 28.59

Excluding the 1mm and 2mm light guides, which have relatively large σ_0 values and are less reliable, the 3mm light guide required the smallest net scintillation signal and had the lowest total signal magnitude. As shown in Figure 4, the three analytical regions were determined based on Equations 1 through 3. When the total signal that includes the net scintillation signal is within Region 1, the net scintillation signal cannot be detected. In Region 2, while the net scintillation signal can be detected, it cannot be quantitatively distinguished. At last, when the total signal is within Region 3, the net scintillation signal can be quantitatively separated from the Cherenkov and background signals.

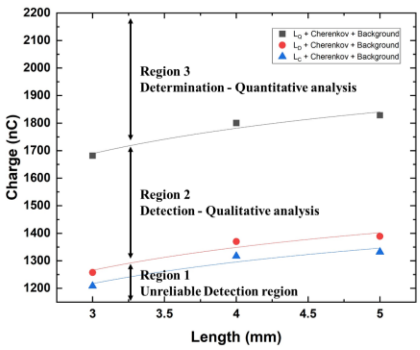

Fig. 4. The three analytical regions for signals considering Cherenkov and background signals.

3. Conclusions

In this study, Cherenkov light signals were obtained for different light guide lengths. The minimum net scintillation signal required to effectively distinguish these Cherenkov light signals from very weak scintillation signals was determined using the calculation formula for the determination limit. The methods and conclusions derived from this study are expected to aid in optimizing the volume of light guides in applications where detecting extremely small signals, such as scintillation signals from skin-imitation layers [3, 4], is crucial.

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