Attenuation length in strip scintillators

Jonathan Button, William McGrew, Y.-W. Lui, D. H. Youngblood

I. Introduction

The ΔE-ΔE-E decay detector as described in [1] is composed of thin strip scintillators, which provide the ΔE signals, and of large block scintillators, which provide the E signals. An important characteristic of scintillators is the attenuation length λ of the light response, which is defined as the length for which the probability that a photon is not absorbed is 1/e. Due to the long and thin geometry of the strip scintillators (Saint Gobain BC408, dimensions 1mm x 1cm x 18cm), the attenuation length of the light response as quoted by Saint-Gobain (λ=210 cm) [2] is not appropriate because it is only valid for a bulk scintillator where the maximum distance from the connected PMT is small relative to the scintillator's height and thickness. A simulation of optical photon transport in the strip scintillators was used to make a more accurate estimate of the attenuation. The results of the simulation are then compared to analyzed data from a test run of the decay detector.

II. Calculated Attenuation Length

Of particular concern with the scintillator strips is the reduction of the light response due to photons which leave the scintillator when they strike a surface boundary of the material before entering the light guide. This was estimated by modeling the strip as a 3D rectangular volume (1 mm x 1 cm x 18 cm) in which photons are emitted randomly in position and momentum with an overall uniform distribution. The fraction of the emitted photons that reach the fiber optic cable is then obtained as a function of position along the strip.

When the photon strikes a boundary, if the angle of the photon trajectory relative to normal is greater than or equal to the critical angle (refractive index of 1.58) [2], then the photon reflects off the surface and remains inside the scintillator. For angles less than the critical angle, the reflection and transmission probabilities are calculated and then used to determine whether or not the photon remains inside the scintillator. The efficiency of the scintillator is determined by dividing the number of photons that arrive at the fiber optic end by the total number of photons generated. The efficiency is plotted with respect to initial position of the randomly generated photon from the end of the scintillator connected to the fiber optic bundle in Fig. 1. The simulated data were fit with a sum of two exponential decay curves ($y=a_1e^{-x/\lambda_1}+a_2e^{-x/\lambda_2}$). The first term is the transmission behavior for photons that travel directly to the end or have angles less than the critical angle measured with respect to normal of the refractive surface, effectively a "solid angle" for photons emitted which decreases rapidly with distance from the fiber optic connection. The attenuation length ($\lambda_1 = 1.8$ cm) for this mode of transmission is very short relative to the length of the scintillator. The second term is the transmission behavior for photons that are not incident on a surface or have angles greater than or equal to the critical angle when incident on a surface. The attenuation length ($\lambda_2 = 104.3$ cm) for this mode is much longer.
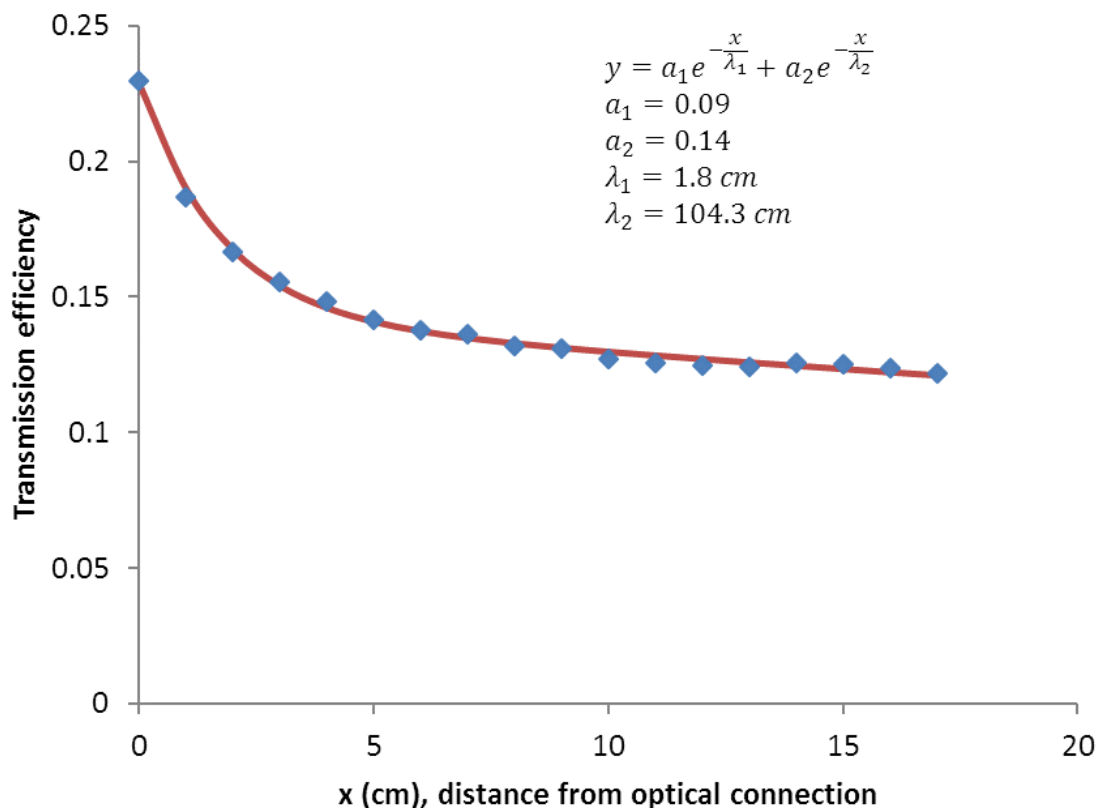
$$y = a_1 e^{-\frac{x}{\lambda_1}} + a_2 e^{-\frac{x}{\lambda_2}}$$
$$a_1 = 0.09$$
$$a_2 = 0.14$$
$$\lambda_1 = 1.8\ cm$$
$$\lambda_2 = 104.3\ cm$$

FIG. 1. Simulation result for the transmission efficiency of optical photons in a thin, strip scintillator (1cm x 1mm x 18 cm) with respect to the initial distance of the photon from the scintillator connection with its PMT.

III. Test Run Results

A test run of the completed decay detector was done using a beam of 30 MeV protons on a ^{12}C target. Overlapping segments of the vertically and horizontally aligned ΔE arrays form pixels which lie at some angle relative to the beam direction. In the array closest to the target, designated ΔE1, 13 scintillator strips are oriented vertically and are labeled V1 through V13, where V1 is the furthest left relative to the beam direction. V7 is centered above the beam path and is not of full-length. In the array ΔE2, 13 scintillator strips fill 12 horizontal rows labeled H1 through H12, where H1 is positioned at the top of the array. The H9 row is composed of 2 shorter length strips (H9L and H9R) located on the left and right of the beam path.

From the pixel geometry shown in Fig. 2, we know that the light response in the horizontal strips of the strip pairs which form the pixels should be the same (in the absence of the attenuation effect) at equal distances, left or right, from the center. This is because those pixels lie at equal angles with respect to the beam direction and will have the same energy deposited. The attenuation length in the individual

strips can then be measured by comparison of the light response from the symmetric pixel pairs about the detector center. This method has the advantage of not relying on estimates of the energy deposited.
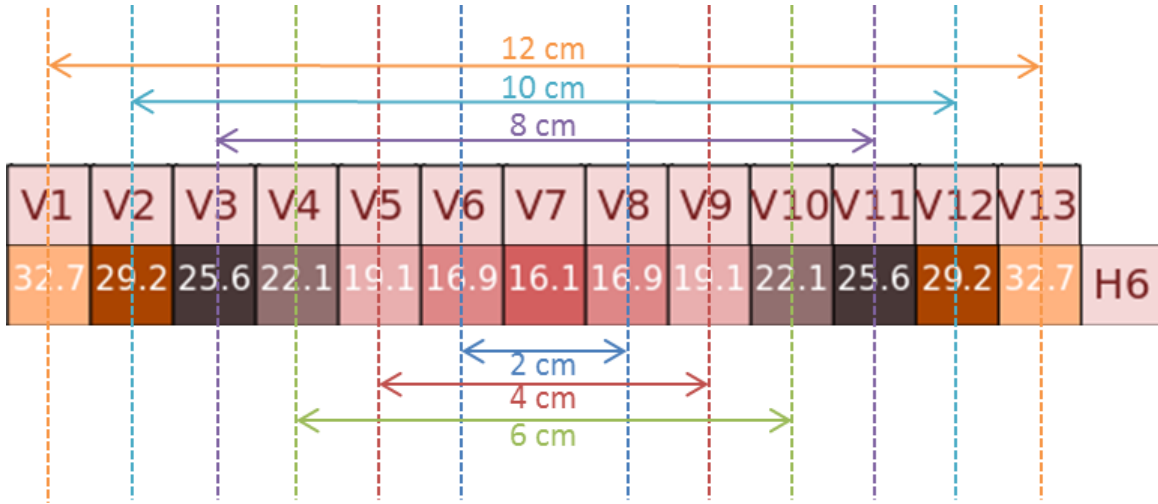

FIG. 2. Median distances between pixels that would have an equal light response in the absence of the attenuation. The value shown inside each pixel is the angle of that pixel relative to the beam direction.

The energy resolution in the 2D $\Delta E1$-$\Delta E2$ spectra is too large to distinguish the different energy protons (Fig. 3). However, examining the 2D $\Delta E1$-$\Delta E2$ spectra is advantageous for determining the attenuation length because of the smaller pitch between strip scintillators than between block scintillators.
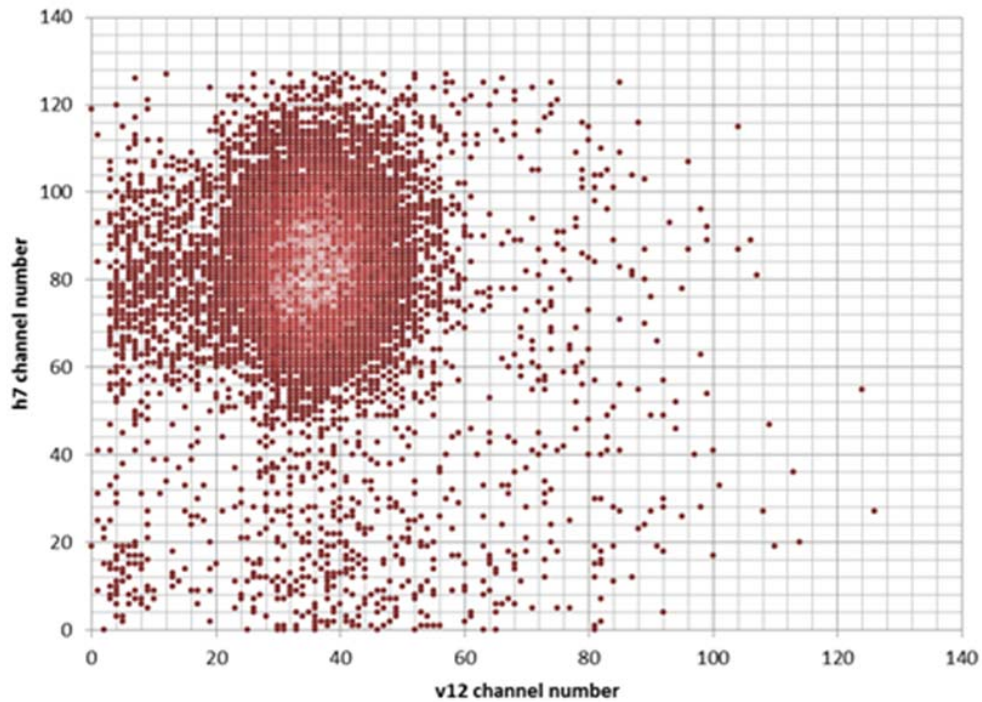

FIG. 3. An example $\Delta E1$-$\Delta E2$ 2D-spectrum. The three peaks visible in the $\Delta E2$-E 2D-spectra are not visible here due to the poorer energy resolution of the strip scintillators.

The ratio of the light response in the symmetric pixel pairs (relative light transmission = light response in the pixel further away from the optical connection / light response in the pixel closer to the optical connection) can be directly compared to the result from the simulation of the attenuation behavior (Fig. 1). The light response is taken to be the average peak position in the raw spectra and is shown in Fig. 4. The calculated ratios of the light responses are also shown in Fig. 4. The calculated ratios assume λ_1 = 1.8 cm and λ_2 =104.3 cm. Since none of the pixels are within 3 cm of the optical connection, the fits to the measured attenuation is not sensitive to the value of λ_1. They are shown for varying values of the distance from the optical connection to the pixel coincident with vertical strip V7 (which sits at the center of the vertical strip array). This distance is difficult to measure precisely because when the strips are wrapped and installed onto the frame, the position of the optical connection is hidden from view. Consequently, the distance between the center of the array and the optical connection for the horizontal strips used to calculate this attenuation length has a large uncertainty and is taken to be 10±1 cm. The
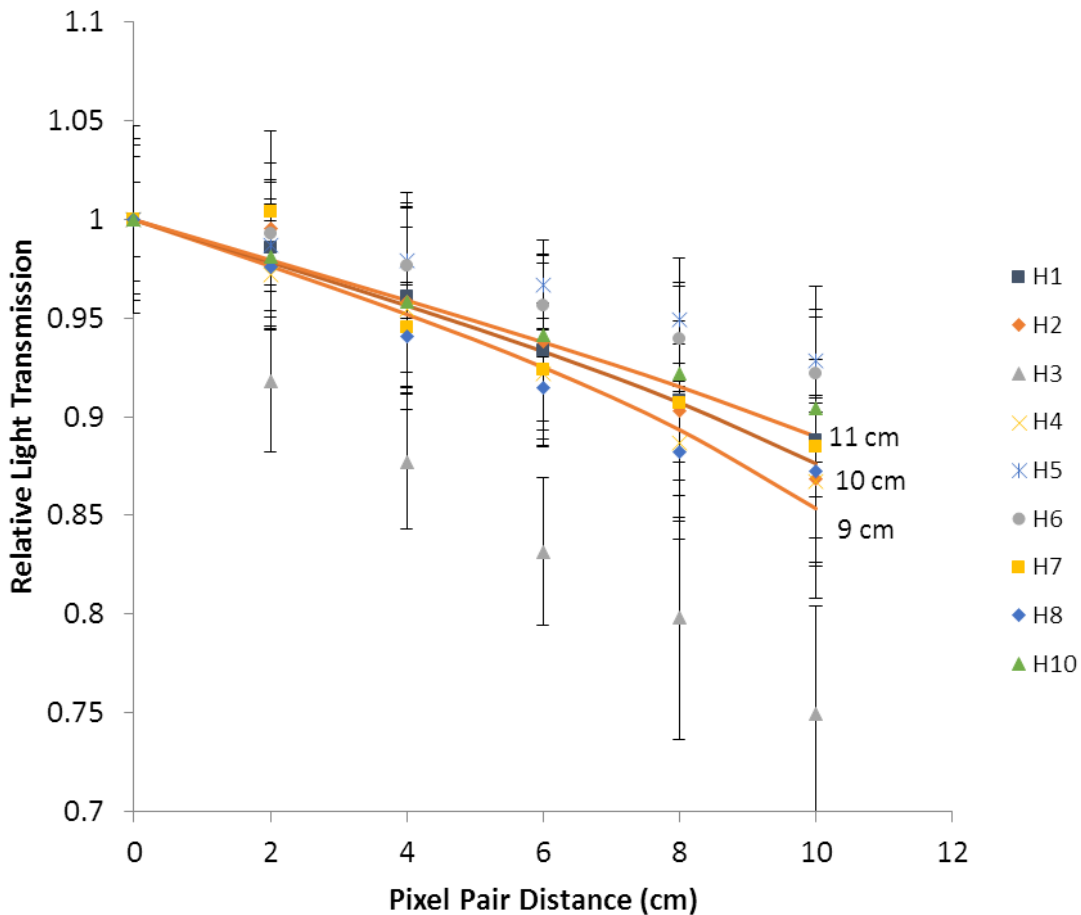

FIG. 4. Relative light transmission in horizontal strips vs. the distance between pixel pairs. The relative light transmission is the ratio of the light responses between the paired pixels. The pixel pair distance is described in Fig. 2. The plotted lines are the calculated values of the relative light transmission for varying distances (11 cm, 10 cm, and 9 cm) from the optical connection to the V7 strip.

measurement fits within the calculated range in all but three of the horizontal strips (H3, H5, and H6). In strip H3, the transmission efficiency decays faster than expected. The best fit to the data from strip H3 gives attenuation lengths of $\lambda_1 = 1.8$ cm and $\lambda_2 = 36.4$ cm. Damage to the scintillator strip is a possible cause of the shorter attenuation length λ_2. In strips H5 and H6, the observed attenuation length, $\lambda_2 = 165$ cm, is much longer than expected but $\lambda_1 = 1.8$ cm in these strips as well. Further tests should be done with these strips in order to understand the cause of the better than expected performance.

IV. Conclusion

The response by the ΔE1 and ΔE2 layers in coincidence was used to make a measurement of the attenuation length of the light response. Analysis of the attenuation behavior as a function of the distance between symmetric pixel pairs showed that the majority of the horizontal strips are working as expected. The attenuation behavior should be measured consistently in this manner in order to ensure that the strips are in good condition.

[1] J. Button, Master's Thesis, Texas A&M University, 2013.
[2] Saint-Gobain Ceramics & Plastics, Inc., Saint-Gobain Ceramics & Plastics, Inc. BC 400-404-408-412-416 Data Sheet, 2008), 2012.