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TECHNICAL REPORT

Optimization of light yield by injecting an optical filler into the co-extruded hole of the plastic scintillation bar

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ABSTRACT: The light yield of 2-m long extruded scintillation bars (strips) are measured with cosmic muons as a function of the distance for different options of the light collection technique. The strips with a 2.6-mm diameter central co-extruded hole were made of polystyrene with the 2% PTP and 0.03% POPOP dopants at ISMA (Kharkov, Ukraine).

It is shown that the optical transparent BC-600 or CKTN-MED(E) resin injected by a special technique into the co-extruded hole with a 1.0-mm or 1.2-mm Kuraray Y11 (200) MC wave-length shifting (WLS) fiber in it improves light collection by a factor of 1.6–1.9 against the "dry" case.

KEYWORDS: Particle detectors; Trigger detectors; Muon spectrometers; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

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1 Introduction

Detectors based on extruded plastic scintillation bars (strips) are widely used in high-energy physics (HEP) experiments, particularly, in most of the neutrino experiments and will be used in the coming experiments [1]. Usually, strips have a rectangular or triangular cross section of a few square centimeters and a length of a few meters: 8 m (MINOS [2]), 7 m (Mu2e [3]), 6 m (OPERA [4]), 3.5 m (MINERvA [5]) and 3 m (T2K [6]). They are co-extruded with groove(s) or hole(s).

The efficiency of detectors based on plastic scintillation counters with wavelength shifting (WLS) fibers is determined by the light yield of the "Scintillation strip — WLS fiber — Photo detector (PD)" system. The WLS fiber partially absorbs blue light produced by the scintillator, re-emits it to the longer-wave light (according to dopant) and transmits it to the PD. The most world famous WLS fibers manufacturers are Kuraray (Japan) [7] and BICRON (U.S.A.) [8].

WLS fibers are usually inserted into the groove or the hole in the bar, and they are often coupled to the scintillator at the groove by high-transparency optical epoxy cement with the refractive index close to the one of the scintillator. This technique (optical coupling) increases the light yield by a factor of up to 1.8 [2]. In the case of bars with a co-extruded hole, the WLS fiber is usually simply inserted into the hole, which means an air optical contact inside of the hole between the PS and the fiber, a so-called "dry" strip.

We carried out an investigation with cosmic muons for the optimization of the light collection from a 2-m long triangle-shaped extruded scintillation strip with the co-extruded hole accommodating a WLS fiber (1.0-mm or 1.2-mm in a diameter Kuraray Y11 (200) MC fiber). The hole was filled with some optical resins (optical glue without hardener) by the developed special technique. Both ends of the fibers were polished and the readout end was coupled to the EMI9814B PMT with/without optical grease while another end was covered by aluminum Mylar.

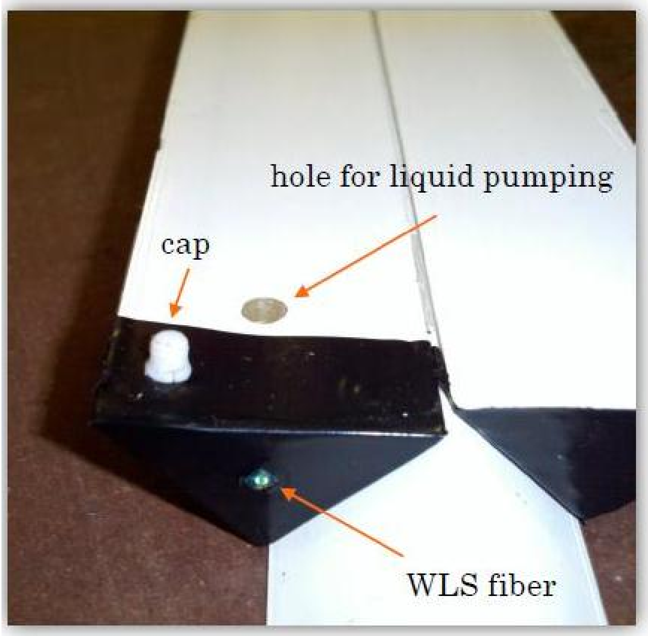


Figure 1. View of the 2-m strip with the co-extruded hole and the WLS fiber inserted in it. The strips have a triangular cross section with a base of 33 mm and a height of 17 mm and a hole 2.6 mm in diameter at the center.

2 Design overview

We tested 2-m long scintillation strips (figure 1) with a triangular cross section based on polystyrene (PS) plastic scintillator with the 2% PTP and 0.03% POPOP dopants extruded at ISMA (Institute for Scintillation Materials, Kharkov, Ukraine) [9]. The strips were covered by a reflective TiO_2 material and had a 2.6-mm diameter hole at the center. Strips with a similar shape were widely used in many experiments (MINERvA [5], T2K [6], D0 [10] et al.).

A very high efficiency (99.99%) of scintillation counters is required in some HEP experiments, for instance, for the Cosmic Ray Veto system in Mu2e [3]. High-quality optical coupling of the WLS fiber to the scintillation strip is one of the promising ways to attain it. The optical grease used for coupling of the WLS fiber end to the PMT window may additionally increase light collection.

In our case, the WLS fiber was inserted into the co-extruded hole of the strip and then the ends of the fiber were fixed by glue at the edges of the strip; the hole was later filled with optical resin of various types and the optical grease was placed between the end of the WLS fiber and the PMT window (figure 1). Finally, the light yield collected on the PMT was studied with cosmic muons crossing the strip at different distances from the PMT.

Different types of optical transparent fillers for the short strips (50 cm) were used in the first series of tests [11]: distilled water ($n = 1.33$ at 20°C); 46% aqueous solution ($n = 1.39$) of medical glycerin; ultralow-viscosity Spectrum-K-59EN glue ($n = 1.46$) [12]; CKTN-MED(E) — synthetic silicone (resin) with low molecular weight ($n = 1.60$) [13].

The first three fillers have low viscosity (< 20 mPa*s) and are easily inserted into the strip hole by a syringe. The CKTN(E) resin has high viscosity of 10 to 20 Pa*s, and we had to develop a

Table 1. Properties of the optical glues used.

Glue	Refractive index, n	Transmittance, %, at wavelength ~ 500 nm	Thickness of glue layer, mm	Viscosity, Pa*s	Cost, USD/kg
BC-600	1.56	> 98	0.130	0.8	~ 270[1]
CKTN-MED(E)	1.606	92–97	10	10–20	~ 30[1]
CKTN-MED(D)	1.606	92–97	10	6–10	~ 30[1]

[1] January 2016, private communication.

special technique for inserting it into the strip hole (see details in chapter 2 or in [11]). The study of the light yield for 50-cm long strips with these optical fillers showed an increment in the light yield up to 40–50% against the "dry" strip case, and the best result was obtained with the resin ([11]).

Once the study of the light yield of the short strips with these fillers was finished, we decided to study the light yield of a 2-m long strip filled with the resin (CKTN-MED(E) or Bicron BC-600).

3 High-viscosity optical glues as a filler

Different optical glues were used for optical coupling in different experiments: BC-600 epoxy glue in [4–6, 14, 15]; Shell EPON 815C epoxy resin in MINOS [2]; SUREL SL-1 silicon resin [13] (St. Petersburg, Russia) in the Belle II end-cup KLM detector [16].

We decided to use the BC-600 resin as a reference and the CKTN-MED(E) resin as its alternative (table 1). CKTN-MED(E) is produced by the SUREL Company [13], it is based on the synthetic silicone resin of low molecular weight, has high flexibility and transmittance at 500 nm (> 95%), is chemically inert and hydrophobic, and its refractive index $n = 1.606$ is very close to the one of the PS ($n = 1.59$).

It is rather difficult to insert the glue into the hole since an ordinary optical glue has a high viscosity (see table 1). This is why WLS fibers are usually inserted in a dry strip. In this case, it is desirable that the diameter of the co-extruded holes and fibers be as close to each other as possible. For instance, the diameters of the hole and the WLS fiber were 0.891 mm and 0.835 mm for the preshower detectors in the D0 experiment [10]; 1.8 mm and 1.5 mm for the SciBar detector in the K2K experiment [17]. However, for strips above 3 m in length, it is difficult to meet this demand: the hole/fiber diameter ratio can be as large as 2 and more, so, it is desirable that a suitable optical filler be injected into the hole.

We restricted our study to only the base (resin) of the two-component glues without a hardener because dependence of viscosity on the polymerization time is not well known.

A special setup was designed and constructed to pump a high viscosity filler into the strip hole (figure 2). The dry type compressor (1) creates the initial pressure, and the SL101N Digital Liquid Dispenser (2) provides a constant pressure at the output (about 0.2–0.4 bar over the normal). The pressure is monitored by the manometer (3). This constant pressure is provided in a special vessel based on the Drechsel bottle (4) with an optical filler in it (5) and forces the filler to flow through the tube (6) and the inlet (7) into the hole of the strip (8) with the WLS fiber (9) in it. It takes about two hours for a 2-m strip under small overpressure of 0.2 bar (approximately). Both ends of the

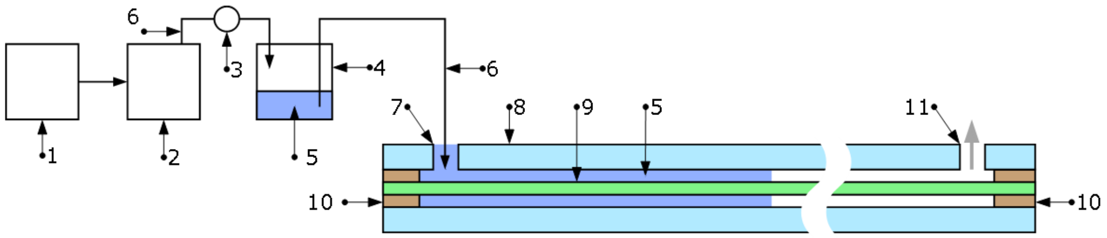


Figure 2. Setup to pump the high viscosity filler into the co-extruded hole of the scintillation bar (no scale): (1) dry type compressor; (2) SL101N digital Liquid Dispenser; (3) manometer; (4) special vessel with filler; (5) filler; (6) polyvinylchloride tube; (7) inlet for filling; (8) strip; (9) WLS fiber; (10) sealing; (11) exhaust outlet for extracting air.

WLS fibers are glued to the strip edges before the filling procedure (10). Air is removed from the strip hole through the exhaust outlet (11).

The reflective coating of the 50-cm long strip sample was preliminarily removed to check visually the filling process. We observed escaping air bubbles inside of the co-extruded strip hole during the filling. Once the filling process was completed, no bubbles were observed along the hole and high adhesion of the resin to the fiber and the hole surface were visually demonstrated.

4 Investigation with high-viscosity fillers

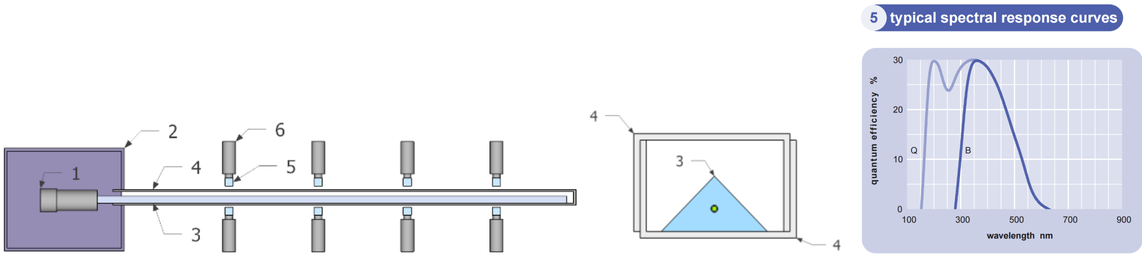
We studied the light yield of 2-m long triangular strips with the WLS fiber filled with the CKTN-MED(E) or BC-600 resin. The tests of the 2-m and 50-cm strips were performed in two stages: first, the light yield was measured from the "dry state" and then, from the same strip filled with the resin. Readout was performed, as described above, from one end by coupling 1.0-mm or 1.2-mm diameter Kuraray Y11(200) MC WLS fibers to the EMI 9814B PMT with a bialkali photocathode (active diameter 46 mm) and quantum efficiency of about 15% at 500 nm [18] . Both ends of the fibers were polished, but the far end was covered by Al Mylar except when it was covered by black paper.

Crossing the boundary of two mating substances (with refractive indices n1 and n2), the light undergoes reflection and so can be partially lost. The amount of the losses depends on the ratio of the refractive indices, on the light incidence angle, etc. In the case of the normal incidence, it can be evaluated by the Fresnel equation for the reflection R: $R = [(n1 - n2)/(n1 + n2)]^2$. So, the optimal light transmission for an optical system including different substances would be achieved if their refractive indices match each other as much as possible.

BC-600 and CKTN-MED(E) optical resins used as fillers in the hole of the PS strip meet the above requirements. Moreover, these fillers have good adhesion with PS. Light is effectively transmitted through the Kuraray Y11(200) MC WLS fiber to the PMT by the total internal reflection due to the reflective indices of the core and inner and outer claddings 1.59, 1.49, 1.42 respectively.

Transmission of light from the WLS fiber end to the PMT is followed by reflection on their boundary, so various optical coupling compounds are usually employed to optimize light transmission. We used the Dow Corning 20-057 optical coupling composition (grease) [19] with the refractive index 1.48, which is close to that of the PMT window (refractive index of quartz glass is about $n_{\text{quartz}} = 1.5$). An air layer was used as reference as well.

The setup for light yield measurements of long strips using cosmic muons is shown in figure 3(a, b). Light was collected by the EMI9814B PMT (1) placed inside of the lightproof box (2). The readout strip (3) was placed inside of two lightproof Al U-channels (4) covered by black paper inside (not shown). The cosmic ray telescope was comprised of four pairs of plastic scintillation counters (5) with dimensions 20x25x30 mm^3 coupled to the FEU85 (6) PMT [20]. High voltage supplied to the EMI9814B PMT and FEU85 PMT was 2200 V and 1000 V respectively. Measurements were performed at eight distances (60, 70, 90, 110, 140, 150, 170, 190 cm) from the PMT in two stages.



(a) (b) (c)

Figure 3. Experimental setup layout (a), cross section of light-proof Al U-channels with a strip inside (b) and spectral response curves of the EMI9814B PMT (c). (1) EMI9814B PMT, (2) black box, (3) strip, (4) lightproof Al U-channel, (5) four pairs of trigger scintillation counters 20x25x30 mm, (6) FEU 85 PMT.

The electronic block diagram of the experiment is shown in figure 4. The analog signal from the PMT is measured by the LeCroy ADC 2249W charge-to-digital converter. Signals from the cosmic telescope are discriminated by the LeCroy 623B; the LeCroy622 coincidence module creates an output signal to mark the position by the Jorway 65 input register and runs the LeCroy 222C gate generator to produce the strobe signal with a width of 100 ns.

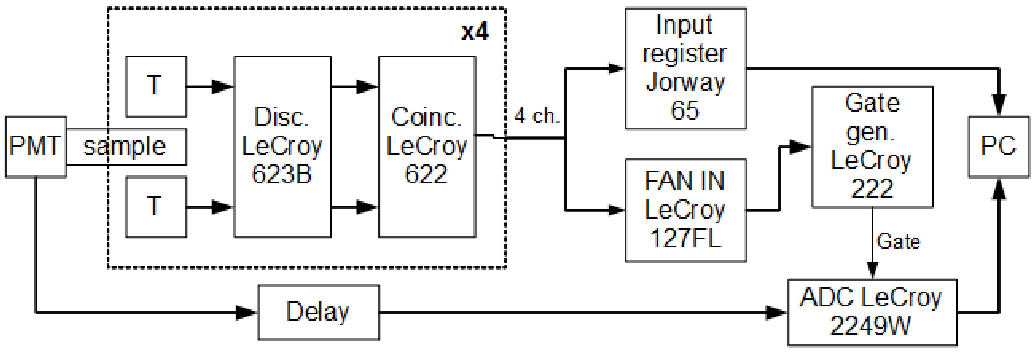


Figure 4. Block diagram of the electronics used for measurements with cosmic muons.

The spectrometric channel was calibrated in absolute units (number of photoelectrons) [21]. The calibration was made by means of a "NICHIA" NSPB310A light emission diode (LED) [22] using light flashes of low intensity incident on the PMT photocathode. One of the typical calibration spectra obtained with the LED is shown in figure 5 where one photoelectron is clearly observed

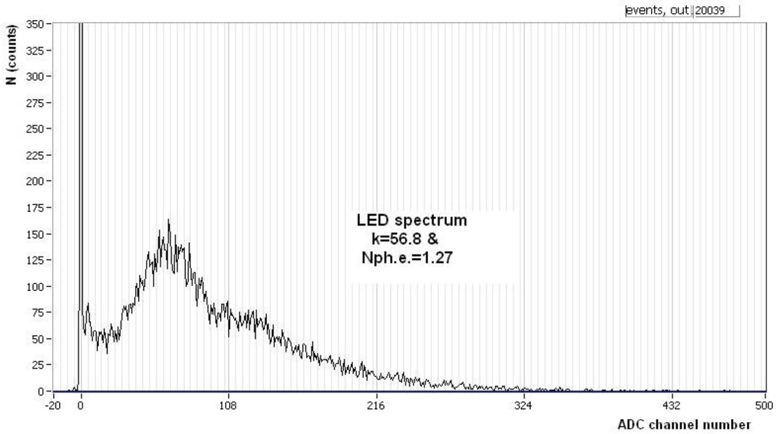


Figure 5. Typical LED spectrum, where k is the expected one-photoelectron position and $N_{\mathrm{ph.e.}}$ is the mean number of photoelectrons incident on the photocathode.

(two-photoelectron position is visible too). LED calibrations were made before and at the end of each individual run.

5 Results of measurements

The light yield of the strip with a WLS fiber was studied at the different distances between the trigger counters and the PMT, with various fillers and diameters of WLS fibers in the strip hole and with different contacts between the fiber end and the PMT (grease or air). The data presented in figures 6–8 were fitted by the exponential function $N_{\mathrm{ph.e}} = N_0 \exp(-x/\lambda)$, where λ is the technical attenuation length (TAL) of the strip + WLS fiber system defined as a length where the intensity of light propagation in such a system decreases by a factor e; x is the distance along the strip, $N_{\mathrm{ph.e.}}$ is the light yield in photoelectrons, and N_0 is the calculated light yield at x_0.

Light yield measurements for the strip with the BC-600 as a filler were only performed with the 1.0-mm WLS fiber (figure 6). One can see that the light yield of the strip filled with BC-600 is 1.6 ± 0.2 times higher than that of the "dry" strip (curves 2 and 3 respectively, no optical grease was used to couple WLS fiber and PMT. Optical grease between the PMT and the WLS fiber gives an additional increase of 15% in light yield (figure 6, curve 1).

Light yield measurements for the strip with the CKTN-MED(E) and the 1.0-mm WLS fiber in its hole (figure 7) were performed in the same way as with the BC-600. One can see that the light yield of the strip with the CKTN-MED(E) is 1.7 ± 0.2 times higher than that of the "dry" strip (curves 2 and 4 respectively), no optical grease was used to couple the WLS fiber and the PMT. Using optical grease between the PMT and the WLS fiber gives an additional increment of 20% in the light yield (figure 7, curves 1).

It is worth noting that the light yield results for the strips with 1.0-mm WLS fiber in the hole filled by CKTN-MED(E) or BC-600 are almost similar.

Light yield measurements of the strip with the 1.2-mm WLS fiber and the CKTN-MED(E) as a filler and without it are presented in figure 8. One can see that the light yield of the strip

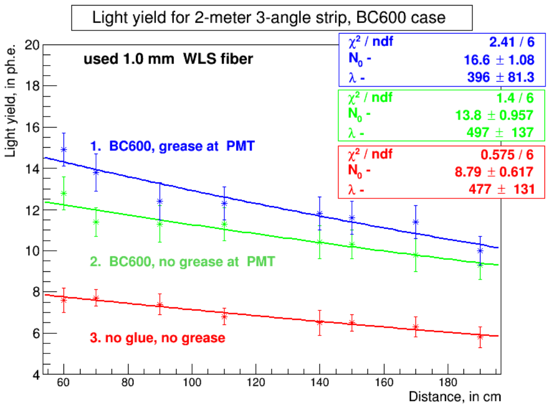


Figure 6. Light yield as a function of the distance for the strip filled with the BC-600 and read out by the 1.0-mm WLS fiber coupled to the PMT with optical grease (1), without it (2) and for the "dry" strip without optical grease (3).

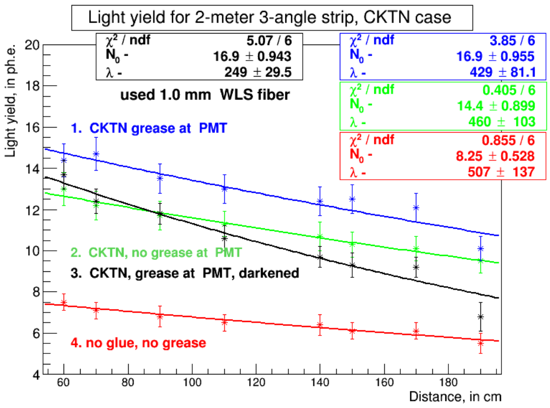


Figure 7. Light yield as a function of the distance for the strip filled with the CKTN-MED(E) and read out by the 1.0-mm WLS fiber coupled to the PMT with optical grease (1); without it (2); with the far end darkened (3) and for the "dry" strip without optical grease (4).

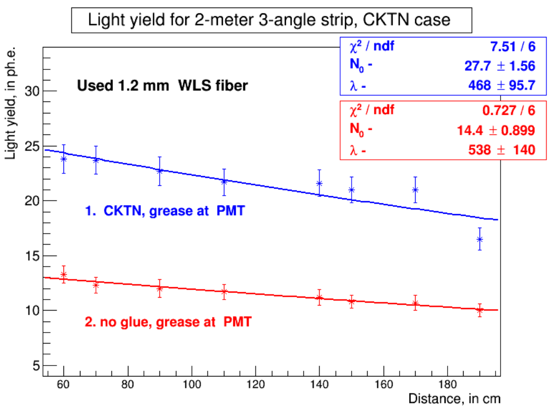


Figure 8. Light yield as a function of the distance for the strip filled with the CKTN-MED(E) and read out by the 1.2-mm WLS fiber coupled to the PMT with optical grease (1) and for the "dry" strip with optical grease (2).

filled with the CKTN-MED(E) is 1.9 ± 0.2 times higher than that of the "dry" strip (curves 1 and 2 respectively); optical grease was used to couple the WLS fiber to the PMT in both cases.

A similar high increment of 1.8 and 1.6 in the light yield was reached in [2] and [23] respectively. For instance, at MINOS [2], the WLS fiber was set totally deep into and glued to the groove on the wide side of the rectangular strip and, moreover, a reflective aluminum Mylar tape was placed over the groove. With this technique, the achieved optical conditions were close to those in the strip with the hole. In [23] the WLS fiber was glued into the groove at several points along the 2.5-m strip at equal distances of 40 cm.

A comparison of the light yield results for the bars with the WLS fibers 1.0 mm and 1.2 mm in diameter and the CKTN-MED(E) filling shows that the light yield in the 1.2-mm fiber case is a factor of 1.6–1.7 higher than in the 1.0-mm fiber case (curves 1 in figures 7 and 8). A similar result for the light yield ratio was obtained with the Bicron WLS fibers 1.0 and 1.2 mm in a diameter [24].

The technical attenuation length (TAL) was found to be about 5 m for the case with the reflector on the far end, and the use of the filler, with other condition being the same, did not produce any obvious changes. A significant decrease in light collection with increasing distance from the PMT (and its uniformity deteriorates as well, curve 3 in figure 7) was observed when the far end of the strip was covered with black paper. TAL also decreased by a factor of 2 (figure 7). This result points to the importance of using a highly reflective material on the far end of the WLS fiber.

But in some cases, when the time resolution of the scintillation counter is of crucial importance, the blackened end of a fiber can be used to exclude a contribution of the reflected light. It improves the time resolution but worsens the light yield from the strip. Injection of the optical resin into the hole with the WLS fiber could be one of the simple solutions to compensate for the light yield losses.

We also investigated the behavior of the light yield in time for the strip with the 1.0-mm WLS fiber and the CKTN-MED(E) filler. No obvious difference in light collection was observed for this strip over the 6-month period: 14.0 ± 0.7 and 13.9 ± 0.7 photoelectrons in the middle part of the strip.

6 Conclusions

The light yield of the 2-m long triangle-shaped extruded scintillation strips with the co-extruded 2.6-mm central hole accommodating a WLS fiber and filled with the CKTN-MED(E) or the BC-600 optical resin was studied using cosmic muons. The light was read out from one of the WLS fiber ends coupled to the PMT, the other end was mirrored or blackened.

We developed a special technique to inject with the BC-600 or CKTN-MED (E) optical resin into the co-extruded hole accommodating the WLS fiber.

Filling of the strip hole with the CKTN-MED(E) or BC-600 optical resin gives the increase in light yield by a factor of 1.6–1.9 against that of the "dry" strip. Both optical resins showed almost similar results.

An increase in light yield with the 1.2-mm diameter WLS fiber is almost 1.6 times large than with the 1.0-mm diameter WLS fiber with other conditions being the same.

One can conclude that the TAL for the "strip + WLS fiber" optical system is mostly determined by the WLS fiber. At the same time, the TAL with the 1.2 mm fiber is about the same as with the 1.0 mm fiber.

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Insertion of an optical resin into the hole with the WLS fiber in it could be one of the simple solutions to compensate for the light yield losses when the blackened far end of a fiber is required to improve the time resolution of the strip counter.

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