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Light yield and radiation hardness studies of scintillator strips with a filler

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ABSTRACT

Detectors based on polystyrene scintillator strips with WLS fiber readout are widely used to register charged particles in many high-energy physics experiments. The fibers are placed into grooves or holes along the strip. The detection efficiency of these devices can be significantly increased by improving the optical contact between the scintillator and the fiber by adding an optical filler into the groove/hole.

This work is devoted to the study of the light yield of a 5 m long scintillator strip with a 1.2 mm diameter Kuraray Y11(200) MC WLS fiber inserted into the strip's co-extruded hole filled with synthetic silicon resin SKTN-MED(E). The light yield was studied using cosmic muons and a ^{60}Co radioactive source.

Viscous fillers and short strip samples were irradiated by neutrons on the IBR-2 pulsed research reactor at JINR.

1. Introduction

Long scintillator strips are used in many high-energy physics experiments. The light collection for these detectors is usually performed by WLS fibers inserted into grooves or holes in the strips. In some experiments [1–3] in order to establish more efficient coupling of the WLS fiber to the strip and to increase the light yield, the fiber was glued into the groove of the strip with an optical glue having a high transparency and a refractive index close to the refractive index of the strip base material (usually polystyrene).

Filling the strip hole with glue a WLS fiber is complicated task due to limited working time of the glue, especially for long strips. Therefore, the WLS fiber is usually inserted into the strip holes without using any filler. For instance, in the Cosmic Ray Veto (CRV) system for the upcoming Mu2e experiment (Fermilab, [4]), WLS fibers will be inserted into the strip holes without the filler. In this case, light propagation from the scintillator to the WLS fiber is through the air layer. Large difference in refractive indices at the "scintillator-to-air" and "air-to-outer WLS fiber cladding" interfaces results in losses of light because of reflection. Earlier we showed [5] that injection of some optically transparent liquids (fillers) into the strip holes led to a light yield increase of up to 50% in comparison to the strips without a filler. Using a liquid filler instead of a glue to fill strip holes is a more simple option, especially for long strips.

A low-molecular weight synthetic resin SKTN-MED(E) [6] revealed good gain in light yield, so we selected it for further studies. However, the resin has a high viscosity (10–20 Pa∗s) and, therefore, its injection into the strip hole 2.6 mm in diameter with a 1.2 mm diameter WLS fiber already installed in it was a complicated task. We developed a special technique to solve this problem [5,7]. Light yield studies of a 2 m long polystyrene strip (with dopants 2% PTP and 0.03% POPOP; produced by ISMA [8]) with a 1.2 mm diameter Kuraray Y1(200)MC WLS fiber [9] inserted in the strip hole and filled with the SKTN-MED(E) silicon resin also showed the increase [7] in the light yield in comparison to the same strip but with no filler. This strip had a triangular cross-section with a base of 33 mm and a height of 17 mm and a 2.6 mm diameter co-extruded hole.

Long-term stability of parameters of detectors based on scintillator strips is important for experiments at modern accelerators. Deterioration of these parameters may be due to influence of radiation and natural factors (temperature, humidity). In particular, part of the CRV system (for Mu2e experiment at FNAL, [4]), which is a multilayer array of strips with WLS fibers, will experience significant exposure to neutron fluxes during data taking (see Fig. 1, [10]). Six CRV modules close to the transport solenoid (CRV-TS) and three CRV modules in front of the pipeline wall (CRV-U) will be irradiated by the highest expected neutron fluence among the CRV modules, up to 10^{11} neutrons per cm^2 [10].

To investigate the effect of this type of radiation, we studied radiation hardness of SKTN-MED (grade E and D), epoxy resin BC-600 [11],

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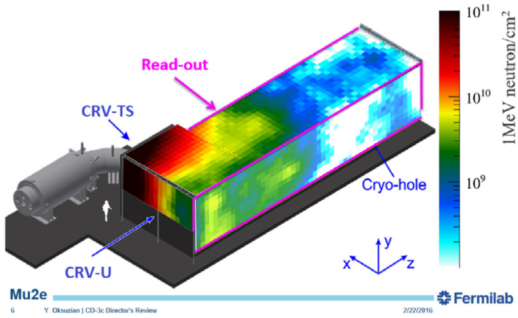


Fig. 1. Expected distribution of neutron fluences [10].

and short strip samples with these fillers at the IBR-2 pulsed research reactor of fast neutrons (FLNP, JINR [12]).

2. Selection of an optical filler and its injection into a strip

The filler, as an intermediate medium transferring light from a scintillator to a WLS fiber, should have a number of properties: high optical transparency, refractive index close to the refractive index of polystyrene and WLS outer cladding, good adhesion to the scintillator, radiation hardness, etc.

Several different substances (water, aqueous solution of glycerin, UV-adhesive SPECTRUM K-59EN [13], SKTN-MED (E)) were tested as fillers [5]. The first three low-viscosity substances (< 20 mPa∗s) were injected into the strip by a syringe, but a special technique was required for injection the high-viscosity SKTN-MED(E) resin (10–20 Pa∗s). This technique was tested on a short (50 cm) strip. The study of the light yield of the 50 cm long strips with these optical fillers showed a 50% increase in the light yield against the strip without a filler. The best result was obtained with the SKTN-MED (E) resin [5].

Full-scale studies of the light yield for 2 m long extruded scintillation bars with SKTN-MED(E) resin as a filler were carried out [7]. This resin has high transparency in the visible region of the spectrum (about 95%). The refractive index is 1.40, which is very close to the WLS outer cladding refractive index of 1.42. This is important since the light undergoes scattering at the interface of two media with refractive indices n_1 and n_2, and the reflection coefficient for the light normally incident on the interface is described by the Fresnel formula

$$R = \left[\frac{n_1 - n_2}{n_1 + n_2}\right]^2 \quad (1)$$

The setup used to inject the SKTN-MED(E) resin into the 5 m long strip was upgraded in comparison with used in [7]. The triangular cross-section of the strip was the same as in [7], with a base of 33 mm and a height of 17 mm and a hole 2.6 mm in diameter in the center. The layout of the pumping setup is shown in Fig. 2. The dry-type compressor (1) produces initial pressure, and the SL101N Digital Liquid Dispenser (2) provides a constant pressure at the output (about 0.2–0.4 bar above atmospheric pressure), which 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.

Both ends of the WLS fiber are glued by 5-min transparent epoxy (Hardman RED 04001 [14]) to the strip edges (10) before the filling procedure. Air escapes from the strip hole through the exhaust outlet (11). Once filling is done, the inlet and outlet holes of the strip are sealed with 5 min transparent epoxy.

3. Light yield of a scintillator strip

We studied the light yield of a 5 m long strip as a function of the distance from the PMT using cosmic muons and radioactive sources. In addition, Monte Carlo (MC) simulation of the light collection from a 5 m long strip was performed.

3.1. Light yield modeling

MC simulation of the light collection was conducted using Geant 4 [15], version 10.3.1. The geometry of the 5 m long scintillator strip with a WLS fiber and a reflective coating described by Geant 4 corresponded to the actual samples used in the measurements. The cosmic muon energy was modeled according to [16].

Muons generated by this model are incident normally on the strip at a certain distance from the strip end where the photodetector is installed.

Light emission initiated by the passage of the muons through the scintillator, light absorption and subsequent re-emission by the WLS fiber, and light reflection and refraction on the fiber and strip coating were simulated according to the optical model described in Geant 4. While modeling, we limited simulations to counting photons at the end of the fiber and did not consider the processes associated with the photodetector. Dependence of the average number of photons arriving at the WLS fiber end on the distance to the point of incidence of cosmic muons is shown in Fig. 3(a). The points in this figure correspond to different ways of light reflection at the far end of the fiber and to the cases without a filler and with an optical filler with properties similar to those of SKTN-MED(E). The curves in Fig. 3(a) correspond to the fit by an exponential function.

The effect of the optical filler on the average number of photons for each point is shown in Fig. 3(b). The ratio between the average numbers of photons for the filled (N_{filled}) and unfilled (N_{dry}) scintillator bars shows a significant advantage of the proposed method for increasing the light collection.

The dispersion of the time for photons to reach the photodetector surface and the signal intensity significantly depend on the reflectivity of the far end of the fiber. Fig. 4 shows dependence of the number of photons versus the time of their arrival at the photodetector for different distances from the point of incidence of cosmic muons and for the blackened and mirrored ends of the fiber.

With the far end mirrored, the delayed signal of the photons reflected from the far end of the WLS fiber was clearly separated (Fig. 4(b)). This fact indicates that the mirroring leads to light yield increase but deteriorates the signal time resolution and should not be recommended for long scintillator strips if the arrival time of the reflected signal exceeds the designed light integration gate.

Knowledge of the light intensity distribution over the WLS fiber cross-section plays an important role in selection of the optimal photodetector. The simulation results (see Fig. 5) show that the light intensity in the optical fiber increases radially from the center outward and reaches the maximum in the region close to the first fiber cladding.

3.2. Light yield study with cosmic rays

Light yield studies of the 5 m long strip using cosmic muons were carried out by the same method as used for the 2 m long strips [7]. The cosmic trigger counters were set at different distances from the PMT along the strip (see Fig. 6). The measurements were done under various conditions: the strip without a filler and with the far end blackened as a first step and then with the strip filled with SKTN-MED(E) resin and the strip and the WLS fiber ends far from the PMT blackened or covered with aluminized mylar. Light was collected by the EMI9814B PMT (1) [17] placed inside of the lightproof box (2). The readout strip (3) was placed inside of two lightproof Al U-channels (4) covered inside by black paper. The cosmic-ray telescope was comprised of four pairs

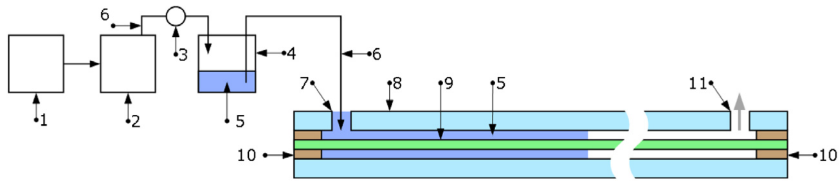


Fig. 2. Layout of the filling setup.

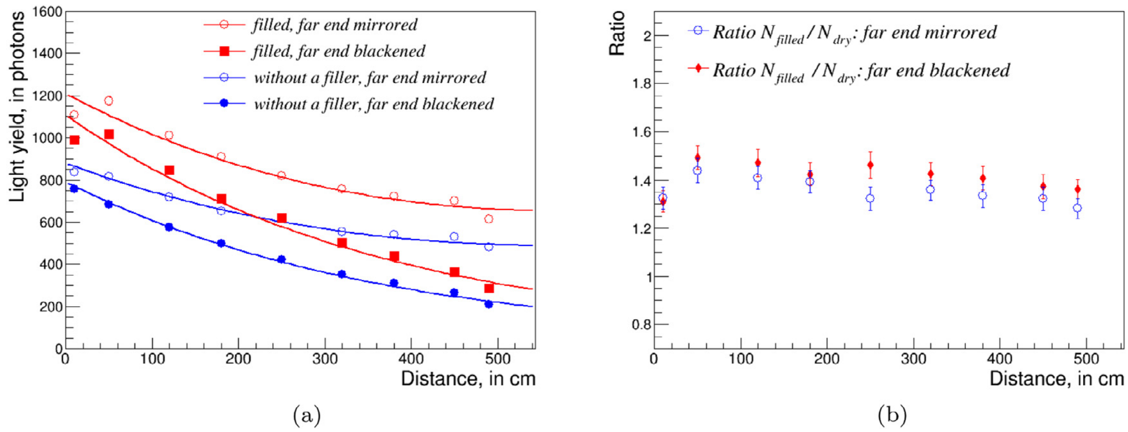


Fig. 3. Simulation results for the light yield from the 5 m long strip with a triangular cross-section (a). Relative increase in the light yield (b).

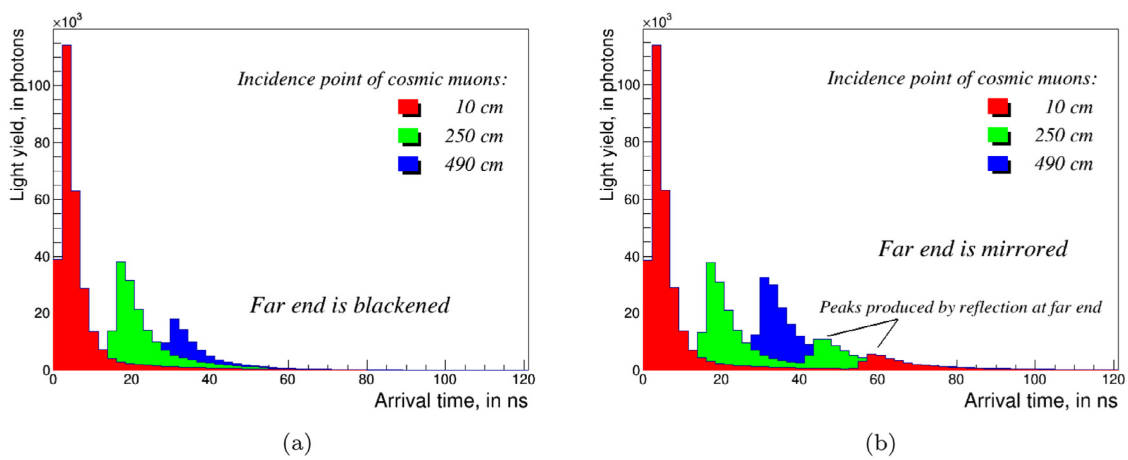


Fig. 4. Simulation results for the light signal arrival at the photodetector from different distances.

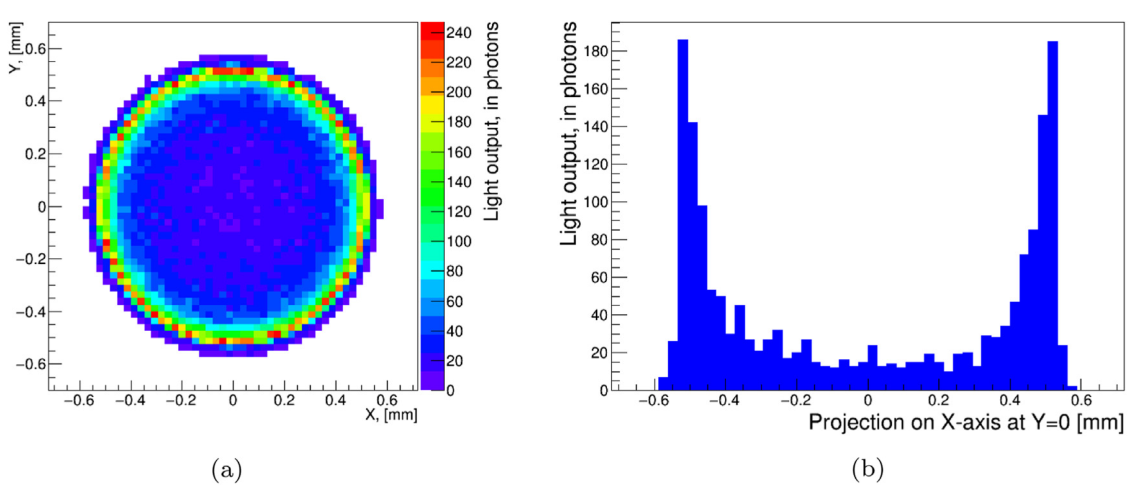


Fig. 5. Light distribution at the WLS fiber end: (a) - 2D distribution chart at the fiber end; (b) - projection on X-axis at Y=0.

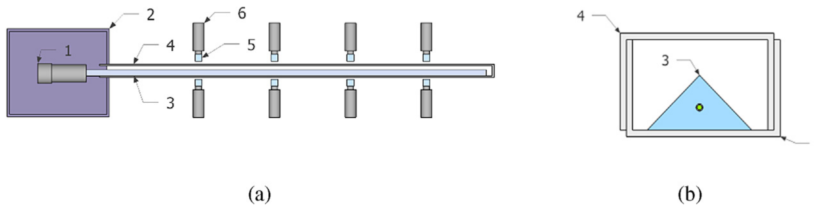


Fig. 6. Layout of the experimental setup (a) and the cross-section of the lightproof Al U-channels with a strip inside (b); (1) EMI 9814B PMT, (2) black box, (3) strip, (4) lightproof Al U-channel, (5) four pairs of $(20\times25\times30)$ mm^3 trigger scintillation counters, (6) FEU 85 PMT.

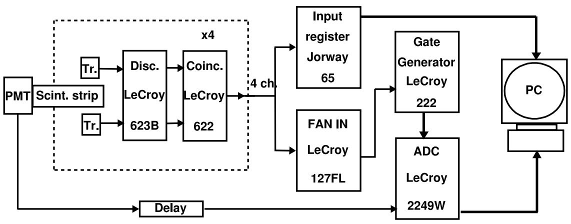


Fig. 7. Block diagram of the electronics used for measurements with cosmic muons.

of $(20\times25\times30)$ mm^3 plastic scintillation counters (5) coupled to the FEU 85 PMT (6) [18].

The DAQ system for the experimental setup is compromised of NIM and CAMAC modules. The electronics block diagram of the experiment is shown in Fig. 7. The analog PMT signal is measured by the LeCroy ADC 2249 W charge-to-digital converter. Signals from the cosmic telescope are discriminated by the LeCroy 623B; the LeCroy 622 coincidence module creates an output signal for the Jorway 65 input register to tag the muon passage position and runs the LeCroy 222C gate generator to produce the strobe signal with a width of 100 ns.

The spectrometric channel was calibrated using the PMT single electron peak. The calibration was performed with a ''NICHIA'' NSPB310A light emission diode (LED) [19] using flashes of low-intensity light sent to the photocathode of the EMI9814B PMT.

Fig. 8 presents the results of measuring the light yield of the strip with the 1.2 mm diameter Kuraray Y11(200) MC fibers and SKTN-MED(E) resin; the ends of the strip and the WLS fiber far from PMT were covered by aluminized mylar (curve 1) or blackened (curves 2 and 3). The experimental data were fit with bi-exponential functions [20]

$$N(x) = N_0\left(e^{-\frac{x}{\Lambda}} + K_{refl}e^{-\frac{2L-x}{\Lambda}}\right) \tag{2}$$

where x is the distance along the strip; N_0 is the approximated value of the light yield at $x=0$ (at PMT); Λ is the technical attenuation length; L is the length of the strip, and K_{refl} is the reflection coefficient of the surface of the material used as a mirror. The mean value for the three technical attenuation length values (Λ) obtained by the fit is 398 ± 17 cm, and the coefficients of reflection from mirrored and blackened ends are 0.74 ± 0.12 and 0.09 ± 0.04, respectively.

For direct comparison of the light yield from the strip with and without a filler the light yield of the strip without a filler was studied first. The light yield increases in the strip with a filler and a blackened end in comparison to the strip without a filler (approximately by 50%) (curves 2 and 3, Fig. 8(a)). Increase in the light yield (up to a factor of two) is observed in the strip with the filled hole when the ends of the strip and the WLS fiber far from PMT are covered by aluminized mylar (curve 1, Fig. 8(a)).

Increase in the light yield of the strip filled with SKTN-MED(E) resin against the light yield of the same strip without a filler as a function of the distance to the PMT is presented in Fig. 8(b); the end far from PMT was blackened. The simulation is close to the experimental data.

Mirroring the end of the fiber far from PMT gives a gain in the light yield, but broadens the light output in time (see Section 3.1). Therefore, when the time resolution and the high repetition rate are crucial, the far end of the strip (fiber) should be blackened. The speed of light in the WLS fiber is around 16 cm/ns [21,22]. This will result in a delay of the light signal reflected from the far end of the strip by about 47 ns for the passing muons in the middle of the 7 m long strip (see also Fig. 4(b)); such a strip corresponds to the longest detectors to be used for the CRV system in the Mu2e experiment.

3.3. Light yield study with a radioactive ^{60}Co source

A radioactive ^{60}Co source was used to study the light yield of the 5 m long strip as a function of the distance to the PMT by measuring the anode current of the EMI9814B PMT using the Keitley 6487 picoammeter [23].

The source was placed on a special support which was moved along the strip. The results of the study are shown in Fig. 9. The experimental data were fitted with biexponential functions similar to Eq. (2), but for the PMT anode current instead of the number of photoelectrons

$$I(x) = I_0\left(e^{-\frac{x}{\Lambda}} + K_{refl}e^{-\frac{2L-x}{\Lambda}}\right) \tag{3}$$

The upper two curves correspond to the strips filled with SKTN-MED(E) resin and the lower one corresponds to the strip without the filler; the ends of the strip and the WLS fiber far from PMT were mirrored (curve 1) or blackened (curves 2 and 3; curve 2 corresponds to the strip with the filler and curve 3 corresponds to the strip without the filler). The light yield of the strip with the filler is 1.5 times higher than the light yield of the strip without the filler. The mean value for the three technical attenuation lengths values (Λ) obtained by the fit is 393 ± 22 cm, and the coefficients of reflection from mirrored and blackened ends are 0.71 ± 0.12 and 0.08 ± 0.02, respectively. These results are close to the results obtained in Section 3.2.

4. Radiation hardness study

Long-term stability of detector parameters based on scintillator strips is important due to long-term continuous operation in modern experiments; these properties can deteriorate under the influence of both radiation and natural factors (temperature, humidity, time). Some aspects of radiation hardness and aging studies are published in [24–34].

Some of scintillator strips of the CRV modules will experience significant exposure to neutron fluxes during the data taking at Mu2e experiment (see), so it is important to investigate the radiation hardness of the fillers.

4.1. Radiation hardness studies at the IBR-2 pulsed research reactor with fast neutrons

The irradiation facility [35] of the IBR-2 pulsed research reactor at the Frank Laboratory of Neutron Physics, JINR was used to investigate radiation damage of strips and synthetic silicon resins SKTN-MED(D) and SKTN-MED(E)[1]

[1] The SKTN-MED(D) and SKTN-MED(E) resins have a different viscosity: 6–10 Pa*s for SKTN-MED(D) and 10–20 Pa*s for SKTN-MED(E) [7].

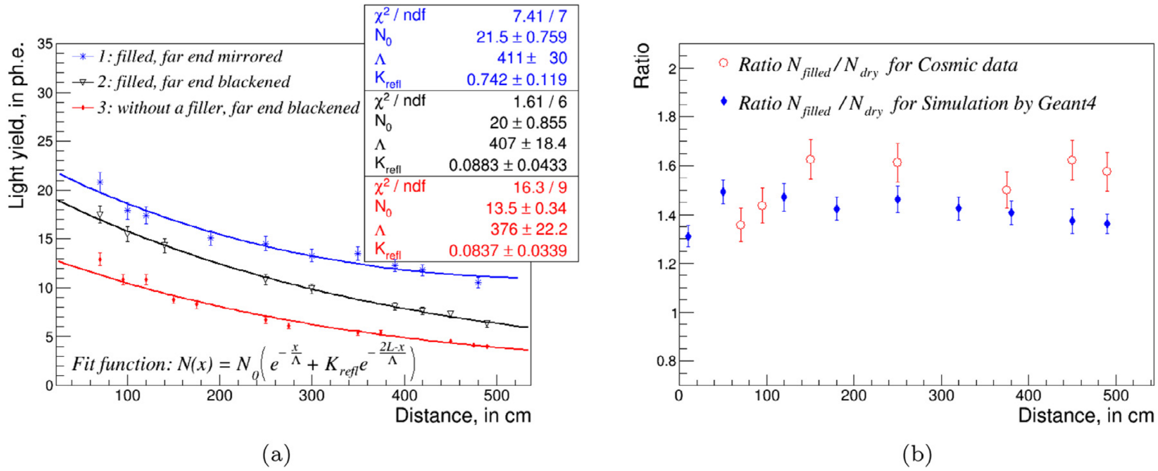


Fig. 8. Light yield (in photoelectrons) of the 5 m long strip on cosmic muons under different conditions of the study (a). The experimental data with the simulation (b).

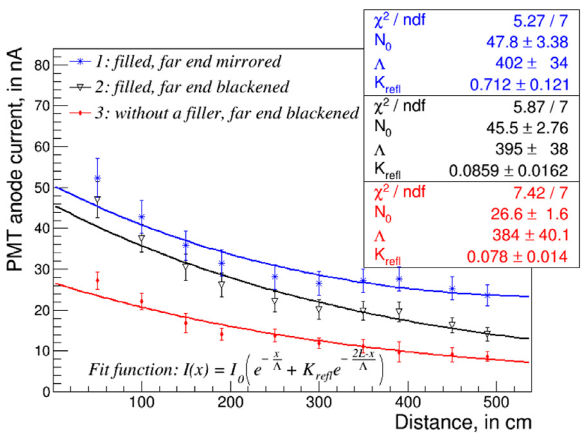


Fig. 9. Light yield as a function of the distance from the PMT for the 5 m long strip irradiated by the radioactive ^{60}Co source.

The SKTN-MED(D), SKTN-MED(E) and BC-600 resins and short polystyrene strip samples with the WLS fiber hole filled or not filled with those resins were irradiated by a neutron beam.

Studies of the 2 m long strips with the SKTN-MED(E) and BC-600 fillers showed very close results in light yield [5,7]; therefore, it was of particular interest to compare radiation hardness of these fillers.

The 2 m long strip was cut into 12 samples each 15 cm long to carry out radiation tests; inlet and outlet holes were drilled in each sample for injecting the filler in and letting the air out during the filling. The 1.2 mm diameter Kuraray Y11(200) MC WLS fibers were inserted into the strips. The ends of the fibers were fixed with 5-min transparent epoxy [14] at the ends of the strips and polished. The strip ends were covered with black plastic with a hole to bring the fiber out.

These 12 short strips were divided into three groups. In each group one strip was without a filler and the other three were filled with SKTN-MED(E), SKTN-MED(D) or BC-600 resin. Each of the resins was also poured into plastic containers (a total of nine containers). Then strips with different fillers and containers with different resins were placed at different distances from the reactor core. Thus, three different radiation exposures (fluences) of 1.2×10^{14}, 3.8×10^{14} and 16.0×10^{14} neutrons/cm^2 were obtained (see Table 1, which also presents the corresponding neutron flux densities and absorbed doses for γ rays). The indicated fluxes refer only to fast neutrons ($E > 1$ MeV), and the fluxes of slower (thermal and resonance) neutrons are not included in this table. Therefore, the total radiation doses received by the samples were somewhat higher.

Table 1
Neutron flux density, fluence, and γ rays dose for the irradiated samples ($E > 1$ MeV)

Location	Flux density n/cm^{2}s	Fluence n/cm^2	γ background Mrad
1	1.35×10^8	1.2×10^{14}	0.37
2	4.4×10^8	3.8×10^{14}	0.47
3	1.8×10^9	16.0×10^{14}	5.4 … 1.4

4.2. Optical properties of glues and their bases after irradiation at the IBR-2

The transmittance of the glues and their bases (just resins) for the wavelength (λ) region from 200 to 800 nm was measured before and after irradiation by a Shimadzu SolidSpec 3700DUV spectrophotometer [36]. The resins were poured into small cuvettes for measurements. The cuvettes were made on a 3D printer providing the resin layer thickness of 4 mm. The windows of the cuvettes were made from a regular 1 mm thick Plexiglas sheet, which led to the suppression of the ultraviolet region of the spectrum with a wavelength less than 300 nm. The results of these measurements for the SKTN-MED(E) and SKTN-MED(D) resins are given in Figs. 10(a) and 10(b), respectively. Small variations in the curve behavior are due to the uncertainty of environment conditions and the transparency of the cuvettes. x

One can see that transmittance of both resins is close to 90% at wavelengths of more than 400 nm after the irradiation by a neutron beam with the fluences of 1.2×10^{14} and 3.8×10^{14} per cm^2. The transmittance is almost the same as before the irradiation. Note that the irradiation with the fluence of 16.0×10^{14} neutrons per cm^2 led to polimerization of the resin, which made it impossible to pour this resin into the cuvette and measure its transmittance by the spectrophotometer.

It was of interest to study transmittance of the SKTN-MED(D) glue (resin+hardener). We made 4 mm thick sheets using the SKTN-MED(D) glue. Only 2%–6% of hardener are needed for polymerization, which proceeds fast (in about 30 min). Transmittances of these sheets were measured before and after the neutron irradiation (1.2×10^{14}, 3.8×10^{14}, and 16.0×10^{14} neutrons per cm^2; see Fig. 11). One can see that their transmittances are at a level of 90% as high as for the resin transmittance (see Fig. 10). However, the actual transmission spectrum of the glue starts from about 225 nm. Note that this shift of the transmission spectrum is due to the fact that the Plexiglas windows do not transmit ultraviolet light with wavelengths longer than 300 nm.

It is also of interest to study radiation hardness of the widely used BC-600 optical epoxy glue and compare the results with those for SKTN-MED. We measured transmission of polymerized BC-600 glue and unpolymerized BC-600 base (just resin) samples. The results for the BC-600 glue and the BC-600 resin before and after the irradiation by the

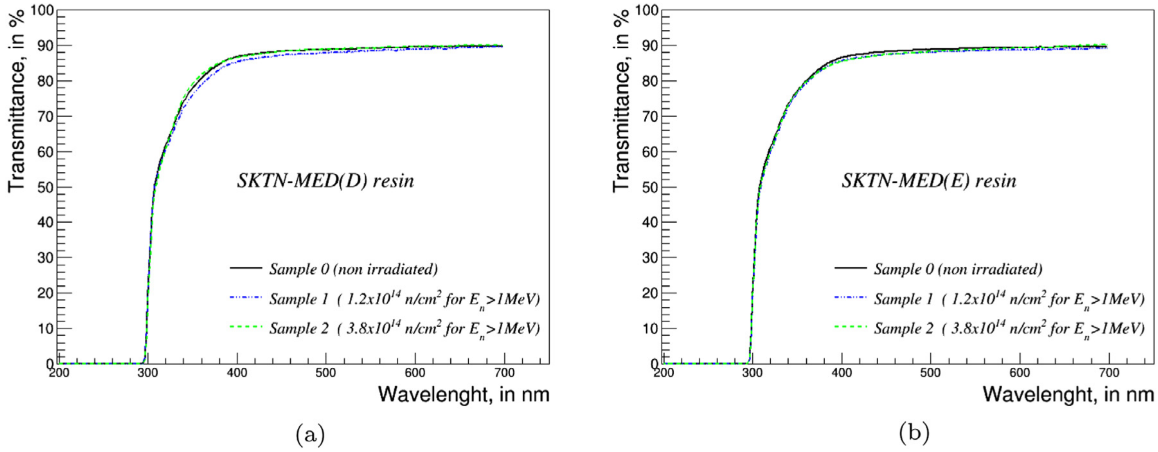


Fig. 10. Transmittance of SKTN-MED(D) and SKTN-MED(E) resins as a function of the light wavelength before and after the irradiation by the neutron beam with different fluences. The Plexiglas window suppressed strong ultraviolet light (less than 300 nm).

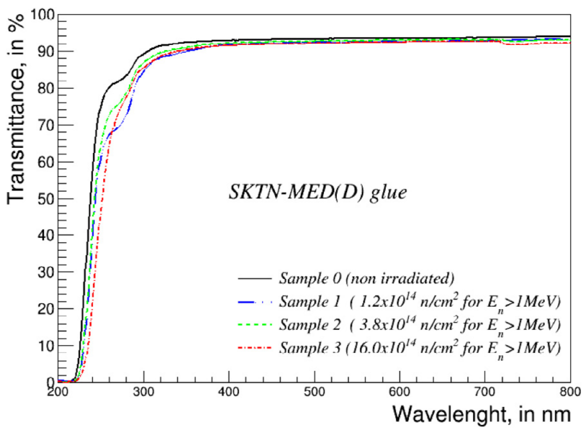


Fig. 11. Transmittance of the sample made of the SKTN-MED(D) glue before and after the irradiation by the neutron beam with different fluences.

neutron beam as described in Section 4.1 are shown in Figs. 12(a) and 12(b) respectively.

In [30], losses of transmission were studied in thin samples of BC-600 glues with the thickness of 1.5 and 3.0 mm. These samples were irradiated with γ rays emitted by ^{60}Co with the dose of 27 kGy. The dependence of the transmittance on the acquired dose shown in this article is in agreement with our results shown in Fig. 12(a).

4.3. Changes in the light yield of the strips with and without a filler after irradiation at the IBR-2

It is of interest to study how radiation affects optical properties of strips with a filler and WLS fiber. For this purpose, 15 cm long strip samples with and without a filler were irradiated at the IBR-2 with fast neutron (E > 1 MeV) fluxes as described in Section 4.1. The light yield of the strips without a filler and filled with various resins was measured using a picoammeter and radioactive source before and after the irradiation. The radioactive source was placed in the middle of the sample.

Measured values of anode currents for the strips filled with different resins were quite similar before the irradiation, while they decreased with increasing neutron fluence after the irradiation (see Table 2; errors came from distributions of 2000 current measurements). For location 1, the light yield decrease of the strip without the filler is similar to one of strips filled with SKTN-MED (D and E), and the slightly worse result obtained for the strip filled with the BC-600 resin. At the same time, optical transmittance of SKTN-MED (D and E) practically did not change and dropped about by 10% for BC-600 for blue light at this neutron flux (see Figs. 10 and 12(b)). Summarizing all the above, one can conclude that light yield losses are mainly caused by the deterioration of the strip and the WLS fiber for this level of exposure.

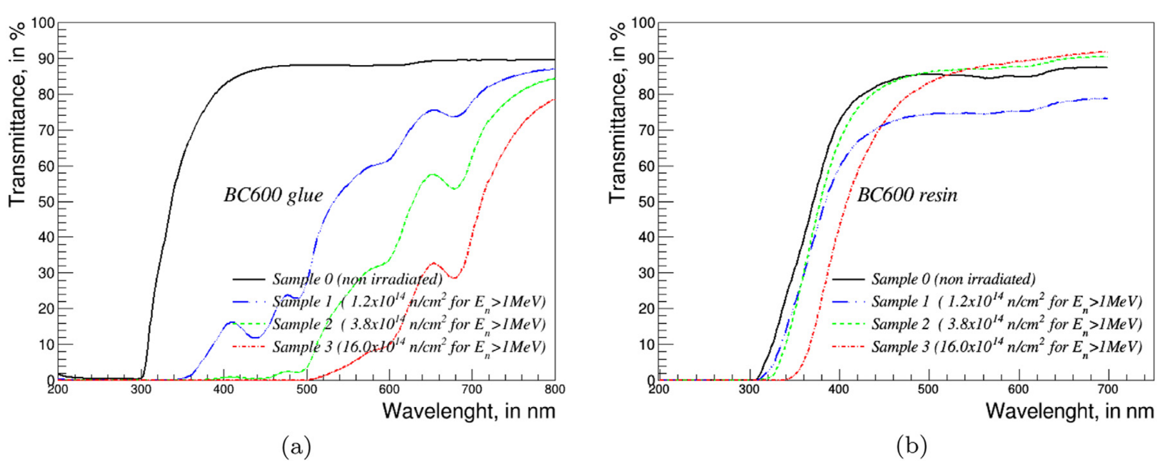
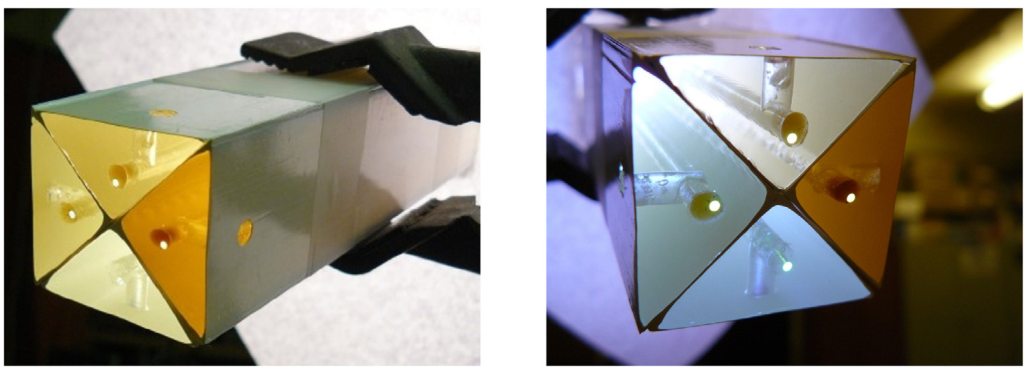


Fig. 12. Transmittance of the BC-600 glue (a) and the BC-600 resin (b) before and after the irradiation by the neutron beam with different fluences.

Table 2
The light yield of the strips without a filler (Dry1, Dry2, Dry3) and strips filled with various resins (bases only) before and after the irradiation by a neutron beam with various fluences.

Sample number	Sample name	Filler	Initial PMT anode current (before irradiation) I_a, nA	Irradiation: Fluence, 10^{14} neutrons per cm^2 ($E > 1$ MeV)	PMT anode current after irradiation I_b, nA	Decrease of the anode current after irradiation $\frac{I_a-I_b}{I_a}$, in %
1.1	Dry 3	None	89 (±7)	1.2	64 (±5)	28 (±8)
1.2	SKTN(E) 3	SKTN(E)	148 (±10)	1.2	105 (±8)	29 (±8)
1.3	SKTN(D) 3	SKTN(D)	147 (±10)	1.2	103 (±8)	30 (±8)
1.4	BC-600 3	BC-600	151 (±10)	1.2	86 (±7)	43 (±6)
2.1	Dry 2	None	65 (±5)	3.8	13 (±2)	80 (±4)
2.2	SKTN(E) 2	SKTN(E)	144 (±10)	3.8	81 (±6)	44 (±6)
2.3	SKTN(D) 2	SKTN(D)	166 (±11)	3.8	55 (±4)	67 (±4)
2.4	BC-600 2	BC-600	149 (±10)	3.8	80 (±6)	46 (±6)
3.1	Dry 1	None	102 (±7)	16.0	14 (±3)	86 (±4)
3.2	SKTN(E) 1	SKTN(E)	126 (±9)	16.0	18 (±3)	86 (±3)
3.3	SKTN(D) 1	SKTN(D)	147 (±10)	16.0	22 (±3)	85 (±3)
3.4	BC-600 1	BC-600	141 (±10)	16.0	20 (±3)	86 (±3)



(a) (b)

Fig. 13. Unexposed strip is located in the lowest position, followed clockwise by three other strips irradiated by the neutron beam with the fluences of 1.2×10^{14}, 3.8×10^{14}, and 16×10^{14} neutrons per cm^2 respectively. The left photo was taken under the illumination by a regular incandescent lamp and the right photo was taken under blue light.

Please note, that in this location the fluence of fast neutrons did not exceed 1.2×10^{14} neutrons/cm^2 and it was three times higher compared to expected for CRV system at Mu2e experiment [10],

Photos of four strips are shown in Fig. 13. The unexposed strip is in the lowest position, followed clockwise by three other strips irradiated by the neutron beam with the fluences of 1.2×10^{14}, 3.8×10^{14}, and 16.0×10^{14} neutrons per cm^2 respectively. One can see noticeable changes in the transparency of the irradiated strips in comparison to the unexposed strip as the absorbed dose increases. Degradation of plastic scintillator transparency in the blue light region due to the absorbed radiation dose rate is visible under exposure to blue light. It is also seen that the Hardman RED 04001 optically transparent quick-cure 5 min epoxy glue completely lost transparency.

5. Conclusions

Technology for injection of a highly viscous optical filler, particularly SKTN-MED, into a 5 m long polystyrene strip with a co-extruded hole and with a WLS fiber embedded is developed.

Light yield studies of a 5 m long strip filled with SKTN-MED(E) carried out with cosmic muons and a radioactive source show an increase in the light yield by a factor of up to 1.5 in comparison to the light yield of the strip without a filler when the strip and the WLS fiber far from PMT end are blackened.

SKTN-MED (D and E) and BC-600 resins have a good transparency (above 90%) in a wide range of the light spectrum ($\lambda > 400$ nm) and hold it under the exposure to a neutron flux of fast neutrons with $E > 1$ MeV and fluences up to 3.8×10^{14} neutrons per cm^2. This result allows using SKTN-MED(D) as a filler for the longest strips in the Mu2e experiment, where fluence of 10^{11} neutrons per cm^2 [4,10] is expected during the operation time.

Deterioration of optical properties of the strip and the WLS fiber is the main reason of light losses in the strips filled with the SKTN-MED optical resin after irradiation by neutrons with fluences up to 1.2×10^{14} neutrons per cm^2.

MC simulation using Geant 4 shows an increase in the light yield of the 5 m long strip with a filler is consistent with experimental observations.

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