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**RADIATION DAMAGE ON PLASTIC
SCINTILLATORS AND OPTICAL FIBERS**

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Abstract

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The paper presents experimental results on the radiation damage study of some plastic scintillators BC-400, BC-404, BC-408, NE-102a, NE-110 (on the base of polyvinyltoluene) in comparison with polystyrene-based ones and some wave length shifting fibers-Y-7, BCF-92a, RK-27, RR-26. Our measurements showed that scintillator on the base of granulated polystyrene of PSM-115 trade mark and RK-27 fiber were the most radiation resistant among those investigated.

Аннотация

Васильченко В.Г., Протопопов Ю.М. Исследование радиационной стойкости полимерных сцинтилляторов и оптических волокон: Препринт ИФВЭ 93-104. – Протвино, 1993. – 12 с., 10 рис., 4 табл., библиогр.: 7.

В работе представлены экспериментальные результаты по изучению радиационной стойкости серии сцинтилляторов BC-400, BC-404, BC-408, NE-102a, NE-110 (на основе поливинилтолуола) в сравнении с полистирольными сцинтилляторами и серии волокон Y-7, BCF-92a, РК-27, РР-26. Наши измерения показали, что полистирольный сцинтиллятор на основе гранулированного полистирола марки РСМ-115 и спектросмещающее волокно РК-27 с добавкой К-27 обладают наилучшей радиационной стойкостью среди исследованных.

During last few years, interest in radiation resistance of scintillators and wave length shifting (WLS) fibers for application in scintillator-based particle detectors at new generation of particle accelerators, SSC, LHC and RHIC, has been renewed. It is expected that some parts of new experimental setups will have to work in severe radiation environment. Among the devices most strongly affected by high radiation environment are electromagnetic (EM) calorimeters since, by design, they absorb the entire energy of the incoming particles. It is now realistic to expect that some components of EM-calorimeters will have to endure annual doses of at least 1 Mrad or more [1].

One of the new promising technologies is WLS fibers coupled with plastic scintillation tile, in which the fiber is a conduit for light to the readout device: phototube, photodiode et al. Several particle detectors on the base of plastic scintillators with WLS fibers for readout were reported in ref. [2,3].

Our radiation resistance measurements of some polystyrene-based scintillators may be found in [4]. Now our aim is to find the best possible pair of scintillation tile and WLS fiber for newly designing EM-calorimeters [1,5,6] that provide the optimum light output and radiation resistance.

We have tested several promising plastic scintillation tiles and polystyrene based WLS fibers that can presently be used in STIC calorimeter at CERN (Y-7) [6], ATLAS hadron calorimeter at CERN (BCF-91a) [5], E-865 experiment at AGS (BCF-92a, RK-27 and RR-26) and PHENIX electromagnetic calorimeter at RHIC (BCF-92a) – (see Table 1).

Table 1. Wave length shifting fibers studied in the present investigation.

Type of WLS fiber	Core matrix known dopants	Cladding	Average light attenuation length, cm ⁶
Y-7 ¹	polystyrene+ (n=1.59)	—	65
BCF-92a ²	polystyrene+(0.1g/l)G-2 ⁷ (n=1.59)	PMMA	63
RK-27 ³	polystyrene+(0.2g/l)K-27 ⁴ (n=1.59)	f-PMMA	50
RR-26 ³	polystyrene+(0.2g/l)R-26 ⁵ (n=1.59)	f-PMMA	63

¹Kuraray Corp., Japan.

²Bicron Corp., Newbury, Ohio 44065, USA.

³Institute for Nuclear Research, Moscow, Russia.

⁴K-27 - benzoxanthene derivative.

⁵R-26 - tioxanthene derivative.

⁶Averaged light attenuation lengths were measured for short samples of about 450 mm long.

⁷G-2 - wave length shifting dopant used in BCF-92a fiber with a concentration of about 0.1 g/l (gramm/litre). Here n — refraction index, PMMA-polimethylmetacrylate (n=1.47) and f-PMMA - fluorinated PMMA (n ≈ 1.43).

1. INVESTIGATION OF THE LIGHT OUTPUT OF "SCINTILLATION TILE - WLS FIBERS" PAIRS

We investigated the relative light output, provided by small samples of scintillation tiles of 30 mm diameter and 5 mm thickness and WLS fibers.

Scintillation tiles were excited with a ⁹⁰Sr radioactive source. The light output measurements were carried out using a FEU-84-3 photomultiplier (PM) that had semi-transparent tri-alkaline photocathode with the maximum spectrum sensitivity at $\lambda = 440$ nm. The photocurrent of scintillators on the base of granulated polystyrene was taken to be 1. The accuracy of our measurements was about $\pm 5\%$. This experimental setup allowed us to measure relative light yields from different "tile - WLS fiber" pairs. Our results are presented in Table 2.

We also investigated the relative light output, provided by some types of WLS fibers and scintillation tiles with the sizes $3 \times 55 \times 70$ mm³. In these measurements WLS fibers were coupled to the 55 mm long side of the scintillation tiles. The light output of SCSN-81 (scintillator) - BCF-92a (WLS fiber) pair

was taken to be 1 as minimum among these investigated. Our results for this scheme of light readout is presented in Table 3.

Table 2. Relative light output of different options of scintillator – WLS fiber pairs (separately for concrete fiber).

Type	Scintillator		WLS fibers			
	Light yield, %	λ^{max}	BCF-92a	RK-27	RR-26	Y-7
BC-400 ¹	126	430	1.25	1.25	1.25	1.25
BC-404 ¹	126	408	1.55	1.40	1.15	1.25
BC-408 ¹	124	430	1.0	1.05	1.2	1.1
NE-102a ²	120	423	1.0	1.05	1.2	1.1
NE-110 ²	120	434	0.95	1.0	1.15	1.05
PS ³	100	420	1.1	1.1	1.1	1.1
PSM-115 ⁴	90÷100	420	1.0	1.0	1.0	1.0

¹Bicron Corp., Newbury, Ohio, USA.

²Nuclear Enterprises Ltd., Edinburgh, Scotland.

³Bulk-polymerized polystyrene, containing 2% p-terphenyl and 0.02% POPOP, IHEP, Russia.

⁴Scintillator on the base of granulated polystyrene (trade mark PSM-115), containing 1.5% p-terphenyl and 0.03% POPOP, processed by injection into the mold technology, IHEP, Russia.

POPOP — 1,4-bis-[2-(5-phenyloxasozolyl)]-benzene.

Table 3. Relative light output of different options of scintillator — WLS fiber for 70 mm long samples of scintillator

Scintillator	WLS fiber			
	Y-7	BCF-92a	RK-27	RR-26
PSM-115	3.2	1.3	2.8	1.7
BC-404	6	3	6.5	2.7
SCSN-81	2.8	1	2.4	1.8

The experimental results may be summarized as follows:

(i) The appropriate pairs for the above described particle detectors are "BC-404 (tile) — RK-27" with the highest light output and "PSM-115 — RK-27" as cheapest pair.

(ii) The maximum light output is provided by pairs consisting of fibers with highest trapping and quantum efficiency of WLS dopant i.e. RK-27, tiles with relatively good light yield.

(iii) For many WLS fibers optimal light output is provided by scintillation tiles, having the maximum emission spectra λ^{max} at 405-425 nm, which provide good matching with the absorption spectra of the WLS fibers.

2. RADIATION RESISTANCE TESTS

We have chosen several popular materials for radiation resistance tests. 5 mm thick disks with the diameter 30 mm were cut out of these materials. The samples were irradiated in a flux of γ -quanta from ^{137}Cs radioactive sources of 6 rad/s (or about 22 Krad/h) in air at room temperature. The light output was measured before (I_0) and after irradiation (I) using a FEU-110 photomultiplier (PM) which had semi-transparent tri-alkaline photocathode with the maximum spectrum sensitivity at $\lambda = 480$ nm. The measured samples were coupled with PM without optical contact and excited with a ^{90}Sr radioactive source. Then the PM anode current was compared with that obtained for a polystyrene scintillator polystyrene (containing 1.5% pTp and 0.03% POPOP), which was referred to as a standard sample with $I_0 = 100\%$ light output. Experimental results are presented in Table 4.

Table 4. Scintillation light yield of different types of plastic scintillators before and after irradiation and their recovery in time.

N	Scintillator	I_0 , %	I/I_0 , % (3.4 Mrad)	I/I_0 , % (10 Mrad)	I/I_0 , %, (recovery days)
1	PS ¹	110	48	23	52
2	PSM-115 ²	90 $\div$ 100	92	60	72
3	NE-102a ³	120	60	45	61
4	NE-110 ³	120	63	48	59
5	BC-400 ⁴	126	56	39	61
6	BC-404 ⁴	126	63	53	57
7	BC-408 ⁴	124	61	46	57

¹Bulk-polymerized polystyrene (2% pTp + 0.05% POPOP), IHEP, Protvino, Russia.

²PSM-115-based polystyrene made by injection into the mold technology (2% pTp + 0.03% POPOP), IHEP, Protvino, Russia.

³Nuclear Enterprises Ltd., Edinburgh, Scotland.

⁴Bicron Corp., Newbury, Ohio, USA.

The preliminary results presented above have shown that the scintillator based on the granulated polystyrene of PSM-115 trade mark is the most radiation resistant material for the scintillation tile application, although its light yield is about 20–25% less in comparison with typical polyvinyltoluene-based scintillators. So we have chosen this material for further investigation. We performed radiation damage tests with the scintillation tiles samples on the

base of granulated polystyrene PSM-115. The experimental setup for these measurements is plotted schematically in Fig.1.

The sizes of the tested scintillation tiles were $3 \times 56 \times 170$ mm³. The scintillation samples were covered with aluminized maylar, excluding the edge coupled to WLS fibers and opposite to WLS edge. Scintillation samples were excited using a ⁹⁰Sr radioactive source, the scintillation light was then absorbed by 3 WLS unirradiated fibers BCF-92a transmitting light to a photomultiplier FEU-84-3. The PM photocurrent was measured.

We measured the light attenuation curve of tiles before and after γ -irradiation and the process of recovery in time. Some of these experimental results are shown in Fig.2. These data allowed us to calculate the light attenuation length before (l_0) and after (1) γ -irradiation and to determine the characteristics of the tiles light yield as their linear approximation to the zero length before $I_0(0)$ and after $I(0)$ irradiation. The accuracy of these measurements was about $\pm 5\%$.

Figs.3 and 4 show the normalized attenuation length l/l_0 and light yield $I(0)/I_0(0)$ directly after irradiation and in 10 hours, as well as the process of l/l_0 recovery in time, respectively. Our experimental results have shown a small improvement of l/l_0 at the dose of about 0.5 Mrad. Similar characteristics in optical fibers were reported for the first time in ref. [7].

It is obvious from the comparison with the recovery curves that a noticeable permanent damage for this type of scintillator was observed after the dose of about 1 Mrad and essential permanent damage — after the dose 1.2–1.5 Mrad.

The experimental setup for fibers measurements is plotted schematically in Fig.5. The sizes of irradiated and unirradiated samples of WLS fibers were 1 mm diameter and 450 mm (about 18 inches) long. Tested fibers were excited using (unirradiated) polystyrene-based scintillation bar with the sizes $10 \times 25 \times 55$ mm³ which was excited with a ⁹⁰Sr source. WLS fibers were inserted into a hole with 1.2 mm diameter in the scintillation bar. Scintillation light was absorbed by the WLS fiber under investigation and transmitted to a FEU-84-3 PM.

The light attenuation curve of the fibers before and after irradiation were measured. Note that our fibers were kept coiled in ellipses of 9×20 cm² in the process of γ -irradiation. Some of these data are shown in Fig.6. The data allowed us to calculate the attenuation lengths of the fibers before (l_0) and after (1) irradiation and to determine the characteristics their conversion efficiency as a linear approximation to their zero length before $I_0(0)$ and after $I(0)$ irradiation. The accuracy of these measurements was about $\pm 7\%$.

Figs.7 and 8 show the experimental result for radiation resistance of WLS fibers (RK-27, RR-26, BCF-92a and Y-7). The normalized attenuation length l/l_0 and conversion efficiency of fibers $I(0)/I_0(0)$ are plotted as functions of the absorbed dose D . First measurements of the irradiated samples were carried out directly after exposure (in 15 ± 5 minutes after irradiation).

Figs.9 and 10 show our experimental results for the short-term recovery of the WLS fibers. The normalized attenuation length l/l_0 is plotted as a function of the dose. Our measurements indicated that the normalized conversion efficiency $I(0)/I_0(0)$ of RK-27 and Y-7 fibers did not decrease up to the dose 1.5 Mrad.

These experimental results may be summarized as follows:

— The maximum radiation resistance is provided by RK-27 and Y-7 WLS fibers.

— These fibers provide radiation stability of their characteristics up to the dose of about 1–1.5 Mrad.

CONCLUSIONS

WLS fibers on the base of K-27 WLS dopant have shown the highest light conversion capability and radiation resistance among all other examined WLS fibers.

Cheap polymer scintillator on the base of PSM-115 granulated polystyrene processed by injection into the mold technology with pTp as the primary scintillation dopant and POPOP as wave length shifter has shown the most radiation resistant among all other examined scintillators up to the dose of 1 Mrad.

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Figure 1. Experimental setup for light attenuation of scintillation tiles measurements. 1 — ^{90}Sr radioactive source, 2 — tile, 3 — WLS fibers, 4 — FEU-84-3.

Figure 2. Attenuation of light for PSM-115 scintillation tiles before (1) and after the dose 0.6 Mrad (2), after 6.4 Mrad (4) as well as in the process of recovery after 100 min (3) and 1320 min (5), respectively.

Figure 3. Normalized light attenuation length l/l_0 (1) directly after irradiation and 10 hours later (2) and light yield (3) $I(0)/I_0(0)$ as a function of dose D .

Figure 4. Short-term recovery process for PSM-115 scintillator tiles after doses 6 Krad (1), 60 Krad (2), 0.6 Mrad (3), 1.5 Mrad (4) and 6.4 Mrad (5).

Figure 5. Experimental setup for the light attenuation measurements of WLS fibers. 1 — ^{90}Sr radioactive source, 2 — scintillation bar, 3 — fiber, 4 — FEU-84-3.

Figure 6. Attenuation of light for BCF-92a fiber before (1) and after the dose 0.6 Mrad (2) as well as in the process of recovery after 120 min (3).

Figure 7. Normalized light attenuation length l/l_0 and conversion efficiency $I(0)/I_0(0)$ for the RK-27 (1,3) and RR-26 (2,4) fibers as function of the dose D , respectively.

Figure 8. Normalized light attenuation length l/l_0 and conversion efficiency $I(0)/I_0(0)$ for Y-7 (1,3) and BCF-92a (2,4) fibers as function of dose D , respectively.

Figure 9. Short-term recovery processes after doses 1.5 Mrad and 3 Mrad for RK-27 (1,2) and RR-26 (3,4), respectively.

Figure 10. Short-term recovery processes for Y-7 fibers after the doses 1 Mrad (1) and 2 Mrad (2), and the same process for BCF-92a fibers after the doses 0.15 Mrad (3) and 0.6 Mrad (4).

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