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FEDERAL SCIENCE CENTRE
INSTITUTE FOR HIGH ENERGY PHYSICS

IHEP 94-111

V.G.Vasil'chenko, V.G.Lapshin, A.I.Peresypkin
Institute for High Energy Physics, Protvino, Russia,
A.A.Konstantinchenko, A.I.Pyshchev
Institute for Physical Chemistry, Postov na Donu, Russia,
V.M.Shershukov
Institute of Monocrystal, Khar'kov, Ukraine,
B.V.Semenov
Institute of Nuclear Physics, Moscow, Russia,
A.S.Solov'ev
Joint Institute for Nuclear Research, Dubna, Russia

NEW RESULTS ON RADIATION DAMAGE STUDIES
OF PLASTIC SCINTILLATORS

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Protvino 1994

SCAN-9509030

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Abstract

Vasil'chenko V.G. et al. New Results on Radiation Damage Studies of Plastic Scintillators: IHEP Preprint 94-111. – Protvino, 1994. – p. 12, figs. 3, tables 5, refs.: 18.

This paper presents a comparative study of scintillation and radiation characteristics for a series of new and known plastic scintillators. About 70 new scintillators have been tested. The dose rate effects on some widely used plastic scintillators have been measured. Polystyrene scintillators containing 20% 1-methylnaphthalene + 2% pTP + 0.05% POPOP and 20% 1-methylnaphthalene + 2% pTP + 0.05% POPOP + 0.02% K-27 revealed the maximum radiation resistance about 7-9 Mrad.

Аннотация

Васильченко В.Г. и др. Новые результаты исследований радиационной стойкости пластических сцинтилляторов: Препринт ИФВЭ 94-111. – Протвино, 1994. – 12 с., 3 рис., 5 табл., библиогр.: 18.

В этой работе представлены сравнительные результаты исследований сцинтилляционных и радиационных характеристик для серии новых и известных пластических сцинтилляторов. Проведено исследование около 70 новых сцинтилляторов. Для некоторых широко используемых сцинтилляторов исследовалась радиационная стойкость в зависимости от мощности дозы. Наибольшую радиационную стойкость (около 7-9 Мрад) показали ПС-сцинтилляторы, содержащие 20% 1-метилнафталина + 2% pTP + 0.05% POPOP и 20% 1-метилнафталина + 2% pTP + 0.05% POPOP + 0.02% K-27.

An interest in new radiation-resistant plastic scintillators has increased since high energy physics beam intensities rose and with the advent of a new generation of high luminosity accelerators. A search for new radiation-resistant plastic scintillators was renewed in many scientific centers [1-8]. Polystyrene-based scintillators [PS] attracted the main attention of researchers due to their high level of light yields and comparatively low cost. This search resulted in the discovery of a number of new radiation-resistant scintillators [2,5,7,9-11]. This paper is a continuation of our previous investigations of radiation and scintillation characteristics of new and known plastic scintillators [12-13]. Noticeable attention was drawn to the investigation of the dose rate effects on optical characteristics of different types of prolonged scintillators.

1. EXPERIMENTAL SETUP

The monomer was deinhibited through a column and distilled in vacuum. Then the monomer was placed in cylindrical glass ampoules ($\sim 20 \text{ cm}^3$) and doped with scintillation fluors. The glass ampoules with solutions were sealed off after pumping-out the air and polymerized at the temperature of about 170°C during 24 hours in a polysilicone bath. The 5 mm thick disks with the diameter of 30 mm were cut out of the polymerized blocks of scintillators. The samples were irradiated in a flux of γ -quanta from ^{137}Cs radioactive sources with a dose rate of 6 rad/s (or 190 Mrad/yr) in room temperature air. More cases of dose rate γ -irradiation of material samples will be specially mentioned below. To measure the light output of the samples the scintillation was excited with a ^{90}Sr β -radioactive source. The sample and β -source were placed on the entrance window of a photomultiplier (PMT) FEU-110. The PMT had a multialkaline photocathode with the maximum spectrum sensitivity at $\sim 480 \text{ nm}$.

The samples photocurrent has been measured in comparison with that from a standard polystyrene (PS) scintillator containing 2% pTP + 0.05% POPOP, whose light output was taken to be as 100%. The light output measurements accuracy was about $\pm 3\%$. We measured the light output of unexposed samples L_o , the relative light output L/L_o soon after the exposure and L/L_o after 23 days recovery in room temperature air. Abbreviations of fluors, plastics, solvents, the known decay time constants τ , maximum of wavelength absorption λ_{abs} and emission λ_{em} used in this paper are listed in Appendix.

2. RADIATION HARDNESS OF SMALL SAMPLES

The experimental results of our radiation hardness studies of new and known plastic scintillators are presented in Tables 1-5. Some experimental data of PS-scintillators exhibiting neither a high level of the light output nor radiation hardness are given in Table 1. For comparison, radiation and scintillation characteristics of the standard PS scintillator (sample N 1) are given at the beginning of Table 1.

The experimental data presented in Table 1 show that primary dopants D11 and DvpTP are able to provide a high level of scintillation light output L_o even at a low level of concentration. However the PS-scintillators based on these dopants lack a high radiation hardness. Note that in samples N 29 and N 33 scintillation dopants were introduced into polymer chains by copolymerization of their vinyl derivatives with styrene. The primary dopant DvpTP increases the light output of PS-scintillators a little more than the light output of similar PS-scintillators containing pTP as the primary dopant. The effective primary dopant BO [11] provides the light output $L_o \geq 100\%$ with the concentration $\geq 0.8\%$. We have studied in detail the scintillation and radiation characteristics of PS-scintillators containing BO. The results of our study are presented in Table 2.

According to the experimental data given in Table 2 the primary dopant BO provides a higher level of light output for the PS-scintillators (with all the studied secondary dopants) in comparison with pTP containing scintillators. However such PS-scintillators lack a high level of the radiation hardness.

A set of PS-scintillators with an increased level of the radiation hardness and good recovery properties of their optical and scintillation characteristics is presented in Table 3. The radiation and scintillation characteristics of the standard PS scintillator containing 2% pTP + 0.05% POPOP and NE-110 (based on polyvinyltoluene) are presented at the beginning of Table 3 for comparison.

The experimental data presented in Table 3 show that PS-scintillators N 3-10 offer an increased level of the radiation hardness. A high Nph concentration in sample N 3 has caused to a visible increase of the radiation hardness. A low level of the light output of sample N 12 is due to the absence of a primary dopant.

As is shown in [11], the introduction of 1MN and Nph improved the radiation hardness of PS-scintillators. We kept investigating and further increased the concentration of plasticizers like Dbph [10], 1MN and IN. The highest level of the radiation hardness revealed in N 18-21 PS-scintillators. In comparison with Dbph, the use of 1MN or IN plasticizers in samples N 20-21 provides a high level of the light output of about $\sim 85 - 95\%$ and good transmission properties up to a short wavelength cutoff region $\lambda_{min} \cong 400$ nm for these PS-scintillators. According to our estimations, N 18-21 scintillators exhibited the radiation resistance of about 9-7 Mrad, correspondingly. However the introduction of these plasticizers (Dbph, IN and 1MN) into PS-scintillators under such high level of concentration resulted in an increase of their plasticity. Note that the long-term stability of N 18-21 PS-scintillators needs further investigation.

Table 1. Scintillation and radiation characteristics of some PS-scintillators

№	Scintillators	L _o , %	L/L _o , %	
			10 Mrad	23 days of recov.
1	2% pTP + 0.025% POPOP	100	23	52
2	1.5% pTP + 0.025% L6	95	28	51
3	1.5% pTP + 0.025% L7	70	28	45
4	1.5% pTP + 0.025% L8	69	19	32
5	1.5% pTP + 0.025% L9	72	25	46
6	1.5% pTP + 0.025% L10	53	8	13
7	1.5% pTP + 0.025% L11	58	36	58
8	1.5% pTP + 0.025% L13	31	30	45
9	1.5% pTP + 0.025% L14	49	22	42
10	1.5% pTP + 0.025% D52	42	13	25
11	1.5% pTP + 0.025% D53	65	24	36
12	1% D50	82	11	20
13	1% D51	89	18	53
14	1% MeBO	95	12	17
15	2% MeBO	95	14	17
16	1% MeBO + 0.025% R45	95	11	20
17	1% MeBO + 0.025% R49	58	16	42
18	1.5% pTP + 0.025% EDO	86	20	29
19	1.5% pTP + 0.025% R45	59	16	22
20	1.5% pTP + 0.025% R49	65	24	52
21	0.5% pTP+0.5% Fluor+0.025% POPOP	96	23	46
22	1.5% pTP + 0.025% BPEA	55	17	28
23	1.5% pTP + 0.025% 3M-15	94	20	31
24	1.5% pTP + 0.025% DMPOPOP	102	30	55
25	1.5% pTP + 0.01% BF-203	106	20	34
26	1.5% pTP + 0.025% R6-J	58	27	34
27	1.5% pTP + 0.025% R63	47	15	21
28	2% pTP + 0.025% D15	63	29	53
29	2% pTP + 0.025% vPOPOP	84	23	52
30	2% o-POPOP	62	11	37
31	0.7% D11 + 0.025% POPOP	103	18	48
32	2% pTP + 0.025% D14	42	35	43
33	0.1% DvpTP + 0.025% POPOP	60	13	40
34	1% D16	59	4	16
35	2% pTP + 0.025% D16	89	14	26
36	2% pTP + 0.025% P26	70	27	38
37	2% pTP + 0.02% DPPyr	105	22	30
38	2% pTP + 0.02% STO	67	30	34

Table 2. Scintillation and radiation characteristics of some PS-scintillators containing BO

№	Scintillators	L _o , %	L/L _o , %		
			3.4 Mrad	10 Mrad	23 days of recov.
1	1% BO + 0.025% POPOP	103	42	26	34
2	2.5% BO + 0.025% POPOP	108	38	22	32
3	4% BO + 0.025% POPOP	90	24	14	33
4	1.5% BO + 0.025% ADP	102	34	17	24
5	1.2% BO + 0.03% R45	94	33	16	17
6	0.8% BO + 0.015% R911	93	30	7	9
7	0.8% BO + 0.01% L1	92	38	23	29
8	0.8% BO + 0.01% L6	102	37	20	29
9	0.8% BO + 0.01% X25	90	36	20	27

Table 3. Scintillation and radiation characteristics of PS-scintillators

№	Scintillators	L _o , %	L/L _o , %		
			3.4 Mrad	10 Mrad	23 days of recov.
1	2% pTP + 0.025% POPOP	100	48	23	52
2	NE-110*	126	63	48	59
3	5% Nph + 2% pTP + 0.025% POPOP	96	63	36	51
4	1.5% pTP + 0.05% 3HF	60	75	55	66
5	10% PPO + 0.05% X25	80	72	43	63
6	2% PPO + 0.5% POPOP + 0.05% X25	92	68	40	60
7	10% PPO + 0.5% POPOP + 0.05% X25	92	74	51	72
8	2% 1EN + 1.5% pTP + 0.1% X25	65	73	50	55
9	10% PPO + 0.05% X31	79	65	49	66
10	10% PPO + 0.1% X25 + 0.05% 3HF	88	68	49	67
11	2% pTP + 0.02% NBI	98	68	36	53
12	0.25% D12	16	89	50	63
13	1.5% pTP + 0.025% TPB	89	50	36	45
14	1.5% pTP + 0.025% D36	63	65	38	52
15	5% 1ENph + 0.025% POPOP	68	65	40	45
16	10% PPO + 0.05% 3HF	52	58	36	57
17	2% pTP + 0.05% POPOP + + 0.02% K-27	76	66	56	74
18	20% 1MP + 2% pTP + 0.05% POPOP + + 0.02% K-27	46	102	88	85
19	20% Dbph + 2% pTP + 0.05% POPOP	25-35	98	81	82
20	20% 1MN + 2% pTP + 0.05% POPOP	85-95	102	79	78
21	20% IN + 2% pTP + 0.05% POPOP	90	102	77	76

* Nuclear Enterprises, Edinburgh, England.

As was established long ago, the light output of some commonly used plastic scintillators is practically temperature independent between -10°C and $+20^{\circ}\text{C}$ and has temperature stability of about $-0.125\%/^{\circ}\text{C}$ between $+20^{\circ}\text{C}$ and $+60^{\circ}\text{C}$ [15]. According to our measurements, the light output stability of the radiation resistant N 20 scintillator is about $-0.3\%/^{\circ}\text{C}$ between 0°C and $+60^{\circ}\text{C}$.

The study of scintillation and radiation characteristics of PS-scintillators containing 2% pTP + 0.05% POPOP with different concentration of some plasticizers like Dbph and 1MN is of interest. The experimental results are presented in Table 4.

Table 4. Scintillation and radiation characteristics of PS-scintillators (containing 2% pTP + 0.05 % POPOP) versus the concentration of plasticizers Dbph and 1MN.

№	Scintillators	$L_o, \%$	$L/L_o, \%$		
			3.4 Mrad	10 Mrad	23 days of recov.
1	4% Dbph	72	46	40	67
2	10% Dbph	46	57	55	67
3	20% Dbph	30	98	81	82
4	2% 1MN	90	50	25	58
5	10% 1MN	85	79	56	61
6	15% 1MN	85	101	76	65
7	20% 1MN	95	102	79	78
8	30% 1MN	77	102	71	68

According to the presented data (Table 4) the increase of Dbph concentration in PS-scintillators leads to a growth of the radiation hardness but lowers the light output. At the same time with the use of 1MN the radiation hardness reaches its maximum with the plasticizers concentration of about $\sim 20\%$ in PS-scintillators, while their light output decreases insignificantly.

Ordinary scintillators based on PMMA are known to be characterized by a low level of the light output and radiation resistance [3,14] in comparison with PS-scintillators. Some time ago the increase of Nph concentration in PMMA-scintillator was found to lead to a visible improvement of their radiation hardness. We studied the scintillation and radiation characteristics of some scintillators based on PMMA. The results of a comparative study of some home-made and the well known PMMA-scintillator are given in Table 5.

The comparative study of different types of plastic scintillators shows that although the best PMMA-scintillators show a low level of the light output (of about 0.44-0.65) in comparison with the standard PS-scintillators, their radiation hardness is comparable with that of the best commercially manufactured PS-scintillators. Note that the recovery processes of scintillation and optical characteristics in PMMA-scintillators after γ -irradiation are weak.

Table 5. Scintillation and radiation characteristics of some PMMA-scintillators.

№	Scintillators	$L_o, \%$	$L/L_o, \%$		
			3.4 Mrad	10 Mrad	23 days of recov.
1	POLIPOP*	65	64	29	34
2	SP-293 (0.5% pTP + 0.01% POPOP)**	51	80	48	48
3	SOFG-112 (0.5% pTP + 0.01% POPOP)**	44	79	58	58

* - Pol.Hi.Tech.s.r.l. S.P.Turanense km 44.400, 67061 Carsoli (AQ) Italy.

** - These scintillators were kindly delivered to us by T.M. Murav'eva, V.R.Kargin Institute of Polymers, Dzerzhinsk, Russia.

It is well known that the decrease of the light output of small size scintillator samples in the process of γ -irradiation is mainly determined by their local scintillation efficiency fall [11]. However in particle detectors, plastic scintillators have, as usual, prolonged sizes. So it seems to be very important to add the above presented experimental data to the radiation study of the most applicable types of prolonged scintillation plates.

3. RADIATION HARDNESS OF PROLONGED SCINTILLATORS

The loss of transparency under γ -irradiation mainly determines the value of light output from prolonged plastic scintillators. Three types of plastic scintillators were chosen for our radiation study NE-110, the standard PS-scintillator (N1 in Table 1) and a scintillator based on the granulated polystyrene PSM-115 containing 2% pTP + 0.025% POPOP [7,12] and produced by the injection molding technique. The $3.8 \times 26 \times 170$ mm³ plates were cut off from these scintillators. The plates were polished and covered with the aluminized Mylar (except two 3.8×26 mm² narrow faces).

In order to measure optical characteristics of the plates before and after γ -irradiation, the scintillation was excited by a ⁹⁰Sr β -radioactive source. The scintillation from one of the narrow faces of a plate was absorbed with three unirradiated BC-92a wavelength shifting fibers. The reemitted light from the fibers was fed to a photomultiplier FEU-84-3. The PMT anode current was measured [13].

We studied the light attenuation in the scintillation plates before and after γ -irradiation as well as the process of recovery in time. Some of the experimental data are presented in Fig.1-3. In order to characterize the optical characteristics of the scintillation plates we determined their light attenuation lengths before (l_o) and after (l) the γ -irradiation. The precision of our measurements of l/l_o was about $\pm 3\%$.

The change of the relative light attenuation length l/l_o measured just after finishing the exposure for a group of five scintillation plates (curves 1-5) cut off from one block of the standard PS-scintillator (N 1 in Table 3) is shown in Fig.1. The doses were taken continuously with half an hour interruptions to measure the characteristics.

Fig.1 also shows the recovery process of the value l/l_o measured in 23 days after finishing the exposure (curve 6). This 23 days time interval to recover the characteristics

was chosen on the base of our earlier investigation of the typical recovery times for this type of PS-scintillator [7]. The initial light attenuation length for these plates was about $l_0 \cong 20-24$ cm. The measurement results given in Fig.1 show that noticeable behaviour variations of l/l_0 value from sample to sample during the exposure are observed in the dose interval $10^3 < D < 10^4$ rad. The nature of this variations needs explanation.

Fig. 1. Relative light attenuation length l/l_0 for the standard PS-scintillator plates versus the absorbed dose D : (1-5) – for a dose rate of 6 rad/s. Measurements were carried out immediately after the irradiation; (6) – after 23 days of recovery; (7) – measurements were carried out after the absorption a dose of 10^4 rad and 30 days of recovery; (8) – for a dose rate of 0.32 rad/s. Measurements were carried out immediately after the irradiation; (9) – after 23 days of recovery.

Under real conditions of plastic scintillators exploitation, the dose pile up will be often accompanied by periodic 20-40 days interruptions in exposures, which can make other prolonged processes of characteristics changes noticeable. The most significant changes can be expected at the initial stages of irradiation up to a dose of about $D < 10^5$ rad. We studied the influence of the preliminary exposure with a dose of $D \cong 10^4$ rad and subsequent 30 days interval recovery (which is enough for the recovery of characteristics practically to their initial values) on the dependence l/l_0 (Fig.1). Note that for PSM-115 based scintillators, such pattern of exposure failed to lead to visible l/l_0 changes different from the curves 1-5, versus the dose, therefore these data are not presented in Fig.2.

Fig. 2. Relative light attenuation length l/l_0 for PSM-115 scintillator plates versus the absorbed dose D : (1-5) – for a dose rate of 6 rad/c. Measurements were carried out immediately after the irradiation; (6) – after 1 day of recovery; (7) – for a dose rate of 0.32 rad/s. Measurements were carried out immediately after the irradiation; (8) – after 1 day of recovery.

Fig.2 illustrates some changes of the relative light attenuation length l/l_0 from sample to sample for a set of 5 scintillation plates (taken from the same batch) based on the granulated polystyrene PSM-115 soon after the exposure (curves 1-5). Fig.2 also shows the process of recovery l/l_0 measured in a day after finishing the exposure (curve 6). Preliminary measurements indicated that for this type of scintillator with analogous size the recovery time was about 7-10 hours [13]. The initial light attenuation length for this plates group was about $l_0 \cong 13-14$ cm. The experimental data presented in Fig.2 show that complex recovery processes may occur under the exposure in the dose interval $0.1 < D < 4$ Mrad of PSM-115 based scintillators. Such an improvement of the transparency for PS scintillators was earlier described in [16,13].

It seems to be interesting to compare the radiation hardness of different types of scintillators. Thus Fig.3 presents some changes of the relative light attenuation length l/l_0 for the plates of a NE-110 scintillator (curve 2). Our preliminary measurements showed that for this type of scintillator with the same size the recovery time interval was about 20 days [11]. Their initial light attenuation length was about $l_0 \cong 13-14$ cm.

Fig. 3. Relative light attenuation length l/l_0 for NE-110 scintillator plates versus the absorbed dose D : (1) – for a dose rate of 6 rad/s. Measurements were carried out immediately after the irradiation; (2) – after 20 days of recovery; (3) – for a dose rate of 0.32 rad/s. Measurements were carried out immediately after the irradiation; (4) – after 20 days of recovery.

It is known that the dose rate noticeably effects the radiation damage for some types of plastic scintillators [17,18]. We studied the influence of a low dose rate of 0.32 rad/s (or 10 Mrad/yr) on the optical characteristics of plastic scintillators. The experimental results are presented in Fig.1-3. When comparing the measurements results for two dose rates one can see that the relative light attenuation length l/l_0 (versus the absorbed dose D) in PS-scintillators improves visibly at the low dose rate, but the extent of recovery l/l_0 value gets worse a little at the same time. Note that similar measurements for the NE-110 scintillator displayed more complex dependence of l/l_0 at different dose rates in comparison with the PS-scintillator.

CONCLUSION

The measurements results allow one to make the following conclusions:

- the primary dopants D11, BO and DvpTP are capable of providing high efficiency for PS-scintillators even at a low concentration level of <1%. However PS-scintillators based on these dopants lack high radiation resistance;
- a high level of the radiation resistance showed PS-scintillators which contained the following scintillation or wavelength shifting dopants: 3HF, X31, D12, Nph etc. and the highest level of the radiation resistance showed the samples containing ~ 20% of plasticiz-

ers such as Dbph, 1MN and IN. The highest radiation resistance (about 7-9 Mrad) exhibited the small samples of PS-scintillators containing 20% IN+2% pTP+0.05% POPOP, 20% Dbph+2% pTP + 0.05% POPOP, 20% 1MN+2% pTP+0.05% POPOP and 20% 1MN + 2% pTP + 0.05% POPOP + 0.02% K-27;

- the radiation hardness of some home-made PMMA-scintillators (SP-293 and SOFG-112) is comparable with that of the best commercially manufactured PS-scintillators. However all PMMA-scintillators recover their characteristics after the irradiation poorly;

- the decrease of the dose rate leads to some improvement of optical transparency immediately after finishing the exposure for the standard PS-scintillators, but at the same time it reduces their capability to recover.

Acknowledgements

The authors are indebted to V.I.Rykalin for his helpful discussions, A.A.Chumakov for his help in the irradiation of our materials and T.V.Alimova, V.V.Morozova and Yu.M.Protopopov for their help in preparation of the samples.

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Received October 21, 1994

Appendix

List of Investigated Luminophores and Dopants

Nph - naphthalene, $\lambda_{abs} \leq 275$ nm, $\lambda_{em} = 330$ nm;
 1MN - 1-methylnaphthalene, $\lambda_{abs} = 280$ nm, $\lambda_{em} = 330$ nm;
 IN - 1-isopropylnaphthalene, $\lambda_{em} \cong 340$ nm;
 1EN - 1-ethylnaphthalene, $\lambda_{em} \cong 340$ nm;
 Dbph - dibutyl ether of phthalic acid;
 Fluor - fluoren, $\lambda_{abs} = 260$ nm, $\lambda_{em} = 310$ nm;
 pTP - paraterphenyl, $\lambda_{abs} = 275$ nm, $\lambda_{em} = 340$ nm;
 PPO - 2,5-diphenyloxazole, $\lambda_{abs} = 310$ nm, $\lambda_{em} = 365$ nm;
 DvpTP - 4,4'-divinylparaterphenyl, $\lambda_{em} = 340$ nm;
 TPB - 1,1',4,4'-tetraphenylbutadiene, $\lambda_{abs} = 340$ nm, $\lambda_{em} = 435$ nm $\tau = 3.1$ ns;
 BO - 2-(4'-diamethylaminophenyl)-benzoxazol, $\lambda_{abs} = 330$ nm, $\lambda_{em} = 400$ nm;
 MeBO - 2-(diamethylaminophenyl)-5-methyl-benzoxazol, $\lambda_{abs} = 330$ nm, $\lambda_{em} = 400$ nm;
 POPOP - 1,4-bis-(2-(5-phenyloxazolyl))-benzene, $\lambda_{abs} = 365$ nm, $\lambda_{em} = 420$ nm;
 oPOPOP - 1,2-bis-(2-(5-phenyloxazolyl))-benzene, $\lambda_{abs} = 310-330$ nm, $\lambda_{em} = 420$ nm;
 vPOPOP - 1-vinyl-POPOP, $\lambda_{em} \cong 420$ nm;
 DMPOPOP - 1,4-di-2-(4-methyl-5-phenyloxazolyl))-benzene, $\lambda_{abs} = 370$ nm, $\lambda_{em} = 430$ nm, $\tau = 2.8$ ns;
 L1 - 4-(5-phenyloxadiazolyl)-4'-(3,5-diphenylpyrazolyl-1)-stilbene, $\lambda_{abs} = 450$ nm, $\lambda_{em} = 560$ nm, $\tau = 4$ ns.
 L6 - di-(4, 4'-naphthyloxazolyl)-stilbene, $\lambda_{em} \cong 460$ nm;
 L7 - 4-methoxyphenyl-2-(3,4-dihydro-2-quinolone-3)-oxazole, $\lambda_{em} \cong 500$ nm;
 L8 - α (anthryl-9)-4-(5-phenyloxadiazolyl-2)-styrene, $\lambda_{em} \cong 500$ nm;
 L9 - α (anthryl-9)-4-(5-biphenilyloxadiazolyl-2)-styrene, $\lambda_{em} \cong 500$ nm;
 L10 - 9,10 -di(methylaniline) anthracene, $\lambda_{em} \cong 530$ nm;
 L11 - 4-methoxyphenyl-2-(hexahydrochroman-3-yl-2-on)-oxadiazole, $\lambda_{em} \cong 430$ nm;

L13 – α -(4-methoxyphenyloxazolyl-2)-4-(4-phenyloxazolyl-2)-styrene, $\lambda_{em} \cong 500$ nm;
 L14 – 1,4-di(1-chlorophenyl-4-2-furyl-2-vinyl)-benzene, $\lambda_{em} \cong 500$ nm;
 D36 – 4-(1,5-diphenyl-pyrazol)-N-phenylnaphthalimide, $\lambda_{em} \cong 500$ nm;
 D50 – 2-(4-dimethylaminophenyl)-5,7-tretbutyl-benzoxazole, $\lambda_{abs} = 330$ nm, $\lambda_{em} = 400$ nm;
 D51 – 1,4-bis-(5,7-ditretbutyl-benzoxazolyl-2)-benzene, $\lambda_{abs} = 350$ nm, $\lambda_{em} = 405$ nm;
 D52 – 2-biphenyl-6-methoxy-quinoline, $\lambda_{abs} = 342$ nm, $\lambda_{em} = 387$ nm;
 D53 – 2-(2'-fluorophenyl)-phenanthro-9,10-[d]-oxazole, $\lambda_{abs} = 360$ nm, $\lambda_{em} = 392$ nm;
 ADP – 1-(o-anisil)-3,5-diphenyl-2-pyrazoline, $\lambda_{abs} = 360$ nm, $\lambda_{em} = 460$ nm, $\tau = 6.8$ ns;
 R6-J – 1-(2'-methoxyphenyl)-3-(4"-iodophenyl)-5-phenylpyrazoline, $\lambda_{abs} = 390$ nm, $\lambda_{em} = 490$ nm;
 P-26 – thioxanthene derivative, $\lambda_{em} = 530$ nm;
 K-27 – benzoxanthene derivative, $\lambda_{em} = 500$ nm, $\tau = 12$ ns;
 EDO – 2-(2'-ethoxynaphthyl)-6-diethylaminobenzoxazole, $\lambda_{abs} = 390$ nm, $\lambda_{em} = 500$ nm;
 R45 – pyrazoline derivative, $\lambda_{abs} = 390$ nm, $\lambda_{em} = 500$ nm;
 R49 – (1-cyan-2,4-diphenylpyrido-1,2 [a])-benzimidazole, $\lambda_{abs} = 400$ nm, $\lambda_{em} = 530$ nm;
 R63 – bromopyrazoline derivative, $\lambda_{abs} = 390$ nm, $\lambda_{em} = 510$ nm;
 R911 – benzoxazole derivative, $\lambda_{abs} = 380$ nm, $\lambda_{em} = 490$ nm;
 3M-15 – pyrazoline derivative, $\lambda_{abs} = 360$ nm, $\lambda_{em} = 490$ nm, $\tau = 5.7$ ns;
 BF-203 – secondary solute used in polyvinyltoluene scintillator BF-404, $\lambda_{em} = 410$ nm;
 BPEA – 9,10-bis-(phenylethylene)-anthracene, $\lambda_{abs} = 470$ nm, $\lambda_{em} = 505$ nm;
 DPPyr – 1,3-diphenyl-2-pyrazoline, $\lambda_{abs} = 364$ nm, $\lambda_{em} = 450$ nm;
 NBI – naphthailenebenzimidazole, $\lambda_{abs} = 390$ nm, $\lambda_{em} = 490$ nm;
 3HF – 3-hydroxyphlavone, $\lambda_{abs} = 350$ nm, $\lambda_{em} = 530$ nm, $\tau = 7$ ns;
 X25 – 4-morpholinyl-naphthalic anhydride, $\lambda_{abs} = 400$ nm, $\lambda_{em} = 480$ nm;
 X31 – 4-morpholinyl-N-phenylnaphthalimide, $\lambda_{abs} = 390$ nm, $\lambda_{em} = 490$ nm;
 STO – 2-(4-sulfofluoridophenyl)-5-(p-tolyl)-1,3,4-oxadiazole, $\lambda_{em} \cong 560$ nm;
 D11 – 2,5-bis-(styryl-4)-oxadiazole, $\lambda_{abs} = 300$ nm, $\lambda_{em} = 360$ nm;
 D12 – 2-(biphenyl)-5-(hydroxyphenyl-2)-thiazole, $\lambda_{abs} = 330$ nm, $\lambda_{em} = 490$ nm, $\tau \cong 19$ ns;
 D14 – 2-(hydroxyphenyl-2)-quinolinyl oxazole, $\lambda_{em} = 490$ nm;
 D15 – 2-phenyl-5-(phenyloxazolyl-2)-phenol, $\lambda_{abs} = 360$ nm, $\lambda_{em} = 500$ nm;
 D16 – 2-(N,N-dimethylaminophenylene)-N'-methyl-2-oxynolinyl oxazole, $\lambda_{em} \cong 480$ nm.

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сцинтилляторов .

Оригинал-макет подготовлен с помощью системы $\text{\LaTeX}$.
Редактор Е.Н.Горина. Технический редактор Н.В.Орлова.

Подписано к печати 24.10.1994 г. Формат 60 × 84/8.
Офсетная печать. Печ.л. 1,5. Уч.-изд.л. 1,152. Тираж 240. Заказ 180.
Индекс 3649. ЛР №020498 06.04.1992.

Институт физики высоких энергий, 142284, Протвино Московской обл.

ПРЕПРИНТ 94-111, ИФВЭ, 1994