

Radiation damage studies on polystyrene-based scintillators

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The radiation resistance of polystyrene-based scintillators containing various scintillation solutes is reported. All samples were irradiated with ^{137}Cs gamma rays in air at room temperature. The examination of radiation resistance of about thirty fluorescence compounds has been made. The most radiation-hard fluorides are X25, X31, 3HF and M3HF.

1. Introduction

During the last few years, interest in radiation-resistant scintillators for application in scintillator-based particle detectors at new high energy accelerators, SSC, LHC and UNK, has been renewed. As has been pointed out elsewhere [1], polystyrene (PS), as a solvent for scintillation solutes, has limited application in terms of high radiation resistance (polyvinyltoluene (PVT) has similar properties). But owing to the fact that polystyrene constitutes the basis for a series of low cost and efficient plastic scintillators, studies on radiation hardness of polystyrene-based scintillators (PSSC) have been the subject of many recent investigations (see the review in ref. [2]). Scintillation solutes which increase the radiation resistance of PSSC were reported in refs. [3–6].

Radiation hardness of an organic scintillator and its recovery process are strongly influenced by the conditions (temperature and presence of oxygen) under which it is irradiated. This is the reason why in some studies [3–6] of the radiation resistance the samples were held not only under normal conditions (air, room temperature). For example, the samples used in the experiments reported in refs. [3,4] were heated at 50°C during both the irradiation and recovery periods. In refs. [5,6] during irradiation the samples were maintained in nitrogen atmosphere, and in ref. [6] held at 5°C. In the present paper the study of the radiation hardness of PSSC doped with various fluors was car-

ried out under normal conditions. One may expect that a PSSC, which is radiation-resistant in air, will be also more stable in an oxygen free atmosphere.

Since a decrease in the light output of small plastic samples is mainly due to a decrease in the local scintillation yield of the scintillator, rather than to the reduction in the optical transmission of the sample [7], in the search for radiation-resistant PSSC the main attention was paid to the light output measurements. Moreover, the optical transmission measurements of the 5-mm thick samples (which were used in this study) may give only a qualitative estimate for the decrease in the light absorption lengths of long fibres and bars (tens of cm or a few meters).

2. Experimental

The monomer was de-inhibited through a column, distilled in vacuum, placed in a cylindrical glass container, and then dyes were added. Then the solution was de-oxygenated, the container sealed off and the material polymerized in a silicone oil bath at 170°C for 24 h. The material was then machined to polished disks of 25-mm diameter and 5-mm thickness.

The samples were irradiated with a ^{137}Cs source (20 krad/h) in air at room temperature. The light output measurements were made using a FEU-110 photomultiplier (PM) with tri-alkaline photocathode (maximum sensitivity at $\lambda = 480 \pm 15$ nm). The test samples were

coupled to the PM (without optical contact) and exposed to a ^{90}Sr source. Then the anode current of the PM was compared to that obtained for a standard PSSC (2% pTP + 0.025% POPOP). Since the scintillation yield of PSSC can vary, depending upon a set of polymer matrix parameters, such as concentration of residual monomer, molecular weight, structure of polymer chain, etc. (distribution for the scintillation yield has a width = 5–10%), one of several samples with the standard formulation was referred to as the standard sample with 100% light output.

3. Results

The experimental results are presented in tables 1–6 and in fig. 1. Formulae of the fluors used and their peak absorption and emission wavelengths are listed in the appendix.

First of all, we have investigated the radiation resistance of PSSCs doped with well known fluors. These results are presented in tables 1–3. Samples presented in table 1 were irradiated to two different doses, 3.3 Mrad and 14.3 Mrad. The samples nos. 7–10 have a PVT base. L_0 is the relative light output (in percent) before irradiation, and L after irradiation. L/L_0 is the light output normalized relative to the scintillator pre-irradiation value (in percent). The two last columns of table 1 list the values of L/L_0 after three months and after ten months of recovery in air at room temperature. From table 1, one sees the low radiation resistance of UV scintillators (nos. 8–10) and samples containing pyrazolines DBP and mPDP (nos. 11–13) or the benzoxazole derivative BO (no. 14). The same conclusions can be drawn from table 3.

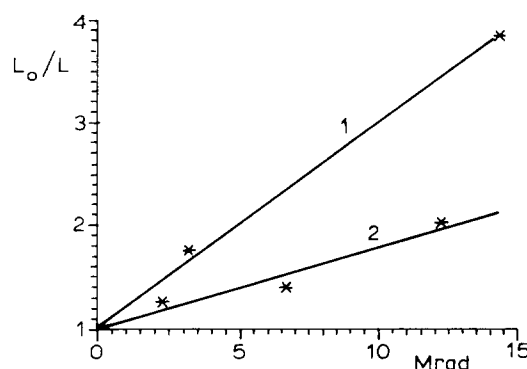


Fig. 1. Dependence of L_0/L on the total dose D [Mrad] for the sample doped with the standard fluors (2% pTP + 0.01% POPOP, sample no. 3 from table 1), curve 1, and for the sample doped with the radiation-hard secondary solute X25 (2% pTP + 0.1% X25, sample No. 3 from table 6).

The light output (before and after 14.3 Mrad irradiation dose) of scintillators containing only POPOP without any primary scintillation solute are given in table 2. The recovery, after three and ten months, is also shown. The absence of a primary scintillation solute does not significantly change the radiation resistance of PSSC.

The scintillators containing BPO or PPD as primary solutes have a smaller radiation resistance relative to the scintillators doped with pTP, PPO or PBD (see table 3). The sample containing BBOT as the secondary solute has the same radiation resistance as those doped with POPOP. Samples nos. 2 and 3 (table 3) with the same concentrations of the same fluors demonstrate fluctuations in radiation resistance.

Table 1

Relative scintillation light outputs of polystyrene-based and polyvinyltoluene-based scintillators before (L_0) and after irradiation (L). The values of L/L_0 [%] after three and ten months of recovery are listed in the two last columns

No	Scintillator	L_0 [%]	L/L_0 (3.3 Mrad)	L/L_0 (14.3 Mrad)	L/L_0 (3 m. rec.)	L/L_0 (10 m. rec.)
1	2.0% PPO + 0.10% POPOP	87	55	21	46	44
2	1.5% pTP + 0.01% POPOP	87	67	23	25	21
3	2.0% pTP + 0.01% POPOP	82	57	26	45	38
4	PVT + 2.0% pTP + 0.01% POPOP	89	73	29	45	45
5	2.0% PBD + 0.01% POPOP	103	70	32	43	42
6	1.5% PBD + 0.01% POPOP	88	65	30	43	43
7	PVT + 2% PBD + 0.01% POPOP	100	72	37	48	45
8	PVT + 2.0% PBD	68	62	24	32	26
9	PVT + 3.0% PBD	68	62	25	33	26
10	2.0% PPO	58	53	24	30	24
11	1.5% pTP + 0.01% DBP	31	49	23	17	6.5
12	1.5% PPO + 0.01% mPDP	77	48	19	27	24
13	2.0% pTP + 0.1% mPDP	90	52	20	27	23
14	1.0% BO	71	43	20	19	12

Table 2

Light outputs of POPOP-containing PSSCs before and after 14.3 Mrad dose, and after three and ten months of recovery

No	Scintillator	L_0 [%]	L/L_0 (14.3 Mrad)	L/L_0 (3 m. rec.)	L/L_0 (10 m. rec.)
1	0.1% POPOP	37	36	43	37
2	1.0% POPOP	91	22	52	53

Table 3

Light outputs of PSSCs for total doses of 2.3 and 10 Mrad. L_0 and L light outputs before and after irradiation. Last column is the value of L/L_0 after 23 days of recovery

No	Scintillator	L_0 [%]	L/L_0 (2.3 Mrad)	L/L_0 (10 Mrad)	L/L_0 (23 d. rec.)
1	2.0% pTP + 0.01% POPOP	85	50	25	50
2	1.5% pTP + 0.01% POPOP	96	67	23	45
3	1.5% pTP + 0.01% POPOP	94	56	19	42
4	2.0% pTP + 0.025% POPOP	98	71	23	52
5	2.0% PPO + 0.50% POPOP	102	31	8	52
6	1.5% PPO + 0.01% POPOP	85	42	15	43
7	0.5% PPO + 0.50% POPOP	92	40	9	51
8	2.0% PBD + 0.01% POPOP	95	54	13	44
9	1.5% BPO + 0.025% POPOP	84	33	8	15
10	1.0% PPD + 0.025% POPOP	75	40	13	35
11	1.5% PPD + 0.025% POPOP	74	42	19	40
12	1.5% pTP + 0.025% BBOT	86	71	22	50
13	2.0% pTP + 0.025% PDdPPS	74	51	18	37
14	0.1% 3HF	18	77	34	46
15	2.0% pTP + 0.025% dStB	45	42	15	29
16	1.5% PPO	59	29	11	28
17	1.5% pTP	43	39	18	22
18	3.0% PBD	68	36	11	32
19	2.0% BO	87	22	12	14
20	10.0% PPO + 0.5% POPOP	98	73	36	67
21	5% N + 2% pTP + 10% PPO + 0.1% POPOP	66	92	58	62
22	(21) + 0.1% DSP	84	52	36	60
23	5% N + 2% pTP + 10% PPO + 0.5% POPOP	71	93	59	69
24	5% N + 2% pTP + 10% PPO + 1.0% POPOP	72	86	57	67
25	2% pTP + 0.025% POPOP + 1% BAP	22	55	21	48

Common polymethylmethacrylate (PMMA) scintillators are known to be radiation-soft [7]. But the PMMA-based scintillator with high naphthalene (N) concentration (15% N + 0.4% POPOP) was observed ^{#1} to have a better radiation resistance than a polystyrene sample containing 2% pTP + 0.1% POPOP. A similar attempt to increase the radiation resistance of PSSC by adding N and by increasing the fluors concentration is shown in table 3 (nos. 20–24). Scintillators nos. 20, 21, 23 and 24 have relatively high radiation stability. Sample no. 22 is worse due to the presence of a pyrazoline derivative, DSP.

^{#1} S.A. Malinovskaya, Plastic scintillators on the base of acrylic polymers, P.D. Thesis, Institute of Monocrystals, Kharkov, 1970.

In ref. [8], the following dependence of L on the dose, D , was found for small values of the dose

$$L_0/L = 1 + K_D D, \quad (1)$$

where K_D is a degradation rate constant. Our experimental results approximately consist with eq. (1) for the dose values up to 14 Mrad, but several samples showed some deviations from linear dependence (1). Fig. 1 displays the L_0/L dependence on D for standard PSSC (no. 3, table 1) and a scintillator doped with X25 as the secondary solute (no. 3, table 6).

Eq. (1) is similar to the dependence of L_0 on the concentration of quencher c_Q [9]. One may assume that dependence (1) is due to the absorption of PS's or/and the primary solute's emission by the radiation-induced compounds (products of radiolysis) which cause

Table 4

Scintillation light outputs and the recovery process of PSSCs before and after irradiation

No	Scintillator	L_0 [%]	L/L_0 (4 Mrad)	L/L_0 (4 d. rec.)	L/L_0 (10 Mrad)	L/L_0 (23 d rec.)	L/L_0 (6 m. rec.)
1	2.0% pTP+0.025% X25	78	72	73	53	58	57
2	2.0% pTP+0.025% X31	85	65	70	47	55	52
3	2.0% pTP+0.025% POPOP	90	42	49	29	48	49
4	1.5% pTP+0.025% sfPDdmaP	85	40	46	27	40	36
5	1.5% PPO+0.025% sfPDdmaP	83	34	38	25	34	39
6	2.0% pTP+0.025% M-NBI	32	49	52	40	53	44
7	2.0% pTP+0.025% dmaNBI	27	45	41	42	48	37
8	2.0% pTP+0.025% Coum 30	76	32	36	23	33	28
9	2.0% pTP+0.025% Coum. 7	63	34	38	23	35	29
10	2.0% pTP+0.025% mPDP	85	40	46	24	34	30

fluorescent quenching, and that the concentration of these compounds is proportional to the dose D .

This consideration suggests that the radiation resistance of PSSC can be improved by addition of a quencher. The quenched scintillation yield is $L_{0Q} = L_0/(1 + K_Q c_Q)$ before irradiation, and after irradiation $L_Q = L_0/(1 + K_Q c_Q + K_D D)$. Now instead of eq. (1), we obtain

$$L_{0Q}/L_Q = 1 + K'_D D, \quad (2)$$

where $K'_D = K_D/(1 + K_Q c_Q)$. In this case one can see a slowed dependence of L_{0Q}/L_Q on D in comparison with eq. (1) because K_D is replaced with K'_D where $K'_D < K_D$.

This hypothesis was investigated by using benzalacetophenone (BAP, $\lambda_{abs} = 310$ nm) as a quencher. The radiation resistance of the quenched sample, no. 25 (table 3), is not affected by the quencher and is close to that of the unquenched sample, no. 4 (table 3). This fact means that the ratio L_{0Q}/L_Q is given by

$$L_{0Q}/L_Q = 1 + K_D D, \quad (3)$$

Table 5

Scintillation light outputs of PSSC before and after irradiation and the recovery process

No	Scintillator	L_0 [%]	L/L_0 (2.3 Mrad)	L/L_0 (5 m. rec.)
1	1.5% pTP+0.01% POPOP	92	49	76
2	2.0% pTP+0.025% 3HF	50	77	82
3	1.5% pTP+0.01% DP	97	52	69
4	1.5% pTP+0.01% mBIdeaBO	106	45	59
5	1.5% pTP+0.01% R931	95	54	71
6	1.5% pTP+0.01% R932	78	53	67
7	2.0% mPBD+0.025% POPOP	103	27	75
8	2.0% pTP+0.01% PEP	92	48	57
9	2.0% 1 MN+0.025% POPOP	60	50	65
10	(9)+0.3% PPO	88	50	73
11	0.3% PPO+0.025% POPOP	80	35	63

instead of eq. (2), and hence $L_Q = L_0/[(1 + K_D D)(1 + K_Q c_Q)]$. Thus we conclude that the decrease in the scintillation yield after irradiation is mainly due to the destruction of the polymer base rather than to the quenching products of the radiolysis.

In tables 4–6 some new PSSCs as well as known PSSCs (for the sake for comparison) are presented. Low values of L_0 for samples nos. 6 and 7 (table 4), and nos. 7 and 12 (table 6) are due to the low photocathode sensitivity for the red emission of these samples. Best of all examined are X25, X31, 3HF and M3HF fluors.

From table 4 one finds low radiation resistance for PSSC containing coumarin derivatives. It should be noted that pyrazoline derivatives are not photostable, while coumarins are photostable. There is no explicit correlation between photostability and radiation resistance of a fluorescence compound.

The oxazole, oxadiazole and naphthoylen-benzimidazole derivatives exhibit the same or less radiation resistance than POPOP (see tables 4–6). Some pyrazoline and benzoxazole derivatives (DP, R931 and R932) have the radiation resistance comparable to POPOP-containing PSSC, unlike other pyrazoline and benzoxazole derivatives.

The value of the decrease in transparency of the samples was measured in the following manner. The test sample was inserted between the non-irradiated sample and the photomultiplier window. Let the anode current in this case, before irradiation of the test sample, be I_0 and I is the anode current after irradiation. The value of I/I_0 is a measure of the optical losses of the irradiated sample. These losses are small for doses of 2–4 Mrad, for example $I/I_0 = 97\%$ for sample no. 1 from table 5 (dose of 2.3 Mrad) while $L/L_0 = 76\%$. For a larger dose, 12.3 Mrad (see table 6), $I/I_0 = 93\%$ for sample no. 1 ($L/L_0 = 55\%$), $I/I_0 = 80\%$ for sample no. 3 ($L/L_0 = 59\%$) and $I/I_0 = 80\%$ for sample no. 6 ($L/L_0 = 50\%$). Note that the optical losses in the light output measurement are smaller

Table 6

Scintillation light outputs of PSSC before and after irradiation and their recovery

No	Scintillator	L_0 [%]	L/L_0 (2.3 Mrad)	L/L_0 (6.6 Mrad)	L/L_0 (12.3 Mrad)	L/L_0 (3.5 m rec.)
1	2.0% pTP + 0.025% M3HF	59	77	60	41	55
2	2.0% pTP + 0.05% X25	75	81	62	43	52
3	2.0% pTP + 0.10% X25	71	80	69	50	59
4	0.1% X25	35	69	62	37	52
5	0.3% X25	37	75	66	41	51
6	2.0% butyl-PBD + 0.025% POPOP	104	43	33	20	50
7	2.0% pTP + 0.025% dmaPD-NBI	38	42	45	21	58
8	2.0% pTP + 0.025% bis-dmaP-D	82	46	34	16	31
9	2.0% pTP + 0.025% sfPOdmaP	73	60	44	24	47
10	2.0% pTP + 0.05% MI-DMAN	75	64	59	34	45
11	2.0% pTP + 0.05% cmPdaPO	88	60	42	21	43
12	2.0% pTP + 0.05% DP-PNI	24	53	54	25	42

than $1 - I/I_0$ because β -particles penetrate the sample and the average light path in the sample is thus less than that in the transparency measurement described above. But the value of $1 - I/I_0$ allows one to estimate the optical losses in the sample.

An important characteristic of a scintillator is its emission decay time constant τ . The shape of the scintillation pulses from PSSCs were measured using the usual single photon counting technique. The scintillators, containing 3HF, X25 and X31 fluors, were observed to have the decay constants $\tau = 7$ ns, $\tau = 12$ ns and $\tau = 10$ ns respectively. The M3HF doped scintillator has two components: $(p_1/\tau_1) \exp(-t/\tau_1) + (p_2/\tau_2) \exp(-t/\tau_2)$ with $p_1 = 0.6$, $\tau_1 = 3.5$ ns, $p_2 = 0.4$ and $\tau_2 = 9$ ns.

4. Conclusions

The primary scintillation solutes pTP, PPO, PBD, mPBD and bPBD showed no considerable difference in terms of the radiation resistance of polystyrene scintillators doped with these fluors. The primaries BPO, BO, and PPD are less stable.

Secondary solutes X25, X31, 3HF and M3HF are the most radiation-resistant among all other examined secondaries.

The radiation resistance of a scintillator can be increased by increasing the primary fluor concentration (up to 10%) and by adding naphthalene.

Appendix

The list of fluors used in this study

N – naphthalene, $\lambda_{\text{abs}} \leq 310$ nm, $\lambda_{\text{em}} = 325\text{--}340$ nm
 1 MN – 1-methylnaphthalene, $\lambda_{\text{abs}} = 320$ nm, $\lambda_{\text{em}} = 400$ nm

pTP – para-terphenyl, $\lambda_{\text{abs}} = 290$ nm, $\lambda_{\text{em}} = 360$ nm
 PPO – 2,5-diphenyloxazole, $\lambda_{\text{abs}} = 310$ nm, $\lambda_{\text{em}} = 365$ nm
 PBD – 2-phenyl-5-(4-biphenyl)-1,3,4-oxadiazole, $\lambda_{\text{abs}} = 305$ nm, $\lambda_{\text{em}} = 365$ nm
 mPBD – 2-(4'-methylphenyl)-5-(4''-biphenyl)-1,3,4-oxadiazole, $\lambda_{\text{em}} = 365$ nm
 bPBD – 2-(4'-t-butylphenyl)-5-(4''-biphenyl)-1,3,4-oxadiazole, $\lambda_{\text{abs}} = 310$ nm, $\lambda_{\text{em}} = 365$ nm
 BPO – 2-biphenyl-5-phenyloxazole, $\lambda_{\text{abs}} = 330$ nm, $\lambda_{\text{em}} = 390$ nm
 PPD – 2,5-diphenyloxadiazole, $\lambda_{\text{abs}} = 280$ nm, $\lambda_{\text{em}} = 350$ nm
 BO – 2-(4'-dimethylaminophenyl)-benzoxazole, $\lambda_{\text{abs}} = 330$ nm, $\lambda_{\text{em}} = 400$ nm
 BAP – benzaleacetophenone (quencher, $\lambda_{\text{abs}} = 310$ nm)
 POPOP – 1,4-bis-[2-(5-phenyloxazolyl)]-benzene, $\lambda_{\text{abs}} = 365$ nm, $\lambda_{\text{em}} = 420$ nm
 BBOT – 2,5-di-(tert-butyl-2-benzoxazolyl)-thiophene, $\lambda_{\text{abs}} = 380$ nm, $\lambda_{\text{em}} = 436$ nm
 dStB – 4,4'-distyrylbiphenyl, $\lambda_{\text{em}} = 430$ nm
 mPDP – 1-(o-methoxyphenyl)-3,5-diphenyl-2-pyrazoline, $\lambda_{\text{abs}} = 360$ nm, $\lambda_{\text{em}} = 460$ nm
 DSP – 1,5-diphenyl-3-styryl-2-pyrazoline, $\lambda_{\text{abs}} = 390$ nm, $\lambda_{\text{em}} = 460$ nm
 PDdPPS – 4-(5-phenyloxadiazolyl)-4'-(3,5-diphenylpyrazolyl)-1-stilbene, $\lambda_{\text{abs}} = 450$ nm, $\lambda_{\text{em}} = 560$ nm
 X25 – naphthalic anhydride derivative, $\lambda_{\text{abs}} = 400$ nm, $\lambda_{\text{em}} = 500$ nm, $\tau = 12$ ns
 X31 – naphthalimide derivative, $\lambda_{\text{abs}} = 400$ nm, $\lambda_{\text{em}} = 500$ nm, $\tau = 10$ ns
 3HF – 3-hydroxyflavone, $\lambda_{\text{abs}} = 350$ nm, $\lambda_{\text{em}} = 530$ nm, $\tau = 7$ ns
 M3HF – 2-(4'-methoxyphenyl)-3-hydroxyflavone, $\lambda_{\text{abs}} = 350$ nm, $\lambda_{\text{em}} = 430$ nm, $\tau_1 = 3.5$ ns (60% of light), $\tau_2 = 9$ ns (40%)
 sfPDdmaP – 2-(4-sulfofluorophenyl)-5-(4'-dimethylaminophenyl)-1,3,4-oxadiazole, $\lambda_{\text{abs}} = 370$ nm, $\lambda_{\text{em}} = 495$ nm

sfPOdmaP – 2-(4-sulfofluorophenyl)-5-(4'-dimethylaminophenyl)-1,3-oxazole, $\lambda_{\text{abs}} = 400$ nm, $\lambda_{\text{em}} = 513$ nm
 Coum. 30 – 7-diethylamino-3-(3'-methylbenzimidazolyl-2')-coumarin, $\lambda_{\text{abs}} = 420$ nm, $\lambda_{\text{em}} = 480$ nm
 Coum. 7 – 7-diethylamino-3-(benzimidazolyl-2')-coumarin, $\lambda_{\text{abs}} = 460$ nm, $\lambda_{\text{em}} = 510$ nm
 dmaNBI – 4-dimethylamino-1,8-naphthoylen-1',2'-benzimidazole, $\lambda_{\text{em}} = 600$ nm
 M-NBI – 4-morpholino-1,8-naphthoylen-1',2'-benzimidazole, $\lambda_{\text{em}} = 575$ nm
 PEP – 4,4'-bis-(2-(5-phenyloxazolyl)-stilbene, $\lambda_{\text{abs}} = 385$ nm, $\lambda_{\text{em}} = 450$ nm
 DP – 1,3-diphenyl-2-pyrazoline, $\lambda_{\text{em}} = 450$ nm
 mBIdeaBO – 2-(1'-methylbenzimidazolyl-2')-6-diethylamino-benzoxazole, $\lambda_{\text{em}} = 460$ nm
 R931 – benzoxazole derivative, $\lambda_{\text{em}} = 490$ nm
 R932 – benzoxazole derivative, $\lambda_{\text{em}} = 490$ nm
 bis-dmaP-D – 2,5-bis-(4-dimethylaminophenyl)-oxadiazole, $\lambda_{\text{abs}} = 350$ nm, $\lambda_{\text{em}} = 400$ nm
 dmaPD-NBI – 5-(4-dimethylaminophenyl)-2-(1,8-naphthoylen-1',2'-benzimidazolyl-5)-oxadiazole, $\lambda_{\text{abs}} = 440$ nm, $\lambda_{\text{em}} = 565$ nm

MI-DMAN – 4-dimethylaminonaphthalic acid N-methylimide, $\lambda_{\text{em}} = 480$ nm
 cmPdaPO – 2-(4'-carbomethoxyphenyl)-5-(4''-dimethylaminophenyl)-oxazole, $\lambda_{\text{abs}} = 353$ nm, $\lambda_{\text{em}} = 460$ nm
 DP-PNI – 4-(1,5-diphenyl-2-pyrazoliny-3)-N-phenyl-naphthalimide $\lambda_{\text{em}} = 580$ nm

References

- [1] V.M. Feygelman, J.K. Walker and J.P. Harmon, Nucl. Instr. and Meth. A290 (1990) 131.
- [2] C. Zorn, IEEE Trans. Nucl. Sci. 37 (1990) 504.
- [3] C. Zorn et al., Nucl. Instr. and Meth. A271 (1988) 701
- [4] C. Zorn et al., Nucl. Instr. and Meth. A273 (1988) 108.
- [5] A.D. Bross, Nucl. Instr. and Meth. A295 (1990) 315.
- [6] A.D. Bross et al, Fermilab-Pub-91/54 (1991).
- [7] G. Marini et al., CERN report 85-08 (1985).
- [8] O.A. Gunder, V.S. Koba, High Energy Chem. (USSR) 8 (1974) 83.
- [9] J.B. Birks, The Theory and Practice of Scintillation Counting (Pergamon Press, 1964).