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Radiation damage studies on new liquid scintillators and liquid-core scintillating fibers

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Abstract

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The radiation resistance of some new liquid scintillators and capillaries filled with liquid scintillators has been presented. It was found that scintillation efficiency of the liquid scintillator based on 1-methylnaphthalene with a new dye R39 fell only by 30% at the dose of 190 Mrad and the radiation resistance of thin liquid-core scintillating fibers exceeded 60 Mrad.

Аннотация

Головкин С.В. и др. Исследование радиационной стойкости новых жидких сцинтилляторов и сцинтилляционных волокон на их основе: Препринт ИФВЭ 94-33. – Протвино, 1994. – 19 с., 15 рис., 1 табл., библиогр.: 35.

В работе представлено исследование радиационной стойкости известных и новых жидких сцинтилляторов и сцинтилляционных волокон на основе капилляров с жидким сцинтиллятором. Было найдено, что сцинтилляционная эффективность жидкого сцинтиллятора на основе 1-метилнафталина с новой добавкой R39 уменьшилась на 30% после получения дозы 190 Мрад. Радиационная стойкость тонких капилляров, заполненных этим жидким сцинтиллятором, превышает 60 Мрад.

During the last few years the interest in radiation-resistant organic scintillators to be used in calorimeters and tracking detectors has been renewed. As for tracking detectors the radiation resistance of vertex detectors is of great importance for future colliders. For example, the integral dose during 10 years of irradiation will reach hundreds of megarads [1] for a LHC vertex detector.

Recently notable advance has been made in the development of high resolution detectors based on capillaries filled with liquid scintillators [2-9]. They are very promising detectors for current high energy physics as well as for the new generation of colliding beam and fixed target experiments. Due to high scintillating and trapping efficiencies the track hit density is higher than that of detectors based on plastic fibers or semiconductors. The large attenuation length $l = 1.5\,m$ for the capillaries with the diameter of $20\,\mu m$ [7] and $l \geq 3\,m$ for the diameter of 0.5 mm allows one to construct detectors with the length $\geq 2\,m$ and spatial resolution $\leq 20\,\mu m$ per hit.

The use of liquid-core fiber tracking detectors will have an important advantage in high radiation environment of future experimental setups. With an appropriate choice of a liquid scintillator (LS) and capillary glass it is possible to obtain a high level of the radiation resistance (>60 Mrad). Besides, the replaceability of an LS increases significantly the radiation resistance of detectors. The investigation results of luminescent, optical, and radiation properties of a series of new and known LSs based on 1-methylnaphthalene (1MN), isopropylbiphenyl and the recent IPN solvent (for the abbreviations of fluors, plastics and solvents see Table 1) as well as liquid-core scintillating fibers are being presented.

1. Experimental procedure

The radiation resistance measurements have been carried out at IHEP. For doses over than 10 Mrad the samples were irradiated in a flux of γ-quanta from

^{60}Co radioactive sources at the dose rate of 600 rad/s. For lower doses ^{137}Cs radioactive sources were used at the dose rate of 6 rad/s. Before the irradiation various samples of LSs and capillaries filled with LSs were placed in glass ampoules which were pumped out and sealed. The samples were irradiated at room temperature. We took precautions to avoid a long-term air contact of unirradiated and irradiated LSs because it causes the deterioration of transparency and the LSs light output. The examples of the air influence on LSs during the irradiation will be given bellow.

The scintillating efficiency of our LSs was measured by exciting the samples of an LS ($2\,cm^3$) with a ^{90}Sr radioactive source. The samples were fixed upon the input window of a photodetector (an image intensifier) having the maximum quantum efficiency of a multialkaline photocathode in the green wavelength region (500 nm). The relative scintillation efficiency of various LSs was measured in comparison with a standard polystyrene (PS) plastic scintillator (PS+1.5%pTP+0.1%POPOP) of the same volume ($2\,cm^3$). The light yield of the plastic scintillator was set equal to 100%.

For the attenuation length measurements of our liquid-core fibers we used the special setup [3,6] with the same type of the photodetector. The fibers were excited in this setup by the collimated β-source ^{90}Sr. In all the measurements the concentration of the dyes was 3 g/l. There are two irradiation sensitive elements (an LS and thin-wall glass of capillaries). We investigated the radiation resistance of liquid-core scintillating fibers as well as the sensitive elements of fibers separately.

2. Radiation damage studies on liquid scintillators

First of all we investigated the radiation resistance of LSs which were irradiated in ampoules. Experimental results of the relative light output of our LSs in comparison with some BICRON liquid scintillators (based on isopropylbiphenyl) are presented in fig.1. These results showed that the LS based on 1MN has a higher light output. Relatively fast drop in light outputs for 1MN containing the R45 dye (1MN+R45) and BC-599-13G at doses less than 50 Mrad was due to degradation of the dyes. The scintillation efficiency of the LS based on 1MN+R39 fell by only 30% at the dose of 190 Mrad.

The light attenuation of our irradiated and unirradiated LSs was measured in unirradiated quartz capillaries with the inner diameter of 0.5 mm and wall thickness of 60 μm. An influence of γ-irradiation on the attenuation length and light output up to the dose of 190 Mrad is shown in figs.2-4. The LS based on 1MN+R45 is characterized by the excellent attenuation length at zero dose ($l = 313\,cm$) but by the worse radiation resistance in comparison with the LS based on 1MN+R6 or 1MN+R39. The light output of the LS 1MN+R6 fell by 2.6 times at the distance of 1 m for the dose of 48 Mrad. Despite the worse radiation resistance the LS based on 1MN+R45 has almost the same light output at the distance of 1 m at the dose of 48 Mrad as that for 1MN+R6 and 1MN+R39 owing to the better attenuation length.

We have also tested the radiation resistance of LSs based on other types of solvents. The experimental results from this study are shown in figs.5-7. Fig.5 presents the radiation resistance of the LS based on the new solvent IPN. The best light output was attained for IPN+3M-15. Unfortunately, the LS with this dye has the worst radiation resistance. For the LS based on IPN+R39 dye the light output is reduced by a factor of 2.27 at the 1 m distance for the dose of 10 Mrad. From fig.6 one can see that the LS based on IPN has better radiation resistance in comparison with 1MN. This is true for all our dyes. At the same time some Bicron LSs BC-599 have much worse radiation hardness (fig.7). The light output at the distance of 1 m fell by 10 times and 130 times for BC-599-13B and BC-599-13G for the dose of 48 Mrad, respectively. From these data (figs.1-7) one can conclude that among the investigated solvents the recent IPN solvent provides the best radiation resistance. The best radiation resistant dyes are R6 and R39.

Owing to large attenuation length it is possible to use the capillaries with smaller diameters of 15–150 μm for the capillary tracking detectors. The light attenuation of liquid-core fibers having the core diameter of about 110 μm and wall thickness of about 20 μm have been measured. The unirradiated quartz capillaries were used in these tests. Some experimental results for liquid-core scintillating fibers (up to the dose of 64 Mrad) are given in fig.8. For the solution 1MN+R6 at the dose of 64 Mrad the light output halved to its original value at the distance of 1 m.

Note that 6 months later we observed no recovery of luminescent and optical characteristics of our LSs.

As is known from our experience a long-term exposure to air deteriorates the luminescent and optical characteristics of the LS based on 1MN. The air influence on some LSs during the irradiation is illustrated by fig.9. These data show a dramatic decrease of the attenuation length and light output. At present we are investigating the air influence on the LS based on IPN and other solvents.

3. Influence of radiation damage of glass on radiation resistance of liquid-core fibers

The capillaries made of a pure quartz do not influence the radiation resistance of liquid-core fibers because the radiation hardness of a pure quartz is excellent and exceeds 1 Grad [10]. To establish an influence of the radiation damage of glass we tested capillaries made of a low grade quartz. The transmission T of the low grade quartz sample 1 cm thick at different doses is shown in fig.10.

The capillaries without LSs were irradiated and then filled with the unirradiated LSs. Experimental results for the capillaries of 150 μm inner diameter are presented in fig.11. For these tests we used the 1MN solvent and R45 dye of high purity. The attenuation length of unirradiated 150 μm liquid-core fibers is equal to 320 cm (fig.11). The capillaries irradiated at the dose of 48 Mrad decreased the attenuation length down to 170 cm.

The influence of the absorption losses in capillary walls versus the radiation dose on the light attenuation in liquid-core fibers can be estimated.

The scintillating light trapped in a capillary by the total internal reflection at the LS-glass interface penetrates several wavelengths deep in the glass. This results in additional light losses for propagating rays due to the darkening of the glass.

Let us consider a light ray inclined at the polar angle Θ to the fiber axis, and having the azimuthal angle ϕ between the projection of this ray onto the plane orthogonal to the fiber axis and tangential to the surface of the liquid-glass boundary in the point where the ray reflects. When such a ray propagates in the circular fiber these angles (Θ,ϕ) remain the same in all reflections. The dependence of the light intensity on the distance z along the fiber from the point of light emission is as follows

$$I(z,\Theta,\phi) = I_0 \cdot e^{-z \cdot a(\Theta,\phi)/\cos\Theta}, \tag{1}$$

where $a(\Theta,\phi)$ is determined by formula [11]:

$$a(\Theta,\phi) = a_1 + (a_2 - a_1) \cdot \frac{\sin^2\Theta/\sin^2\Theta_c}{1 + (\pi n_1 d/\lambda)^2 \cdot \sqrt{\sin^2\Theta_c - \sin^2\Theta \cdot \sin^2\phi}}, \tag{2}$$

where n_1, n_2 are the refractive indexes of liquid and glass, respectively, a_1, a_2 are the inverse attenuation lengths in the bulk liquid and glass, λ is the light wavelength, d is the internal diameter of the capillary, $cos\Theta_c = n_2/n_1$.

To calculate the light output at the distance z one should integrate expression (1) for all trapped (Θ, ϕ) rays. The condition of the total internal reflection is given as:

$$\sin\Theta \cdot \sin\phi < \sin\Theta_c. \tag{3}$$

The distribution of light intensity I_0 over the Θ, ϕ angles in case of uniformly excited LS cross-section and isotropic scintillating light emission is given by the formula:

$$\frac{d^2 I_0(\Theta,\phi)}{d\Theta \cdot d\phi} = \frac{1}{\pi} \cdot \sin\Theta \cdot \sin^2\phi. \tag{4}$$

The calculational and experimental results are compared (fig.11) and are in a good agreement. To calculate the attenuation curve in irradiated capillaries two parameters (a_1, a_2) are needed. The first parameter $a_1 = 0.25\,m^{-1}$ was determined from the attenuation curve in the unirradiated capillary (fig.11), the second $a_2 = 1.2\,cm^{-1}$ - from the transmission spectra of the $1\,cm$ thick quartz sample irradiated at several doses (fig.10). The result of the numerical integration of expression (1) is close to the experimental results (fig.11).

Expression (1) can be integrated only numerically, but for the first approximation one can assume that the attenuation in the irradiated capillary l_{irr} filled with the LS is equal to

$$1/l_{irr} \simeq 1/l_0 + 1/l_{add}, \tag{5}$$

where l_0 is the attenuation in the unirradiated capillary $(a_2 = 0)$ filled with the same LS and l_{add} denotes the additional attenuation produced by the darkening of the glass. It corresponds to the attenuation in the fiber filled with perfectly transparent LS $(a_1 = 0)$ and darkened glass $(a_2 \neq 0)$. The l_{add} as a function of a_2 for different sets of n_1, n_2 and the diameter d is shown in fig.12. When $d \gg \lambda$ expression (2) can be simplified and l_{add} can be approximately calculated as:

$$l_{add} \propto \frac{1}{a} \propto \frac{n_1 d}{a_2 \lambda}. \tag{6}$$

This permits to estimate the value of l_{add} for n_1, n_2, d (other than those represented in fig.12).

According to fig.12 the influence of the glass darkening on the attenuation in a capillary is relatively small. Even when the darkening of quartz glass is noticeable $(a_2 = 0.3\,cm^{-1})$ the additional attenuation l_{add} for capillaries of $20\mu m$ diameter is about 1 m and for capillaries of 0.5 mm diameter is about 10 m. It is quite acceptable with account for the attenuation length l_0 for unirradiated capillaries to be 1.5 m for capillaries of 20μm diameter and about 3 m for capillaries of 0.5 mm diameter. Thus the radiation resistance of capillaries filled with an LS is limited by the resistance of an LS rather than the capillary glass, and the radiation resistance of the whole detector could be significantly improved using the replaceability of an LS.

There are quartz glasses which practically do not change transmission up to doses > 1 Grad that permits to build a capillary detector composed of 20 μm capillaries which can withstand doses > 1 Grad in case of periodical renovation of an LS. If such a detector is built of ordinary quartz or borosilicate glasses its radiation hardness will be also determined by the LS. However, in order to obtain radiation hardness of such a detector about 50 Mrad it is necessary to use glasses which at this level of irradiation have the bulk attenuation length of several cm. For capillaries of large diameter (0.5–3 mm) which can be applied in tracking detectors or calorimeters the radiation stability > 1 Grad is quite possible even for ordinary quartz or borosilicate glasses in case of periodical renovation of an LS. Without the LS replacement the radiation stability of the detector is determined by the LS.

The total influence of irradiated capillaries and the LS on the attenuation length in liquid-core fibers is presented in fig.13. The attenuation length in 150 μm capillaries filled with the mixture 1MN+R6 is equal to 66 cm at the dose of 48 Mrad. When comparing this value with the data from fig.8 (85 cm attenuation length at 32 Mrad and 64 cm at 64 Mrad for 110 μm unirradiated capillaries) and that obtained experimentally (at the 32 Mrad dose the 57 cm attenuation length for 110 μm irradiated capillaries filled with the irradiated solution 1MN+R6) one can conclude that the influence of capillary walls on the radiation damage of liquid core scintillating fibers is quite small (20–50%) even at high dose and low glass radiation resistance. The glass darkening caused by irradiation has a weak effect on the attenuation length because the scintillating light trapped in a capillary due to the total internal reflection from the LS-glass interface penetrates into glass only a few wavelengths deep.

4. Comparison of radiation resistance of plastic and liquid-core scintillating fibers

We have investigated the radiation resistance of plastic scintillators based on polystyrene containing pTP as the primary fluor and new dyes (R6. R39) as the secondary fluor. The samples of these plastic scintillators showed a low level of the radiation resistance. After 10 Mrad irradiation the loss of light output for the polystyrene samples was about 80-90% [12] while for the LS on the base of 1MN and the above dyes the loss of light output was about 3% at this dose. The use of 1MN as a solvent can provide much higher level of the radiation resistance in comparison with conventional polystyrene.

It is interesting to compare the radiation resistance of LS with that of different known plastic scintillators. We would like to emphasize that for tracking detectors not only the radiation resistance is important but also the scintillator light yield. Therefore, the relative light outputs after a recovery of various scintillators (with the normalization error of about 15%) versus the radiation dose are presented in fig.14. This figure shows the best results for plastics and allows one to realize the situation with the radiation resistance and light yield.

Conventional plastic scintillators based on PS or PVT are of low radiation resistance. For example, the light output of BC408 reduces 1.7 times at dose of 30 Mrad [13]. Conventional LSs have even worse radiation hardness. For instance, the light output of NE235 reduces 1.5 times at the dose of 5 Mrad [14].

For the PS or PVT plastic scintillators the main problem is the transmission of the base which changes significantly at short wavelengths caused by irradiation. Therefore plastic fibers emitting in a blue region have worse radiation resistance [15]. In order to decrease the absorption of the emission of the primary fluor due to the base damage (before re-emission by the secondary fluor) one uses the high concentration of the secondary fluor. Quite good results have been obtained for the high concentration of the dye 3HF [16, 17] (fig.14) - one of the best dyes in the green region with a large Stokes' shift. At the dose of 100 Mrad the reduction of light output is about 40%.

One can attain much better radiation resistance for the single component scintillator with high concentration of the single dye when the dominating mechanism of the energy transfer from the base to the fluor is nonradiative. Unfortunately, the light outputs of these plastic scintillators or LSs with the single 3HF dye are low (fig.14 — PS+3HF [18,19], base BC505+3HF [14], toluene+3HF [20, 21]). Plastic scintillators with another large Stokes' shift fluor PMP with high scintillation efficiency have low radiation resistance [14, 22] (fig.14).

Good results were obtained in [23] for PS scintillators with primary fluors MOPOM, O415A, O408 and secondary BBQ (470 nm), K27 (500 nm). One of the best results (PS + O408 + BBQ) is presented in fig.14. These scintillators have long decay constants (τ=11-13 ns) that can limit their application in high intensity beams.

The true way of increasing the radiation resistance is to improve the radiation hardness of the base. It would be interesting to investigate polyvinylxylene (PVX) based scintillator [24], "tailed" PS and "tailed" poly (n-hexyl methacrylate) [25]. But another material – polysiloxane (PMPS) seems more promising. For the PMPS based scintillator with fluors emitting at < 425 nm the light yield reduction by the irradiation is appreciable even in inert atmosphere (1.2 - 3 times at the dose of about 10 Mrad [26, 27, 28]). The presence of oxygen strongly affect the radiation damage extent, at best it reduces the light output 2 times at the dose of 18.5 Mrad (see fig.14, the PMPS + O415 + DMT (415 nm) [28]).

The PMPS scintillator with the secondary fluor TPB emitting in a longer wavelength region the light output does not change up to 16.5 Mrad (PMPS + O374A + TPB (460 nm) [29, 30]. However the light output of this scintillator is 0.25 of that for BC408. In order to use the high radiation resistance of the PMPS for tracking detectors it is necessary to find dyes in the green region with the high light yield in the PMPS.

The radiation resistance of some commercially available LSs was presented in [31, 32, 33]. For the capillary tracking detector [6, 7] one can use only LSs with a high refractive index. In [32] the LS based on 1PN (fig.14 – 1PN+MOPOM (430 nm), 1PN+BPD (500 nm)) was investigated. Unfortunately, the LS with very high light output – 1PN+MOPOM and good radiation resistance (up to 10 Mrad) emits in a blue region where the transparency of 1PN is not so good. The attenuation length for 180 μm capillaries with this binary scintillator is equal to $\sim$40 cm [33]. The green dye BPD has a large Stokes' shift of 150 nm, and it is suitable for the binary LS. But the light yield of this LS reduces 1.3 times at the dose of 10 Mrad [32].

The considered 1MN+R6 or 1MN+R39 LSs successfully combine a high light output and very good radiation resistance. The light output of 1MN+R39 reduces by 17% only at the dose of 112 Mrad (fig.14).

Regard must be paid to the trapping efficiency of fibers. The trapping fraction in quartz capillaries ($n_{co} = 1.46$) with 1MN ($n_{cl} = 1.617$) is 1.5 times larger than that of a conventional polystyrene fiber ($n_{co} = 1.59$) with a PMMA cladding ($n_{cl} = 1.49$) [3]. To calculate the light output at the short distance for fibers or capillaries with LSs we must multiply the data from fig.14 by relative trapping fractions.

Let us compare the radiation resistance of various scintillating fibers. The high radiation resistance of a scintillator in a small volume (a local light yield as in fig.14) does not signify high radiation resistance of long fibers because the main reason of deterioration is the reduction of the fiber transparency by the irradiation.

Fig.15 presents relative light output of 1 mm plastic fibers after a recovery and a liquid-core fiber at the distance of L=1 m versus the radiation dose. One should take into account the attenuation length decrease and light yield versus the radiation dose. This data for plastic fibers have been taken from appropriate papers (fig.15). The comparison with the best plastic fibers shows that the radiation resistance of a liquid-core fiber is much better. Really with plastic fibers it is possible to work at the dose less than 5 Mrad, but liquid-core fibers can be used at the dose more than 60 Mrad without change of the LS.

Conclusion

In this paper the radiation resistance of some new liquid scintillators and capillaries filled with liquid scintillators (LSs) has been studied. We investigated the radiation resistance of LSs on the base of 1MN and new IPN solvents with R6, R39, R45, 3M-15 dyes, and also commercially available Bicron LSs. The samples were irradiated in a flux of γ-quanta up to the dose of 190 Mrad. The air contact during irradiation dramatically deteriorating luminescent and optical characteristics of the LSs, the samples before irradiation were placed in glass ampouies that were pumped out and sealed. The use of vacuumized LSs provided the absence of gas bubbles in liquid-core scintillating fibers from processes of radiolysis up to the dose of 200 Mrad.

Firstly we investigated radiation resistance of LSs itself. The obtained results proved LSs to be very stable: for example, at the dose of 190 Mrad the scintillating efficiency of 1MN+R39 became only 70%, and the attenuation length in 0.5 mm capillaries changed from 144 cm to 59 cm. Thus the radiation hardness of small volumes (where losses due to the attenuation are small) of the LS based on 1MN+R39 or 1MN+R6 is greater than 190 Mrad. The radiation hardness of LS in capillaries may be defined as follows: it is the dose at which the light output of a fiber excited at the 1 m distance from the readout end reduces 2 times. Then the radiation hardness of 1MN+R6 in 110 μm capillaries is about 64 Mrad and in 0.5 mm capillaries about 40 Mrad. Bicron LSs showed much worse results than LSs based on 1MN, investigation of LSs on the base of a new solvent IPN irradiated up to the dose of 10 Mrad indicated that it should have better radiation stability than 1MN. The best radiation resistant dyes were R6 and R39. The dyes which showed the best results before irradiation R45 and 3M-15 turned out to be less resistant. After 6 months of exposure there was no recovery of luminescent and optical characteristics detected.

We also investigated the influence of glass radiation damage on the radiation resistance of liquid-core fibers. It was calculated theoretically and measured experimentally and both methods were in a good agreement. The influence of the glass darkening on the attenuation length in a capillary turned out to be relatively small, especially for capillaries of large diameter (0.5–3 mm), because the scintillating light trapped in a capillary by the total internal reflection from the LS-glass interface penetrates into glass only a few wavelengths deep. The radiation resistance of a capillary filled with an LS is limited by the LS resistance rather than capillary glass, and the radiation resistance of the whole detector could be significantly improved in the case of the LS periodical renovation. Using the replaceability of an LS it is possible to build a capillary detector which can withstand the dose up to 1 Grad for capillaries of $20 - 100\,\mu m$ diameter made of the special radiation resistant quartz glass, the dose up to 64 Mrad for capillaries of the same diameter made of ordinary borosilicate or quartz glass. For capillaries of large diameter (0.5–3 mm) made of ordinary quartz or borosilicate glass it is possible to build a detector which can withstand the radiation dose up to 1 Grad with the LS periodical renovation. Without the LS replacement the radiation stability of the detector is determined by the LS and could reach about 64 Mrad.

We have compared our results with that of radiation resistance of plastics and liquid-core scintillating fibers published elsewhere. The comparison of scintillation efficiencies showed that 1MN+R39 was quite acceptable. But scintillating fibers applications for various detectors involves not only high scintillating efficiency but also high transparency and high trapping efficiency. These requirements could be taken into account if we compared the relative light output of 1 mm fibers when the particle intersected the fiber at the distance of 1 m from the readout end. This comparison showed that the radiation resistance of the LS based on 1MN+R6 was much better.

Thus the studies showed fine luminescent and optical characteristics of capillaries filled with an LS, their excellent radiation resistance. This makes capillary detectors very attractive for a lot of applications in high energy physics experiments.

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Table 1. Abbreviations of fluors, plastics and solvents.

abbreviation	description
1MN	1-methylnaphthalene
1PN	1-phenylnaphthalene
IPN	new solvent
PS	polystyrene
PVT	polyvinyltoluene
PMMA	polymethylmethacrylate, acrylic
PMPS	polydimethyldiphenyl siloxane
PVX	polyvinylxylene
pTP	para-terphenyl
3HF	3-hydroxyflavone (λ_{max} = 530 nm)
BPD	2,2'-bipyridyl-3,3'-diol (λ_{max} = 500 nm)
PMP	1-phenyl-3-mesityl-2-pyrazoline (λ_{max} = 420 nm)
POPOP	1,4-di-2-(5-phenyloxazolyl)benzene (λ_{max} = 420 nm)
MOPOM	phenyloxazol derivative (λ_{max} = 420 nm)
O408	bridged oligophenylene (λ_{max} = 410 nm)
O415A	bridged oligophenylene (λ_{max} = 415 nm)
O374A	bridged oligophenylene (λ_{max} = 375 nm)
BBQ	isoquinoline derivative (λ_{max} = 470 nm)
K27	benzoxanthene derivative (λ_{max} = 500 nm)
TPB	1,1',4,4'-tetraphenylbutadiene (λ_{max} = 440 nm)
DMT	2,2"-dimethylterphenyl (λ_{max} = 415 nm)
R6	pyrazoline derivative (λ_{max} = 485 nm)
R39	pyrazoline derivative (λ_{max} = 495 nm)
R45	pyrazoline derivative (λ_{max} = 500 nm)
3M-15	pyrazoline derivative (λ_{max} = 490 nm)
Y7	secondary green dye used by Kuraray
Y8	secondary green dye used by Kuraray

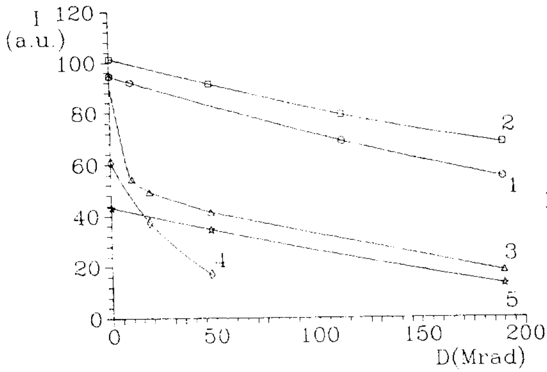

Fig. 1. Light output of different LSs versus irradiation dose: 1. ○ 1MN+R6; 2. □ 1MN+R39; 3. △ 1MN+R45; 4. ◇ BC-599-13G; 5. ⋆ BC-599-13B.

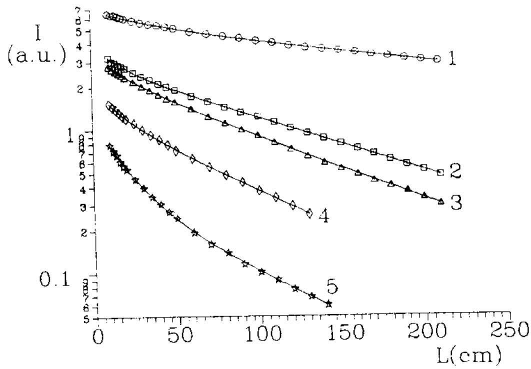

Fig. 2. Light attenuation in 500 μm unirradiated capillaries filled with 1MN+R45 at different irradiation doses: 1. ○ 0 Mrad (l=313 cm); 2. □ 19 Mrad (l=118 cm); 3. △ 48 Mrad (l=101 cm); 4. ◇ 112 Mrad (l=80 cm); 5. ⋆ 190 Mrad (l=71 cm).

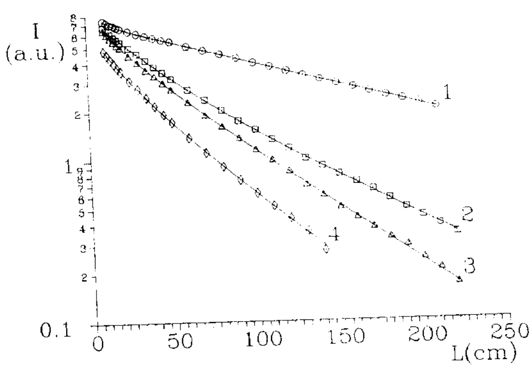

Fig. 3. Light attenuation in 500 μm unirradiated capillaries filled with 1MN+R6 at different irradiation doses: 1. ○ 0 Mrad (l=163 cm); 2. □ 48 Mrad (l=81 cm); 3. △ 112 Mrad (l=63 cm); 4. ◇ 190 Mrad (l=52 cm).

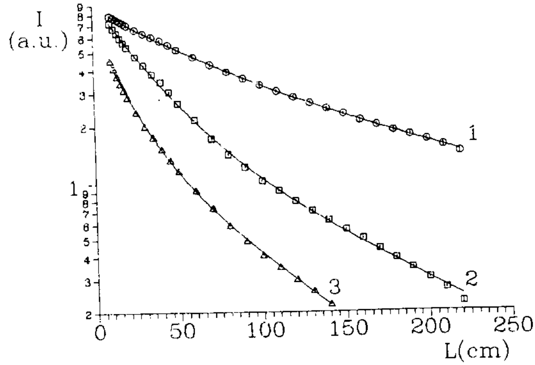

Fig. 4. Light attenuation in 500 μm unirradiated capillaries filled with 1MN+ +R39 at different irradiation doses: 1. ○ 0 Mrad (l=144cm); 2. □ 48 Mrad (l=81cm); 3. △ 190 Mrad (l=59cm).

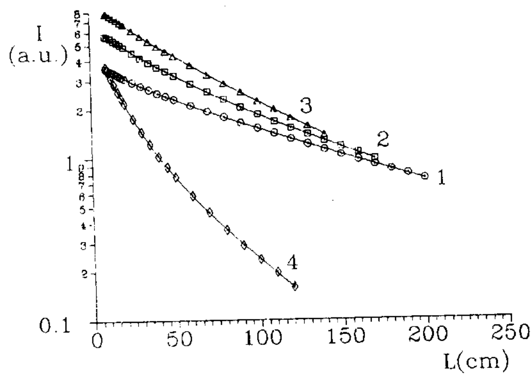

Fig. 5. Comparison of light attenuations in 500 μm unirradiated capillaries filled with the LSs based on new solvent IPN before and after irradiation at the dose of 10 Mrad: 1. ○ IPN+R45. (l= =140 cm); 2. □ IPN+R6. (l=120 cm); 3. △ IPN+ +R39. (l=90 cm); 4. ◇ IPN+3M-15. (l=49 cm).

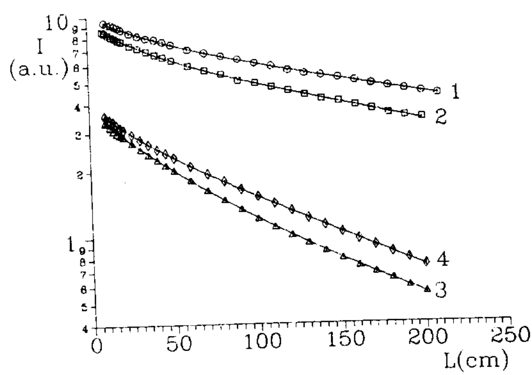

Fig. 6. Comparison of light attenuations in 500 μm unirradiated capillaries filled with LSs based on 1MN and IPN with the same R45: 1. ○ 0 Mrad 1MN+R45 (l=313 cm); 2. □ 0 Mrad IPN+R45 (l=272 cm); 3. △ 10 Mrad 1MN+R45 (l=152 cm); 4. ◇ 10 Mrad IPN+R45 (l=136 cm).

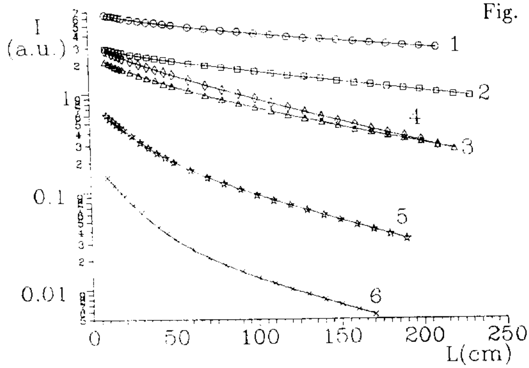

Fig. 7. Comparison of light attenuations in 500 μm unirradiated capillaries filled with LSs based on 1MN and Bicron LSs before and after irradiation at the dose of 48 Mrad: 1. ○ 0 Mrad 1MN+R45. (l=313 cm); 2. □ 0 Mrad BC-599-13G. (l=225 cm); 3. △ 0 Mrad BC-599-13B. (l=129 cm); 4. ◇ 48 Mrad 1MN+R45. (l=102 cm); 5. ⋆ 48 Mrad BC-599-13B. (l=88 cm); 6. × 48 Mrad BC-599-13G. (l=84 cm).

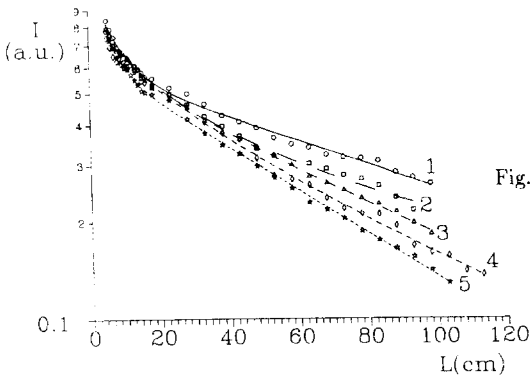

Fig. 8. Light attenuations versus the dose in 110μm unirradiated capillaries filled with 1MN+R6: 1. ○ 0 Mrad (l=118 cm); 2. □ 13 Mrad (l=101 cm); 3. △ 16 Mrad (l=93 cm); 4. ◇ 32 Mrad (l=85 cm); 5. ⋆ 64 Mrad (l=64 cm).

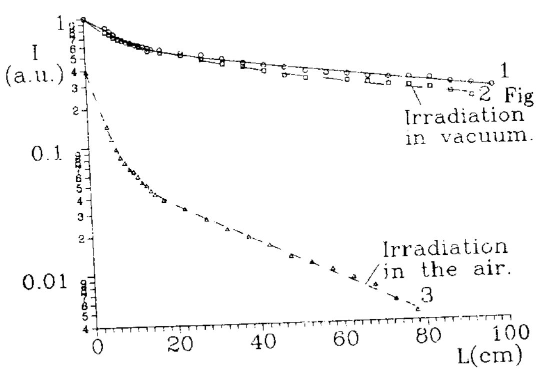

Fig. 9. Influence of air on the light output and attenuation length of the LS (1MN+R6) during the irradiation. Diameter of capillaries is 110 μm: 1. ○ l=118 cm (0 Mrad) No irradiation; 2. □ l=101 cm (12.5 Mrad) Irradiation in vacuum; 3. △ l= 30 cm (13.3 Mrad) Irradiation in air.

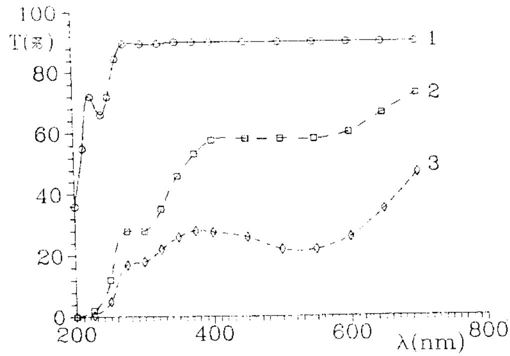

Fig. 10. Transmission spectra of quartz sample 1 cm thick versus irradiation dose: 1. ○ 0 Mrad; 2. □ 12 Mrad; 3. ◇ 100 Mrad.

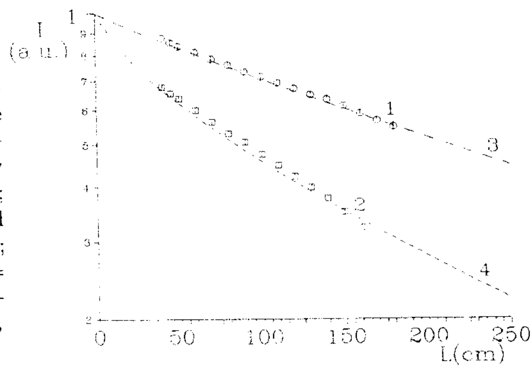

Fig. 11. Influence of irradiation of the 150μm quartz capillaries on the light attenuation. Attenuation curves before and after the irradiation of capillaries at dose of 48 Mrad are shown for unirradiated LS — 1MN+R45: 1. ○ capillary is not irradiated (l=320 cm); 2. □ capillary irradiated up to 48 Mrad (l=170 cm); 3. theoretical curve $a_1 = 0.25\,m^{-1}, a_2 = 0.$; 4. theoretical curve $a_1 = 0.25\,m^{-1}$, $a_2 = 1.2\,cm^{-1}$.

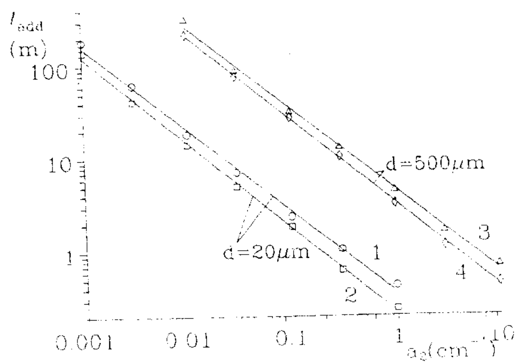

Fig. 12. Additional attenuation l_{add} produced by the glass darkening calculated for different sets of diameters of capillaries d and reflection indexes n_1, n_2. a_2 – inverse attenuation length in bulk glass: 1. ○ $d = 20\,\mu m$ $n_1 = 1.617$ $n_2 = 1.46$; 2. □ $d = 20\,\mu m$ $n_1 = 1.58$ $n_2 = 1.49$; 3. △ $d = 500\,\mu m$ $n_1 = 1.617$ $n_2 = 1.46$; 4. ◇ $d = 500\,\mu m$ $n_1 = 1.58$ $n_2 = 1.49$.

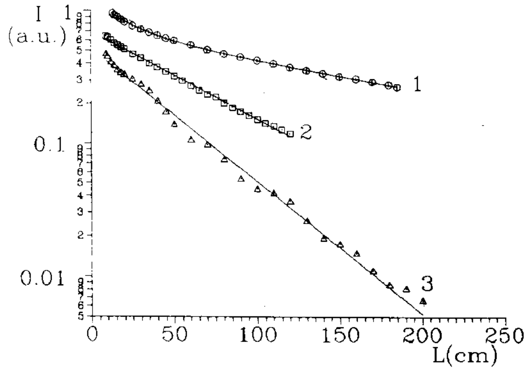

Fig. 13. Attenuation in 150 μm quartz capillaries filled with 1MN+R6 irradiated at the doses 48 and 190 Mrad. Both LS and capillaries were irradiated: 1. ◯ 0 Mrad (l=181 cm); 2. □ 48 Mrad (l=66 cm); 3. △ 190 Mrad (l=44 cm).

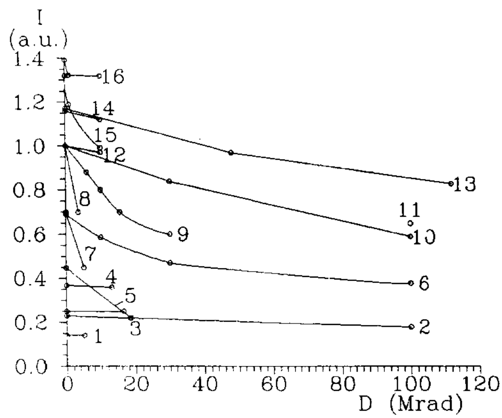

Fig. 14. Relative local light output of various scintillators after recovery versus the irradiation dose. A possible normalization error of 15% is not shown. The light yield of the commercially available BC408 (Bicron corporation) that is used as a standard reference in this figure is equal to 1: 1. Base BC505+3HF [14]; 2. Toluene+3HF [20,21]; 3. PMPS+O374A+TPB [29]; 4. PS+3HF [18, 19]; 5. PMPS+O415+DMT [28]; 6. SCSN81+Y7 [16]; 7. NE235 [14]; 8. PS+PMP [22]; 9. BC408 [13]; 10. Kyowa PS/propr./3HF [16]; 11. Bicron PS/propr./3HF [17]; 12. Bicron PS/PTP/3HF [18,19]; 13. 1MN+R39 [present paper]; 14. PS+O408+BBQ [23]; 15. 1PN+BPD [32]; 16. 1PN+MOPOM [32].

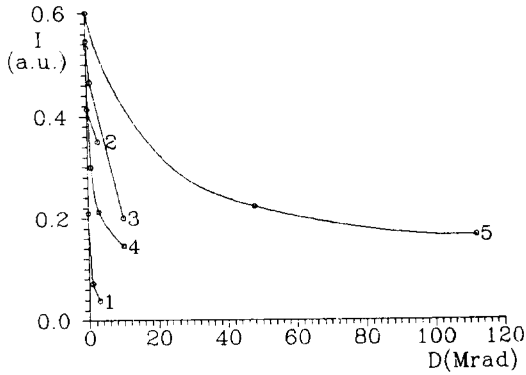

Fig. 15. Relative light output of 1 mm fibers after a recovery at the distance of L=1 m versus the irradiation dose. One take into account decrease of attenuation length and light yield was taken into account. Fibers were painted black near the readout ends to remove light that travels in the cladding: 1. SCSN81+Y7 [33]; 2. BicronG (3HF) [33]; 3. Kyowa 3HF [33,34,35]; 4. RH1 [15,33]; 5. 1MN+R6 [present paper].

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