Radiation hardness of scintillation detectors based on organic plastic scintillators and optic fibers

(review)

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Abstract

Scintillation detectors (SDs) based on organic plastic scintillators and optical fibers are among of the basic detectors at all modern accelerators and in astrophysics and neutrino experiments. In recent years, interest in SDs has increased significantly due to the forthcoming large-scale Updates of LHC, the construction of new accelerators NICA, FAIR, FCC, etc. At the same time, requirements for the stability and reliability of SD operation in the new conditions became stricter and their fullfilment largely depends on the radiation hardness of the scintillators, optical fibers and photodetectors.

The review presents the results of the radiation hardness investigations of various scintillators and optical fibers (scintillating, wave length shifting and clear), and optical glues used to increase the light collection from the scintillators by the fibers. The influence of various factors (dose, radiation dose rate, scintillator materials, fluors) on light output, light collection and light transmission of the irradiated materials and their recovery is considered.

1.Introduction
2. Light creation in organic scintillators and optical fibers, their destruction by irradiation and recovery
3. Irradiation of scintillators, optical fibers and glues on radioactive sources, accelerates and neutron reactors
3.1 Scintillators: Dopands, Base, Dependence on dose and dose rates, Investigations on neutrons beam
3.2 Optical fibers: Scintillating and clear fibers, Wave-shifting fibers, Scintillating fibers based on Nanostructured Organosilicon Luminophores
3.3 Optical glues
4. Conclusion

The report is based on my self-titled article, which will be published in the Journal Nuclei and Particles 50, issue 1
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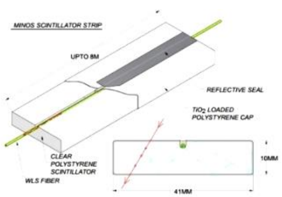
Organic plastic scintillators

Fields of applications Scintillation Detectors based on organic plastic scintillators (OPS):

Calorimeters, Veto-systems, TOF, Triggering, Tracking
Compactness, Limited space occupied
Simplicity in operation (calibration, monitoring)

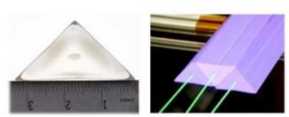
Main properties of OPS:
Good optical and mechanical properties
Reliable and stability characteristics Fast time response(a few ns);
Easy manufacture of OS in almost any shape and sizes;
Cheapness

Samples of strips and tiles of organic plastic scintillators

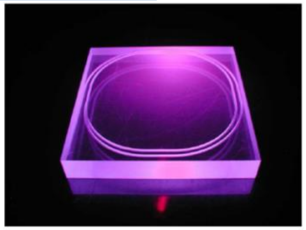


MINOS, T2K
41x10mm

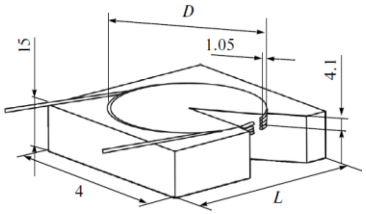
OPERA
26x10mm



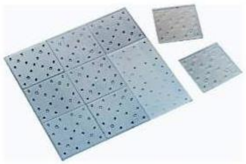
MINERvA, SciBar, T2K(POD)



CDF-II preshower detector



Scheme of tile with deep groove (LHCb)

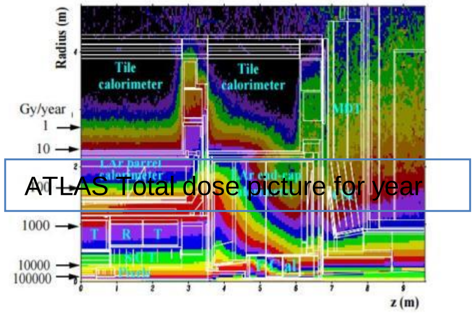


25 000 m² strips for MINOS
0.41x1.0cm² with length up to 8 m.

Tile for TileCal ATLAS
(200 -400) x (97x187)mm 500 000 ps

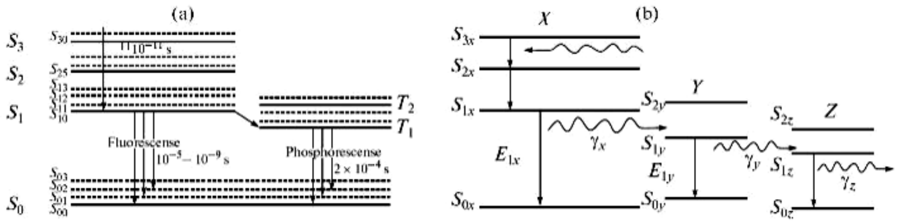
Luminosity of modern and planned accelerators

Accelerator	Luminosity	Particles	Energy	Refer.
LHC, HL-LHC	10^{34} cm^{-2} s^{-1} (in present) 5×10^{34} cm^{-2} s^{-1} (2025)	P+P	14 TeV 14 TeV	4
FCC	5×10^{34} cm^{-2} s^{-1}(2035)	P+P	100 TeV	5
FAIR (HESR)	10^{32} cm^{-2} s^{-1} (2025)	antiP+ions	1-16 GeV	6
NICA	10^{27} cm^{-2} s^{-1} (2020)	Ions Au^{79+}	4-11 GeV	7

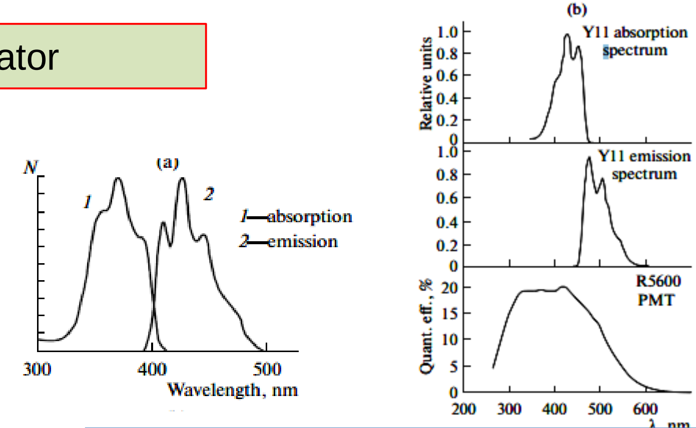


ATLAS Total dose picture for year

Formation of scintillation light in organic scintillator



Light emission mechanism in one- component and three-components OPS



Absorption and emission spectra of POPOP and Y11 and spectral sensitivity of the R5600 PMT

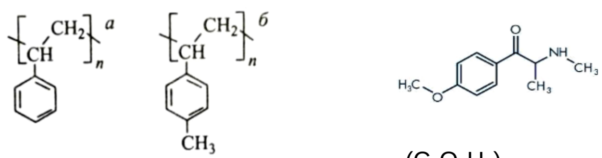
PS → **(1-2)% PPO(pTP)** → **(0.02-0.04)% POPOP**

UV → 370nm → 420nm

Absorption and emission spectra of some popular luminescent flours.

3HF, Y11 have the larger differences in the absorption and the emission peaks hence they have the smallest self-absorption and so they are the best candidates for the light shifting.

Item	Absorption peak, nm	Emission peak, nm	Difference, nm
b-PBD	305	360	55
BDB	360	405/425	45/65
Y7	437/460	490	63/30
3HF	350	530	180
Y11	400	476	76
pTP	290	360	70
POPOP	385	420	35
K27	355	492	37
PPO	310	365	55
Naphthelene	310	325/340	15/30
X25, X31	400	500	100

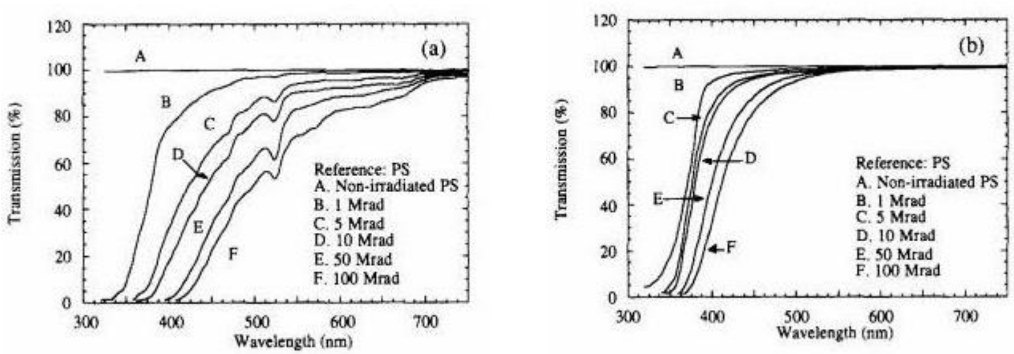


$(C_8H_8)_n$ $(C_9H_{10})_n$ $(C_5O_2H_8)_n$

Molecular structure of the PS, PVT and PMMA scintillators

Irradiation → Destruction of molecular structure Formation radicals (Color centers) → R. + R. --- X annihilation of radicals; R. + O_2 ---RO_2 formation of peroxide

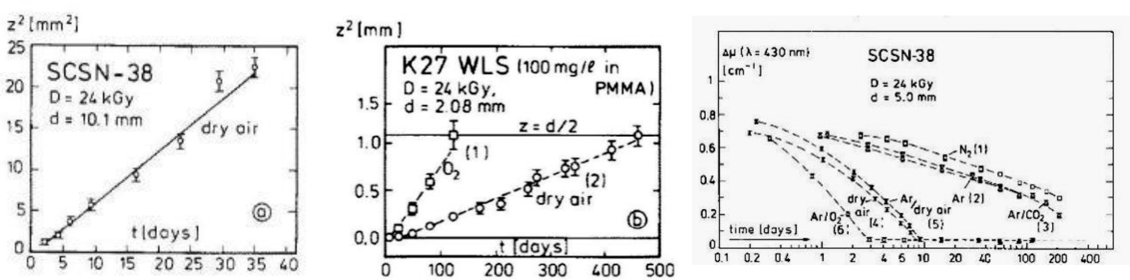
Bross and Dalmau



Examples of transmission damage in undoped PS after high dose rate irradiation .
(a) Immediate post-irradiation and
(b) Residual damage after full annealing in air

Recovery of PS and PMMA based light guides after immediate irradiations(a) and full annealing in O_2 and air (b) for 27 kGy

Wick e.a.



Recovery of SCSN-38 under different gas atmosphere
Very vast in O_2, ~ 2-3 days
Very slow in inert gases > 200 days

In dry air bleaching zone z behave as z^2~t. Such behavior is similar to diffusion O_2 into materials.

Radical concentration in PMMA is 60 times larger than in PS and diffusion coefficient of O_2 is about 10 times larger in PS.

Scintillator's LY on dependence of the fluors

Britvich e.a.1993

About 30 various fluors were investigated at D=2.3, 10, 14.3 Mrad

1. Primary flours pTP, PPO, PBD, bPBD showed good radiation resistance and do not differ much from each other
2. Secondary flours 3HF, M3HF, X25, X31 are most radiation resistance among the many examined secondaries.
3. Adding naphtaline (N) and increasing fluors concentration provide higher rad.resistance

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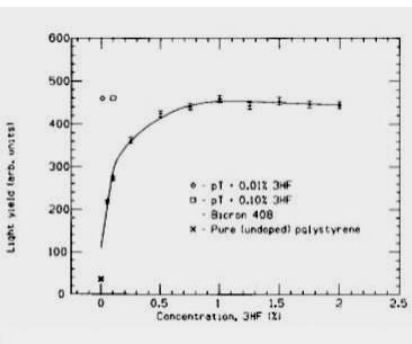
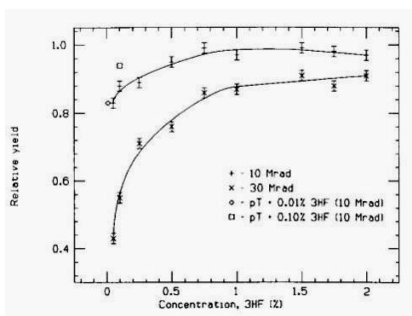
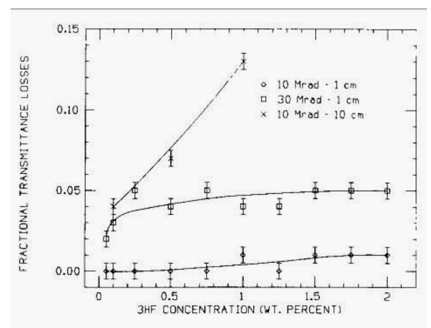
Bross and Dalmau 1993

^{60}Co, D=10Mrad and 30Mrad





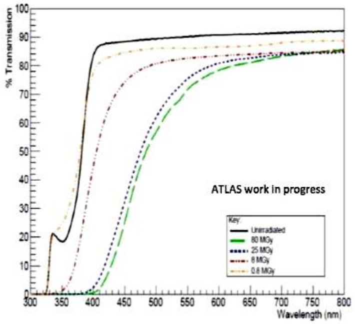


PS ;
PS+3HF;
PS+1%PT+0.01%3HF
PS+1%PT+0.10% 3HF

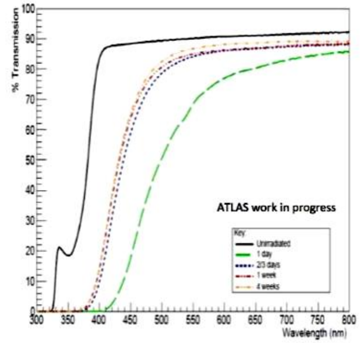
1. PS with 3HF concentrations 1.0%, 0.10% and 0.05% shows 3%, 12% and 17% light loss respectively for 10Mrad. (Minimal light loss reaches at 1% 3HF).
2. Ternary scintillator PS +1%pTP with 0.01%3HF and 0.10% 3HF shows 17% and 6% light loss respectively for 10Mrad.
3. Transmittance losses remain small (~12%) even for 10cm thick 3HF scintillator for 3HF concentration 1% and 10 Mrad.
4. The main causes in the LY loss are destructions in the scintillator base but not in the 3HF

Upgrade for TileCal ATLAS

Liao e.a. Plastic scintillators for TileCal ATLAS, Journal of Physics 2015;
Jivan e.a. NIM B 2017



Transmission vs wavelength for EJ 208 for all doses



Transmission vs wavelength for EJ 208 on different days

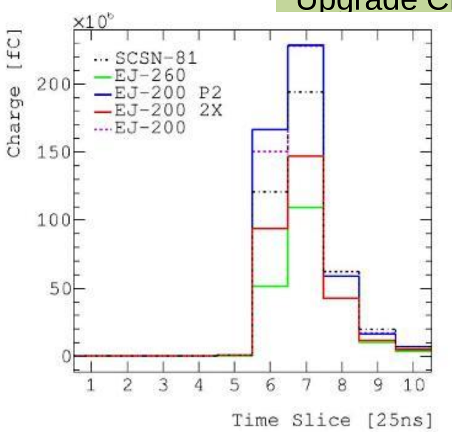
Scintillaters (5x5x0.35мм)ELJEN, Protvino, Dubna, Bicron
Д=(0.8, 8, 25 и 80) MGy for 6 MeV protons
EJ200,EJ208, EJ260 (green), Bicron – BC 408 (PVT).
Dubna for MBTS UPS, Protvino for TileCal (PS)

Dose	Sample	%Trans. diff. (Day1 - 1 Week)
25 MGy	EJ 200	30.38
	EJ 208	37.06
	EJ 260	6.45
		%Trans. diff. (Day 1 - 4 Weeks)
8 MGy	EJ 200	15.05
	EJ 208	5.92
	EJ 260	2.22

Sample	Dose (MGy)	% Trans. loss	Sample	Dose (MGy)	% Trans. loss
EJ 200	80	42.9	Protvino	80	60.8
	25	28.6		25	34.8
	8	14		8	7.4
	0.8	3.9		0.8	3.3
EJ 208	80	29.1	Dubna	80	51.3
	25	14.9		25	35.1
	8	4.7		8	26.6
	0.8	2.5		0.8	5.5
EJ 260	80	44.8	Bicron	80	45.5
	25	15.5		25	39.5
	8	14.3		8	11.5
	0.8	6.6		0.8	8.7

1.EJ scintillators have better transmission than other grades.
EJ - 208 is the best one and beside it's the emission peak(435nm) well matches to the absorption peak of Y11(430nm) used in WLS fibers
2. With increasing dose transmission spectra move to longer λ and loss in transmission increase.
3. Significant recovery occurs during 2-3 days
4. For the lowest D=0.8 Mrad transmission losses of all scintillators are the same
5. For larger doses some structural changes in base and fluors were observed

Upgrade CMS for hadronic calorimeter



Integrated charge per 25 ns time slice

CMS Collaboration, JINST 2018

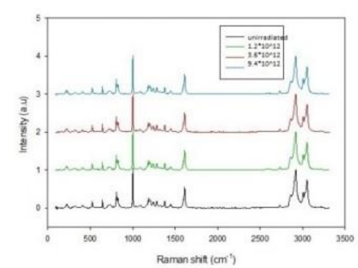
Scintillaters 100x100x4 mm³
EJ-200. EJ-200 2X, EJ-200 2P, EJ-260 and SCSN-81
Beam μ-meson 150 Gev at H2 line SPS CERN

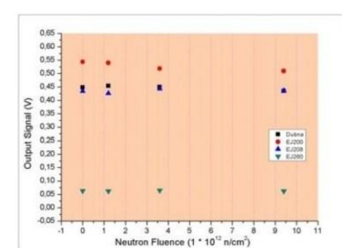
Investigation of light output, light collection and time characteristics show that over-doped concentration of primary flours and green-emitted scintillators are two ways for improving radiation tolerance.

Neutron irradiation of scintillators for TileCal at IBR2

Energy and fluence up to 10MeV and 9.4x10¹² /cm² resp.

Mdhluli e.a. 2017



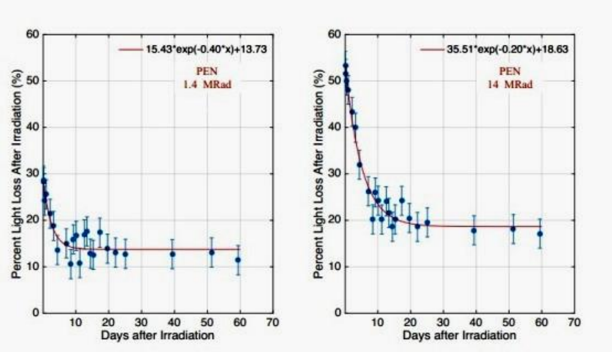


No structural or optical changes observed

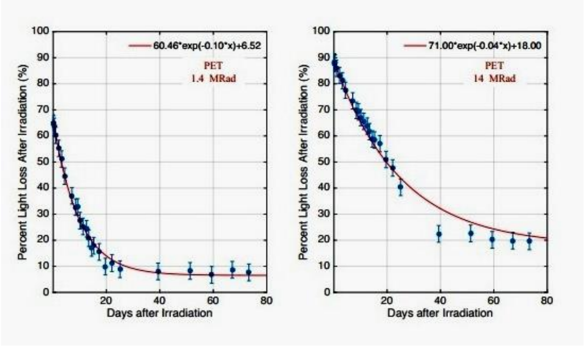
New scintillation materials (common polyester)–

Polyethylene Naphthalate (PEN) 100x100x1 mm, $\lambda_{peak} \approx 450$nm
Polyethylene Terephthalate (PET) 100x100x 2mm, $\lambda_{peak} \approx 350$nm
Cs^{137} D=1.4Mrad and 14 Mrad

Tiras et.al 2016



PEN



PET

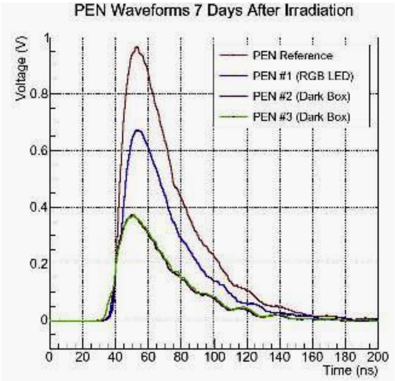
	Initial Light Yield (%)		Recovered Light Yield (%)		Recovery Time (days)	
	1.4 Mrad	14 Mrad	1.4 Mrad	14 Mrad	1.4 Mrad	14 Mrad
PEN	71.4	46.7	85.9	79.5	5	9
PET	35.0	12.2	93.5	80.0	22	60

PEN is more radiation hardness than PET
(factor 2 for 1.4 Mrad, 3.8 for 14 Mrad).
PEN has much shorter recovery time than PET

Recovery testing

of PEN and lab-produced elastomer(ES) and EJ-260(EJN), EJ-260(EJ2P)
under "blue" LED simulation for 100 kGy and 78 kGy

Wetzel et.al NIMA 2017



Tile	'a', Total recovery	'c', Permanent damage	'b', Recovery constant (days^{-1})
ES RGB	56.3 ± 2.4%	30.7 ± 1.6%	0.22 ± 0.03
ES dark box	45.7 ± 2.5%	44.1 ± 1.9%	0.18 ± 0.03
EJN RGB	24.0 ± 2.2%	6.92 ± 0.7%	0.64 ± 0.16
EJN dark box	21.1 ± 1.8%	15.9 ± 0.6%	0.50 ± 0.11
EJ2P RGB	26.9 ± 3.1%	15.2 ± 0.9%	0.75 ± 0.22
EJ2P dark box	26.5 ± 2.2%	13.7 ± 0.7%	0.62 ± 0.14

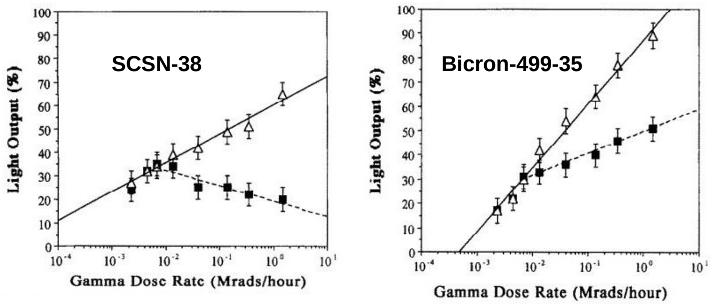
1.After 7 days PEN tile recovered
by LED to 72%; in the dark box only to 40%
The corresponding values for ES are 56% and 46%
.
2. Neither EJN nor EJ2P showed significant effect due to LED (24% and 26% for LED and dark box)

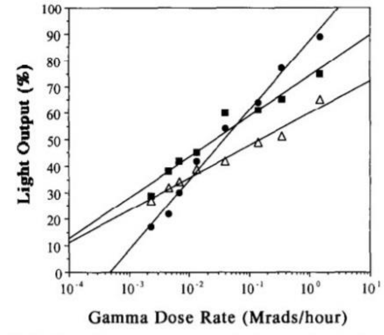
3. PEN and ES are "blue" scintillators whereas Eljien samples are "green".

Dose rate effects:
Light yields of SCSN-38, Bicron-499-35 and SCSN-81

immediately after gamma 10 Mrad for dose rate (2.3 krad/h – 1.5 Mrad/h) irradiation (blackened squares) and after recovery periods (triangles)

Biagtan E. e.a.





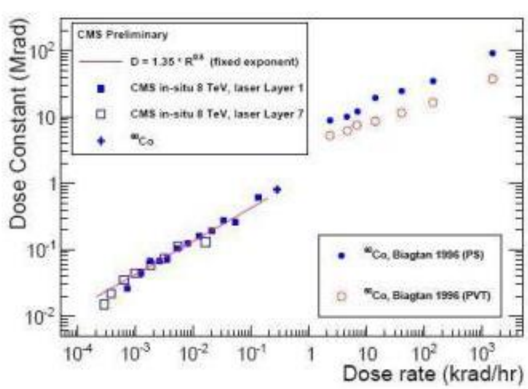
1. Fnal light output (LO) of all species with dose rate shows semi-logarithmic behavior.
2. LO decreases with decreasing dose rate

LO of SCSN-38(triangles), SCSN-81(black squares) and Bicron-499-35(circlers) after 7days recovery.
Differences in LO of the scintillators depend on O_2 permeability,chain mobility of the scintillators and glass transition temperatures

Dose rate effects in the radiation damage of plastic scintillators of CMS HE calorimeter

JINST 2016, Khachatryan e.a.

Biagtan E. e.a.



PS SCSN-81 blue squares

Dose rates (10^{-4} - 0.1) krad/h for D=0.01-0.2 Mrad and ^{60}Co 0.28 krad/h for D=300 krad

PVT BC 499-35 red circles
PS blue full circles
Dose rate 14 krad/h

1. Light loss in CMS scintillators on the dependence of dose rate is consistent with power law as predicted by diffusion of O_2 into scintillator
2. The measured Light losses are in reasonable agreement with results gamma irradiation at higher dose rates
3. Light loss at low dose rates are larger than at high dose rates

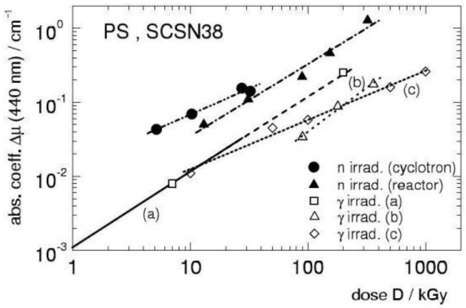
Neutron background at LHC ~10E15 n/cm²/year

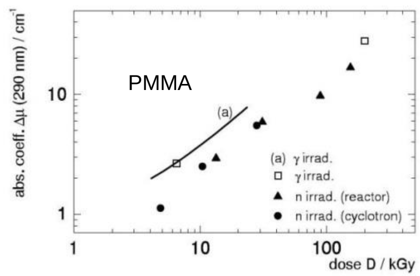
Neutron-irradiated plastic scintillators (pure PS, SCSN38 and pure PMMA)
with low gamma background

PS, SCSN38 Fluence 7x10^{14} n/cm^2, γ-background 7% of the total dose. <E_n>=5MeV
PTV synchrotron Germany $^9Be(d,n)^{10}B$

Bodmann, Holm

Fluence (1.9x10^{15}-4.4x10^{16}) n/cм^2, γ-background 5%, 86.5% thermal, 5.4% epithermal and only 8.6% fast neutrons BR1 neutron reactor Belgium.

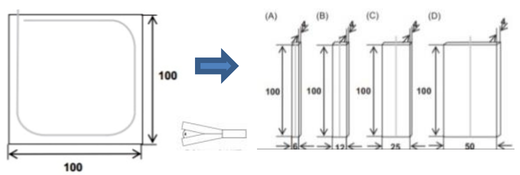


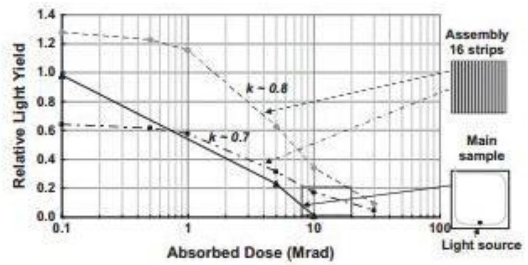


Neutrons produce 3 times more damage in PS and SCSN38 than γ-rays.
(Reactor neutrons introduce somewhat less damage than cyclotron ones (due to often long shutdowns in reactor operation)
γ-rays produce ~1.5 more damage in PMMA than neutrons.

"Finger" structured scintillators (for CMS upgrade)
Light collection from SCSF-81 tile 100x100x4mm is compared with one composed of segmented 2,4,8 or 16 strips.

Afanasiev S.V.e.a. 2013



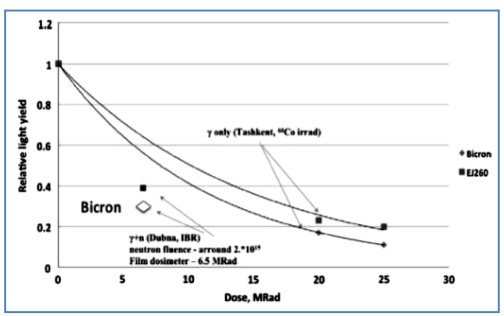


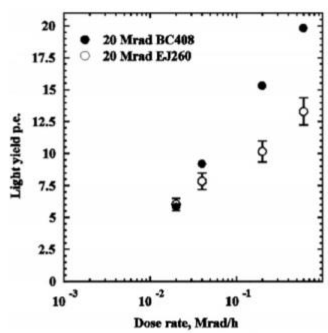
Relative LY from tile and 16 strips ^{90} Sr, E_e ≈4 MeV, D=0.5, 1, 5, 10 and 30 Mrad, Minsk Belarus
Effect - 40% for k=0.8 and Rad.hardness increased up to 20 Mrad

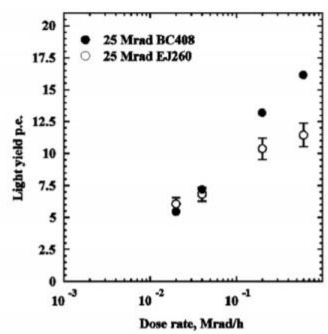
Relative LY of fingered BC-408 and EJ-260
irradiated by gamma-neutron (IBR-2 Dubna) and gamma (^{60} Co,Tashkent)

Fluence 3x10^{15} n/cm^2
<Eγ>~1.5-2 MeV, Dose rate up to 500 Krad/h

Afanasiev S.V.e.a. 2016







At the same dose neutrons have a larger impact on light yield than gamma

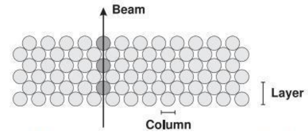
LY from the strips irradiated with γ from ^{60}Co at 20 Mrad and 25 Mrad show that light loss at lower dose rates is greater than at high dose rates

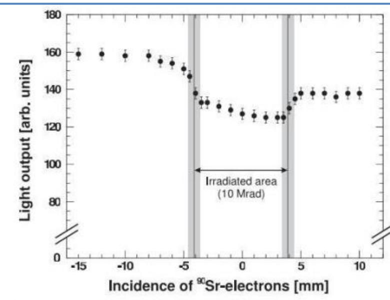
Scintillating fibers(SciFi)

Fields of application Measurements of Luminosity(ALFA at LHC); Tracker (D0, LHCb); Scintillating-fiber beam hodoscope (COMPASS, MUSE) e.a.

SciFi Hodoscope for COMPASS

in the muon beam (100-200)GeV/c
10^8 muons/s (10^6 for fiber channel)
1m SCSF-78MJ under D=100kGy(10Mrad)





Bisplinghoff e.a.

Withstand the high rate environment 10^8 muons/s
LO loss is no more than 15%.
Number of photoelectrons is about 20
Provide sufficient resolution in space and time resolution (400ps)

1.Joint of two fibers ends by means of melting them at T =(105^0 - 110^0) C during several seconds provides light transmission loss <10%. and mechanically strong connection
2. Attenuation length WLS fiber is 60% instead of 20% in case of using clear fibers

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SciFi Tracking at High Luminosity Colllider(LHCb)

Single homogeneous (only 1.1% matirial buget)
Instead of gas straw tubes and silicon microstrip detectors

Joram e.a.

Hopchev e.a.

SCSF-78MJ with base PS+pTP+ tetra butadiene (longer L_{att} , more LY and fast scintillation time)
S=360 m^2, Φ=0.25mm^2 , 2.4-m long

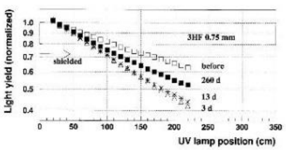
N_e>16, Efficiency 99%, Space resolution 70μm

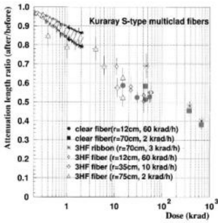
Estimated reduction of L_{att} SciFi as a function of accumulated dose for different particles (protons, gamma, X-rays) and energies for D=35 kGy for 10 years
L_{att} / L_0 for SciFi may be at the level 40%

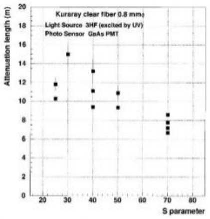
Radiation hardness and mechanical durability

Kuraray Scintillating 3HF and clear fibers S-type
D=0.4 – 500 krad, gamma from ^{60}Co

Hara e.a.





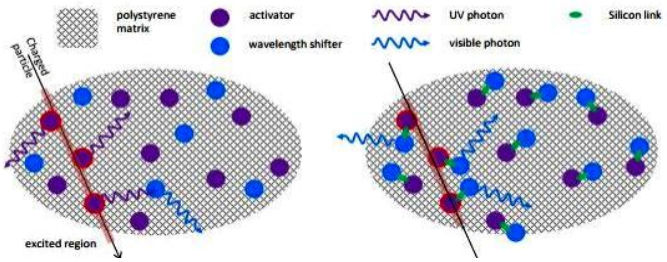


1. **Ratio of the L_{att} before and after irradiation is similar for both CF and 3HF fibers on dependence of dose for different dose rates and fiber curvature**
2. **Recovery rate 3HF is rather insensitive to the dose rate (2-12)krad/h and accumiulated dose 6-48 krad.**
3. **L_{att} as well as LY decrease with increasing S-parameter.**
4. **LY(S40) > LY(S70) is greater for 30%**

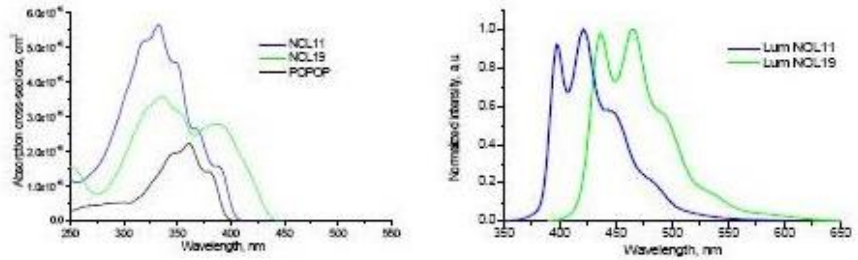
Development of New Class of Scintillating Fibres
with Nanostructured Organosilicon Luminofores(NOL)

Borshchev e.a. 2017JINST 12

Enikolopov institute of synthetic Polymer materials, Moscow



Scintillation light creation in conventional PS (left) and NOL(rigth) scintillators (Fig. from Joram e.a.)



Absorption and luminescene spectra of NOL11 and NOL19 used in the production BPF-11 and GPF-19 fibers 250 μk in diameter

NOL11 λ_{em}= 397, 421, 445nm ε=96% τ=0.98ns
NOL19 λ_{em}= 436, 466, 490nm ε=87% τ=0.93ns

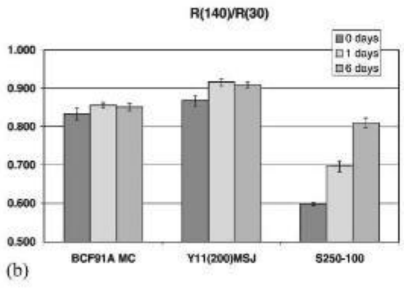
Fibre type	λ_{peak} [nm]	Λ [cm]	LY [p.e./mm]	τ [ns]
BPF-11-1	430	263	23.2	1.34
GPF-19-1	470	· 294	14.2	1.18
SCSF-78	440	351	27.8	2.36
SCSF-3HF	530	330	23.6	6.18

1. LY of NOL11and NOL19 is ~3 times larger than that of POPOP
2. Radiation hardness of the GPS-19-1 and BPF-19-1 fibers after irradiation by X-rays at dose 1kGy and dose rate 23Gy/min is about the same as SCSF-3HF and SCSF-78
3. Decay time of the green GPS-19-1 is ~ 6 times shorter than that of SCSF-3HF and the blue BPF-19-1 fiber is ~2 times shorter than that of SCSF-78
4. NOL fibres may be atractive option for LHCb SciFi tracker

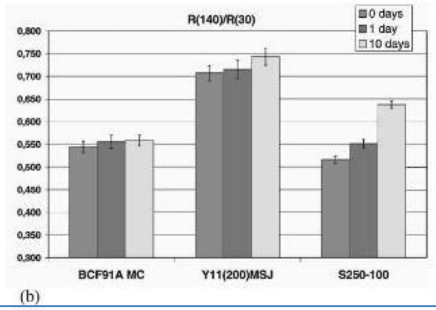
Comparisions of LY of three type WLS fibers BCF91A-MC(Bicron), Y11(200)MSJ (Kuraray) and S250-100(Pol.Hi.Tech.)

Co^{60} D=1.16 kGy and 6.93 kGy1mm WLS fibers

M.J.Varanda et.al.



(b)



(b)

Fiber type	$\frac{R(140)}{R(30)}$ for 1.16 kGy			$\frac{R(140)}{R(30)}$ for 6.93 kGy		
	0 days	1 day	10 days	0 days	1 day	10 days
BCF91A MC	0.83	0.86	0.85	0.54	0.56	0.56
Y11(200)MSJ	0.87	0.92	0.91	0.71	0.72	0.74
S250-100	0.60	0.70	0.81	0.52	0.55	0.64

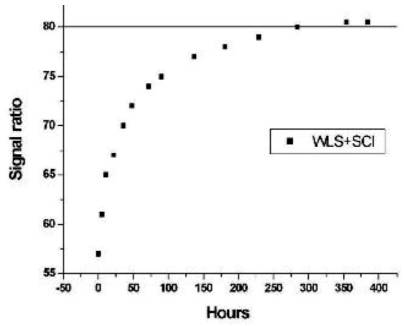
1. **Kuraray fibers have the best LY and Latt.**
2. **Immediate relative light losses are17 (46)%(BCF91A),13(29)% (Kuraray) and 40(48)% (Pol-Hi.Tech for D=1.16 (6.93) kGy**
3. **After 10 days recovery 15(44)%, 9(26)%,and 19(36)% respectively**

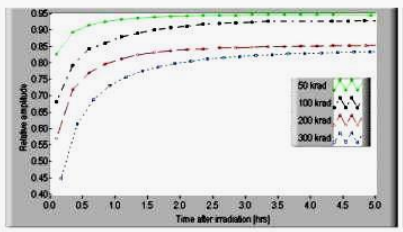
Radiation hardness WLS BC9929 fiber and Scintillator BC404+WlLS fiber

^{60}Co WLS for D=50 krad -1 Mrad, Dose rate 7 krad/min

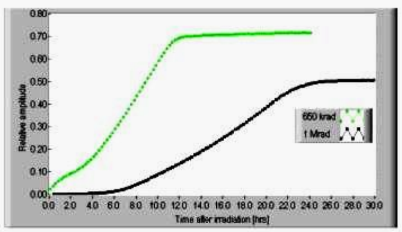
Scintillator + WLS fiber for D=200 krad, dose rate 4,4 krad/min

Alfaro et.al.





D=50,100,200, 300 krad



D=650 krad, 1 Mrad

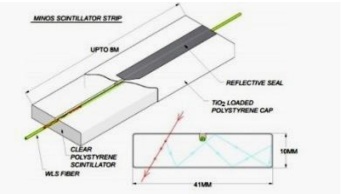
1. **Recovery time of fiber is 2 order of magnitude shorter than that of Scintillator + WLS fiber for D=200krad. (80% permanent level of the latter reached after 300h)**
2. **Permanent level is only 50(70)% for D=1 Mrad(650 krad)**
3. **Recovery time increases significantly at higher dose**

WLS + Scintillator

WLS fiber

Investigation of radiation hardness of optical glues

Light collection by WLS fibers from the groove on the tile filled by the high transparency optical glues is improved up to 1.8 times against the "dry" case (MINOS, Protvino)



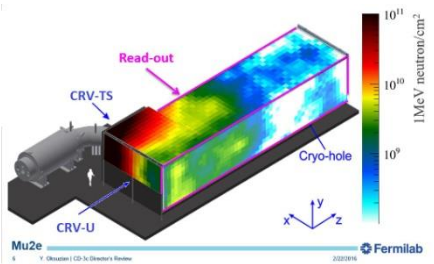
Cross secton UPS strip, L up to 5m

Mu2e dicounters with 2 holes for each counter, 4.5m long

The various glues on the epoxy base (EJ-500, Aqua E-300, BC-600 and Araldite Crystal) are often used as a filler in the groove of tiles.
DLNP JINR group (Leader B.Glagolev) in the frame of research in Mu2e Collab. for CRV-system have been studied light yield of strip filled with synthetic high transparency (T>90% at λ>400hm) and viscosity (10-20Pa*s) resins SKTN(E,D) (SYREL, St Petersburg) .
We developed and realize new technique to inject such high-viscosity filler into small hole of the strip.

It was demonstrated that using this filler provides increase in the light collection up to 1.5 -1.9 times

Artikov e.a. JINST 2016; Artikov e.a. arXiv:1711.11393v1 2018 (to be published in NIMA D)

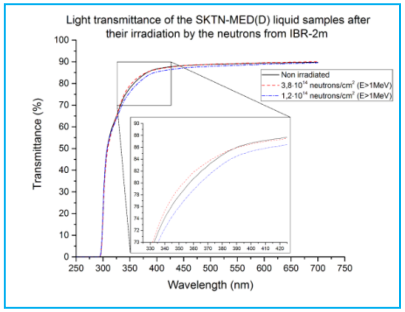


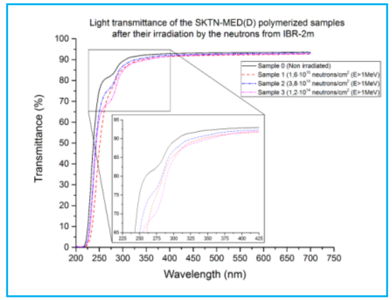
Mu2e detector 10^{11} n/cm^2 /3y near CRV-TS

Location	Flux density n/cm^2c	Fluence n/cm^2	Background of γ $Mrad$
1	1.8×10^9	16×10^{14}	5.4 ... 1.4
2	4.4×10^8	3.8×10^{14}	0.47
3	1.35×10^8	1.2×10^{14}	0.37

Neutron flux, fluence and γ-dose rate for the irradiated sample (E>1 MeV) at IBR-2 JINR

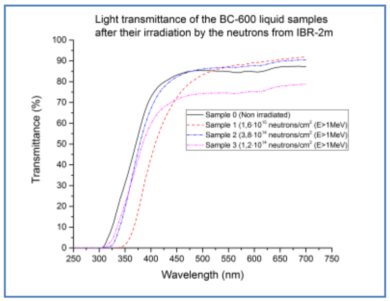
We have studied transmittance and light yield of SKTN(E,D) as well as BC-600 irradiated by neutron beam IBR-2 JINR at various fluencies

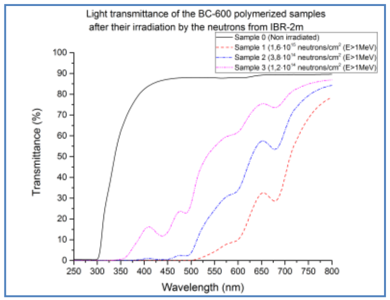


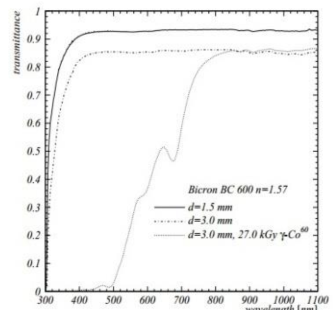


Transmittance of SKTN-MED(D) glue(right) and their base (left) do not differ from each other and >90% for λ>400 nm after the irradiation by a neutron beam with the fluencies of $3.8x10^{14}$ and $1.2x10^{14}$ n/cm2. This result is almost the same as before the irradiation.

The samples of SKTN-MED are rather radiation tolerance for applied neutron fluencies.





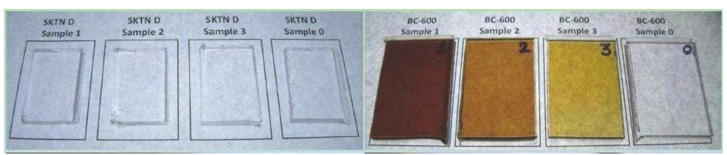


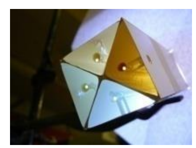
The BC-600 glue (and its base as well) was sensitive to the impact of the applied neutron radiation doses.

Our results are in good agreements with ones presented by Kirn e.a. for irradiation BC-600 at 27kGy gamma of ^{60}Co.

BC-600 glue is more sensitive to radiation than its base.

Transparency of BC-600 glue (in middle), BC-600 base(in left) (our data) and BC-600 (right) (Kirn 's e.a. data)





Photos of unirradiated and irradiated sheets and strips on dependence of the applied neutron fluencies (Clearly visible changes in transparency of the BC-600 samples but no in the SKTN samples)

Radiation influence on the LY were investigated on the short strips (15-cm-long) filled with the various fillers by the considered neutron beams.

Measured anode currents of irradiated strips decreased in accordance with increasing neutron fluencies.

LY decreasing is mainly caused by destructions in the strip and fiber as T of SKTN filler did not change significantly (see photo irradiated strip also).

Conclusions

Part 1(on the base of the research old years for D~1 Mrad)

1. RD of OPS and fibers increases with decreasing dose rates at the same dose
2. RD introduced by neutrons is 5 times higher in PS than by γ but in PMMA vise versa
3. RD in OPS is mainly due to the destruction in their base but not in the flours.The position and shape of the emission peak remain unchanged.
4. Recovery of OPS occurs in O_2 much more rapidly than in inert gases while of PMMA is reverse.
5. The attenuation length of “clear” fibers with increasing parameter S (alignment of base molecular along the fiber axis) decreases
6. Recovery of fibers occurs much faster than scintillator + fiber system

Part 2 (on the base of research recent years)

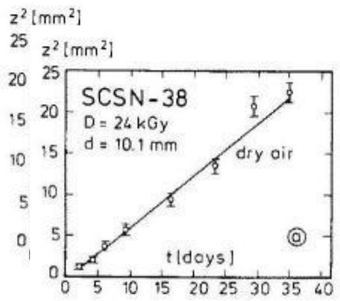
1. At higher doses (>25 MGy) PVT scintillators (ELJEN) are more radiation hardness than BC (Bicron) and PS.
2. Radiation hardness of scintillators can be increased by using flours having emission spectrum shifted to the green region.
3. The fibers with new type of luminophores NOL11 and NOL 19 (Nanostructured Organosilicon Luminophores) have high photoluminescene quantum yield and very short decay time 1.34ns and 1.18ns respectively.
4. New scintillator PEN (Polyethelene Naphthalat) along good radiation hardness show very short recovery time.
5. Time and recovery level of PEN and elastomer scintillator (p-terphenil in epoxy) significantly improved by simulation by LED having wavelength corresponding to absorption and emission spectra of scintillators.
6. Segmentation of tiles in the “fingered” strips provides increasing in the LY and the radiation hardness
7. Deterioration of the LY and T of the scintillator caused by irradiation can be compensated by synthetic low-molecular rubber SKTN-MED embedded between scintillator and fiber.
8. SKTN-MED along its good optical properties showed a high radiation hardness when irradiated by neutron beam with fluencies up to $1.6x10^{14}$ cm^2.

Thank you for attention

Recovery of PS and PMMA based light guides after immediate irradiations(a) and full annealing in O_2 and air (b) for 27 kGy

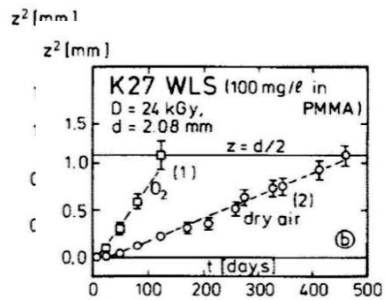
Wick et.al.

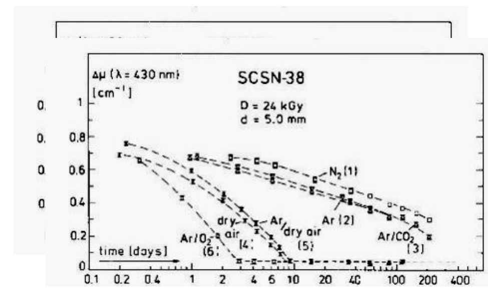
Wick et.al.



z²=άt

z²=άt





In dry air bleaching time of SCSN-38 is ~ 40 hours and of PMMA is >1 year and thickness of bleaching zone z behave as z^2~t. Such behavior is similar to diffusion O_2 into materials.

Recovery of SCSN-38 under different gas atmosphere

Very vast in O_2, ~ 2-3 days

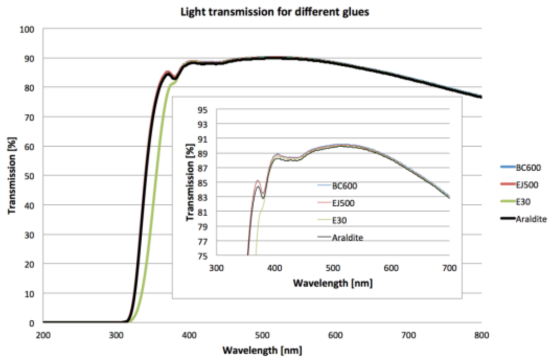
Very slow in inert gases > 200 days

Radical concentration in PMMA is 60 times larger than in PS and diffusion coefficient of O_2 is about 10 times larger in PS.

Wick et.al.

Investigation of radiation hardness of optical glues

Light collection by WLS fibers from the groove on the tile surface filled by the high transparency optical glues is improved up to 1.8 times against the “dry” case (MINOS, Protvino)



The various glues on the epoxy base (EJ-500, Aqua E-300, BC-600 and Araldite Crystal) are often used as a filler in the groove of tiles. Transmittances (T) of their unradiated samples T> 90% for λ>400hm are showed on the left figure)

The optical synthetic high transparency and viscosity resins SKTN (SYREL St Petersburg) as filler in the hole of strip (up to 5m-long) have been tested. (T>90% for λ>400hm)

It was demonstrated that using this filler provides increase in the light collection up to 1.5 - 1.9 times (by our group in the frame of R&D Mu2e Collaboration).

Artikov e.a. JINST 2016; Artikov e.a. arXiv:1711.11393v1 2018 (to be published in NIM D)

We have studied transmittance and light yield of SKTN as well as BC-600 (for comparision) irradiated by neutron beam IBR-2 JINR at various fluencies

Neutron flux, fluence and γ-dose rate for the irradiated sample (E>1 MeV) at IBR-2 JINR

Location	Flux density n/cm^2c	Fluence n/cm^2	Background of γ $Mrad$
1	1.8×10^9	16×10^{14}	5.4 ... 1.4
2	4.4×10^8	3.8×10^{14}	0.47
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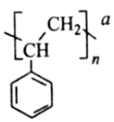
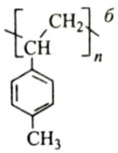
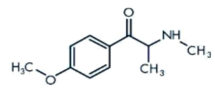


$(C_8H_8)_n$



$(C_9H_{10})_n$



$(C_5O_2H_8)_n$

Molecular structure of the PS, PVT and PMMA scintillators

Irradiation → Destruction of molecular structure; Formation radicals (Color centers) → R. + R. --- X annihilation of radicals; R. + O_2 ---RO_2 formation of peroxide

Yields of Gaseous Products from Irradiated Polymers[a]
(γ- or electron irrad, room temp)

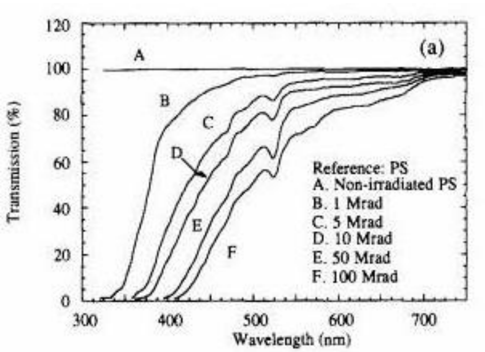
Polymer	Products G (product)(molecules/100 ev)
High-density PE	H_2 ~3; CH_4 ~0.002
Polypropylene	H_2 ~2.5; CH_4 ~0.1
Polyisobutylene	H_2 ~1.5; CH_4 ~0.5
Poly(vinyl chloride)	HCl ~2.7; H_2 ~0.15; CH_4 ~0.002
Poly(vinyl acetate)	H_2 ~0.6; CH_4 ~0.3; CO ~0.28; CO_2 ~0.06
Poly(methyl methacrylate)	CH_4 ~ 0.6; CO ~0.5; CO_2 ~0.4; H_2 ~0.2
Polystyrene	H_2 ~0.03; CH_4 ~ $1x10^{-5}$
Poly-α-methyl styrene	H_2 ~0.04; CH_4 ~0.003

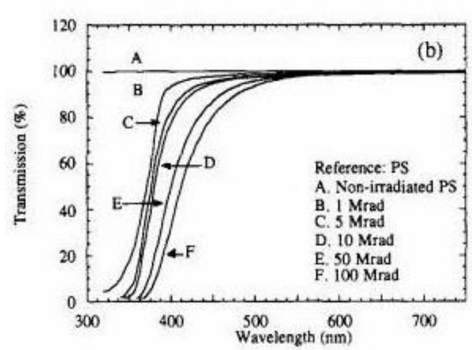
[a] Woods and Pikaev (1994)

Products and **g** values of irradiated polymers by
Wood and Pikhaev;
Wick et,al.

The *g* values for different radiation induced processes occurring in PMMA and polystyrene. Only the most probable gaseous irradiation products of PMMA (mol fraction > 10%) are given.

	g values for	
	PMMA	polystyrene
Radical production	2.4–2.5 [4,5]	0.2 [6]
Gas evolution	1.18 [7] (30.5% CO, 15.7% CO_2, 14.2% $HCOOCH_3$, 13.1% CH_4, 11.7% H_2,...) [8]	0.026 [7] (100% H_2)
Degradation	1.7–2.6 [9]	0.009 [9]
Cross-linking	0 [9]	0.034 [9]



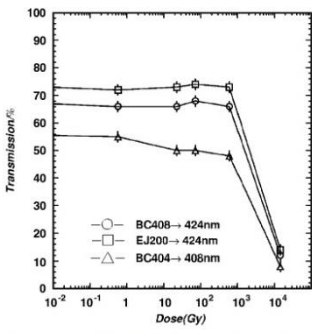


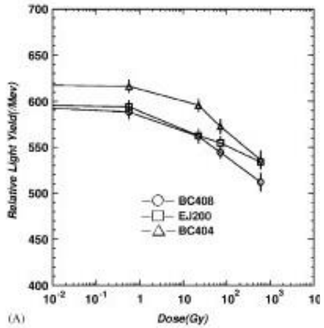
Bross and Dalmau

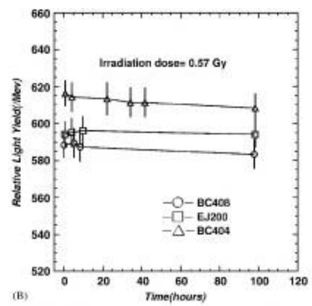
Examples of transmission damage in undoped PS after high dose rate irradiation .
(a) Immediate post-irradiation and
(b) Residual damage after full annealing in air

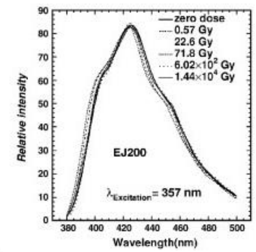
Recovery of fast scintillators BC-408, BC-404 and EJ-200 D=(0.57 – 1.4x10^4) Gy by ^{60}Co

Zhao Li e.a. NIMA 2005(552)449









1.Transmission of all samples is almost unchanged for up to D =600 Gy. Samples destroyed after D>1.4x10^{4}Gy and dose rate 52,7Gy/min
2.No evidence of recovery observed for 100 hours after irradiation D=600Gy
3. Emission spectra (mechanism)of all samples remain unchanged for dose up to 600 Gy for all considered dose.

Scintillator's LY on dependence of the fluors

Britvich e.a.1993

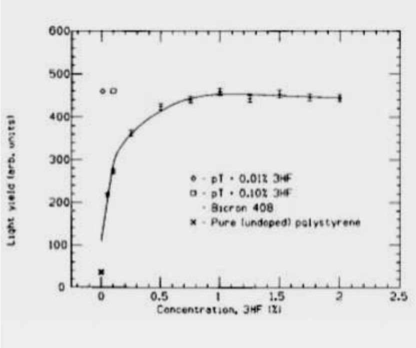
About 30 various fluors were investigated at D=2.3, 10, 14.3 Mrad

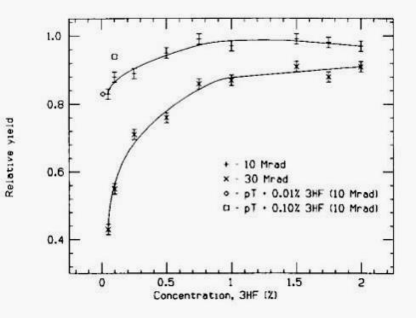
Scintillator	L_0,%	L/L_0,% Dose(Mrad)	L/L_0,% Dose(Mrad)	L/L_0,% (Time)
PVT+2%PBD+0.01% POPOP	100	72(3.3)	37(14.3)	48(3 month)
PS +2%pTP + 0.025%POPOP	98	71(2.3)	23(10)	52(23 day
PS + 10%PPO+ 0.5%POPOP	98	73(2.3)	36(10)	67(23day)
PS+ 5% N+2% pTP+10% PPO+0.5% POPOP	71	93(2.3)	59(10)	69(23 day)
PS+2.0% pTP+0.025% X25	78	72(4)	53(10)	58(23 day) .

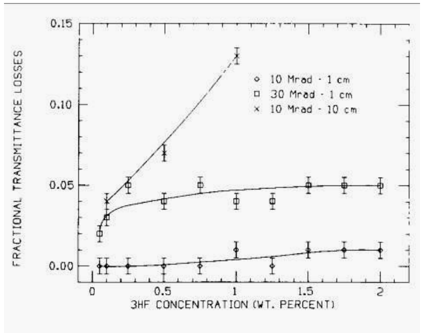
1. Primary fluors pTP, PPO, PBD, bPBD showed good radiation resistance and do not differ much from each other
2. Secondary fluors 3HF, M3HF, X25, X31 are most radiation resistance among the many examined secondaries.
3. Adding naphtaline (N) and increasing fluors concentration provide higher rad.resistance

Bross and Dalmau 1993

^{60}Co, D=10Mrad and 30Mrad







PS ;
PS+3HF;
PS+1%PT+0.01%3HF
PS+1%PT+0.10% 3HF

1. PS with 3HF concentrations 1.0%, 0.10% and 0.05% showed 3%, 12% and 17% light loss respectively fo for 10Mrad. (Minimal light loss reached at 1% 3HF).
2. Ternary scintillator PS +1%pTP with 0.01%3HF and 0.10% 3HF showed 17% and 6% light loss respectively for 10Mrad.
3. Transmittance losses remain small (~12%) even for 10cm thick 3HF scintillator for 3HF concentration 1% and 10 Mrad.
4. The main causes in the LY loss are destructions in the scintillator base but not in the 3HF