DEVELOPMENT OF RADIATION-HARD SCINTILLATORS AND WAVELENGTH-SHIFTING FIBERS

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International Conference on Technology and Instrumentation in Particle Physics
May 22-26, 2017
Beijing
Motivation for Radiation-Hard Scintillator and WLS Fiber Development

Future and upgrade colliders impose unprecedented challenges on the radiation-hardness of the active media of the calorimeters. Scintillators play a central role as the active medium of calorimeters.

What are we looking for?
- Compact
- High light yield
- High resolution
- Radiation resistant
- Fast
- Cost effective scintillators.

<table>
<thead>
<tr>
<th></th>
<th>Dose [MGy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>first layer of the IB (R = 2.5 cm)</td>
<td>~400</td>
</tr>
<tr>
<td>max in forward calorimeters</td>
<td>$5 \times 10^3$</td>
</tr>
</tbody>
</table>
Intrinsically Rad-Hard Scintillators

Commercially Available Scintillating Materials:

- Polyethylene Naphthalate (PEN)
- Polyethylene Terephthalate (PET)

PEN:

✓ Intrinsic blue scintillation (425 nm)

PET:

✓ A common type polymer
✓ Plastic bottles and as a substrate in thin film solar cells.
✓ Emission spectrum of PET peaks at 385 nm [Nakamura, 2013]
Intrinsically Rad-Hard Scintillators

HEM/ESR: sub-µm film stack of Poly(Ethylene-2,6-Naphthalate)/PEN, polyester, polyethylene terephthalate (PET): intrinsic blue scintillation! 425 nm; 10,500 photons/MeV; ....

Evidence of deep-blue photon emission at high efficiency by common plastic

H. Nakamura¹,²(a), Y. Shirakawa², S. Takahashi¹ and H. Shimizu³

Table 1: Properties of the three samples used in the present study.

<table>
<thead>
<tr>
<th>Material</th>
<th>Polyethylene naphthalate</th>
<th>Organic scintillator (ref. [14])</th>
<th>Plastic bottle (ref. [13])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplier</td>
<td>Teijin Chemicals</td>
<td>Saint-Gobain</td>
<td>Teijin Chemicals</td>
</tr>
<tr>
<td>Base</td>
<td>(C₁₄H₁₀O₄)ₙ</td>
<td>(C₉H₁₀)ₙ</td>
<td>(C₁₀H₈O₄)ₙ</td>
</tr>
<tr>
<td>Density</td>
<td>1.33 g/cm³</td>
<td>1.03 g/cm³</td>
<td>1.33 g/cm³</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.65</td>
<td>1.58</td>
<td>1.64</td>
</tr>
<tr>
<td>Light output</td>
<td>~10500 photon/MeV</td>
<td>10000 photon/MeV</td>
<td>~2200 photon/MeV</td>
</tr>
<tr>
<td>Wavelength max. emission</td>
<td>425 nm</td>
<td>425 nm</td>
<td>380 nm</td>
</tr>
</tbody>
</table>

**Abstract:** Polyethylene naphthalate (PEN) thin films were subjected to gamma rays at different doses and changes in both the dielectric and photophysical properties were investigated. Samples were irradiated in air at room temperature by means of a 60Co gamma source at a dose rate of ~31 Gy/min. Total doses of 650 kGy(344 h) & 1023 kGy(550 h) were adopted. The high radiation resistance of PEN film is highlighted.
• PET is faster but emits less light. PEN is radiation resistant up to 10 Mrad and it has a significant light yield but it is too slow.
PEN Performance in Beam Measurements

We tested 2 - 4 mm thick PEN and PET tiles read out with green wavelength shifting fibers with 150 GeV muons.
New SiX Scintillators

- The scintillators have a base material, primary fluor, and secondary fluor.

- The main scintillation comes from the primary fluor.

- The secondary fluor, or waveshifter, absorbs the primary’s emissions and re-emits to a wavelength that is desirable for optimum efficiency.
New SiX Scintillators

Lose only 7% transmission after 40 Mrad proton radiation

Almost no change on emission and absorption after irradiation
PEN Radiation Damage Studies (MSU)

Facilities:
- National Superconducting Cyclotron Laboratory
- Used $^{60}$Co, 1.33 MeV Gammas

Two Samples:
- 1.7 MRad in Air
- 10 MRad in N$_2$

<table>
<thead>
<tr>
<th></th>
<th>Undamaged</th>
<th>10 MRad N2</th>
<th>1.7 MRad Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integral</td>
<td>20208</td>
<td>19012</td>
<td>17311</td>
</tr>
<tr>
<td>(300-450 ns)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative %</td>
<td>100%</td>
<td>94.1%</td>
<td>85.7%</td>
</tr>
<tr>
<td>(damaged / Undamaged)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Transmission

PEN Analysis Setup

- Secured Sample Holder
- Spectrometer
- Attenuator
- Xenon Light Source

Graphs showing data with labels:
- PEN 10 MRad N2
- PEN No Damage
- PEN 10 MRad / No Damage
IRRAD facility at CERN PS

- 10 x 10 cm PEN tile was placed in the PS accelerator IRRAD area.
- First batch – perpendicular to the beam direction. Three different positions were selected to expose to protons.
- Second batch – tilted ~30 degrees to beam direction – three different position were exposed to the proton beam.
- Samples were irradiated during one week. In average 30 Mrad was absorbed per spot.

24 GeV protons,
beam spot (FWHM) 15x15 mm²
proton flux - ~6x10⁹ p cm⁻² s⁻¹

→ 75% loss at 40 Mrad.
We irradiated scintillator samples with using $^{137}\text{Cs}$ gamma source at Iowa Rad Core 1.4 Mrad and 14 Mrad.

- Damage was calculated in terms of light yield.

Initial damage
Permanent damage - plateau

Right after irradiation
Before irradiation
Summary of irradiation results

<table>
<thead>
<tr>
<th>Initial damage</th>
<th>Permanent damage</th>
<th>Time for Recovery</th>
</tr>
</thead>
</table>

- PET was damaged more than PEN initially
- Permanent damage was same at 14 MRad
- PEN was recovered in 5 days only and PET in 25 days – so slow
LED Stimulated Recovery

Can we stimulate the recovery of scintillators damaged from radiation?

✓ By using an array of tri-color red, blue, green (RGB) LEDs

**Different Materials:**

- Eljen brand EJ-260 (N) and overdoped version EJ2P.
- Lab produced plastic scintillator (SiX)
• SiX showed significant effect, the sample on RGB LED recovering 10% more and faster (4.5 vs 5.5 days)

• Neither EJN and EJ2P showed significant effect.

• ‘Blue’ scintillators respond to color spectrum but ‘green’ scintillators are affected very little.

NIM B395, 13, 2017
Quartz with Thin Film Coating

Quartz alone is extremely radiation-hard but only a Čerenkov radiator → very small amount of directional light

→ Quartz plates coated with organic/inorganic scintillators/wavelength shifters ~ scintillators

Scintillator/WLS Films on Quartz Tiles

- Ptp, anthracene
- ZnO:Ga; CsI; CeBr3 – emissions 375-450 nm; T<17ns
- CsI and CeBr3 will be protected with an over-deposited quartz film ≥50 nm thick.

Fermilab’s THIN FILM Facility Coating Systems at Lab 7

- 2 Bell Jar sputtering systems
  - Al, Ag, Au, Cr, Cu, Nb, Pd, Ti, ZnO2-Ga
- 2 tube sputtering systems dedicated to 99.999% pure aluminum sputtering
- Optical fiber mirroring
- 1 Bell Jar system for resistive evaporation
  - Al, Ag, Au, Cr, Cu, Al & MgF2 surface mirrors, Ni, NCF, VN
- 1 Pyrex Bell Jar system for resistive evaporation dedicated to scintillator and WLS materials
  - PTFE, PTFE, PPOF, Cetamis (poly-N,N-dimethylacrylamide-co-methyl methacrylate) brand
- 1 Tall Bell Jar system (17”dia x 70”tall) designed for resistive evaporation with rotating motor at 45° and 6 rpm speeds
  - NCF = “electrode” of MCPs
  - Distance from best to substrate is 34"
- 1 Large Bell Jar (34.5” ID x 50.5” tall)
  - Resistive setup currently

Radiation Damage: FBP6 Binned

- 20 Mrad of n
- 75 Mrad of γ @ ANL

<table>
<thead>
<tr>
<th>HE</th>
<th>PET</th>
<th>PEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>12219</td>
<td>22851</td>
</tr>
<tr>
<td>Mean</td>
<td>78.21</td>
<td>30.92</td>
</tr>
<tr>
<td>RMS</td>
<td>137.1</td>
<td>58.43</td>
</tr>
<tr>
<td>( \chi^2 / \text{ndf} )</td>
<td>425.1 / 40</td>
<td>140.7 / 40</td>
</tr>
<tr>
<td>Constant</td>
<td>1.907e+04 ± 6.925e+01</td>
<td>2533 ± 54.1</td>
</tr>
<tr>
<td>MPV</td>
<td>36.15 ± 1.05</td>
<td>19.83 ± 0.78</td>
</tr>
<tr>
<td>Sigma</td>
<td>15.32 ± 0.12</td>
<td>9.508 ± 0.193</td>
</tr>
</tbody>
</table>

- Anthracene
  - Entries | 39711 |
  - Mean | 25.58 |
  - RMS | 33.48 |
  - \( \chi^2 / \text{ndf} \) | 563.9 / 40 |
  - Constant | 9703 ± 92.5 |
  - MPV | 22.8 ± 0.1 |
  - Sigma | 5.269 ± 0.047 |

- HEM
  - Entries | 40505 |
  - Mean | 30.6 |
  - RMS | 43.66 |
  - \( \chi^2 / \text{ndf} \) | 371.8 / 40 |
  - Constant | 9382 ± 86.2 |
  - MPV | 23.86 ± 0.13 |
  - Sigma | 6.203 ± 0.057 |
Radiation-Hard WLS Fibers

1 Quartz Fibers with pTP Coating
2 Capillaries
3 Cerium-doped Scintillating Glasses

PTP Fiber Plate Charge Distributions

- **Signal**
  - Entries: 41158
  - Mean: 279.1
  - RMS: 810.2

- **Pedestal**
  - Entries: 25081
  - Mean: 87.29
  - RMS: 16.54

- Graphs showing transmittance and intensity against wavelength.
Radiation-Hard WLS Fibers

3HF+Meltmount injected TeflonAF 800μm ID

1. Quartz rods with surface coating
2. Capillaries
3. Doped quartz rods

3HF Core Quartz WLS Capillaries

CdSeZnO nanodots in Sylgard 184
Injected into Capillaries Teflon; AFQuartz

Expected Anthracene Fiber Pulse:
~200 KeV/mm x 0.25mm x 40 photons/KeV x 2% transmission x 20% QE ~ 8 p.e.
Typical Observed Pulse:
~ 8-9 p.e.
Conclusions

• The options of intrinsically radiation-hard scintillators is being expanded with the addition of Scintillator-X. Different combinations e.g. PEN+PET and different variants of Scintillator-X can be probed.

• Quartz is extremely radiation-hard. With the correct combination of coating and readout, it can be the optimal option for forward region in all collider experiments. Coating is a relatively easy process nowadays. We need to probe different types of coatings and also their mixtures.

• Radiation-hard wavelength shifting fibers need to be studied in further detail. Need more and realistically sized samples tested in actual calorimeter environments.