γ-Ray Induced Radiation Damage in PWO and LSO/LYSO

Rihua Mao, Liyuan Zhang, Ren-yuan Zhu
California Institute of Technology
October 28, 2009
Introduction

Crystal scintillators suffer from radiation damage originated from electromagnetic energy deposition (γ-rays), neutrons and charged hadrons. This paper compares γ-ray induced radiation damage effects in two heavy crystal scintillators: PWO and LSO/LYSO.

Possible effects of γ-ray induced radiation damage include (1) damage to the scintillation mechanism; (2) radiation induced absorption; and (3) radiation induced phosphorescence (afterglow), which would cause an increase of the electronic readout noise.

Photo-luminescence and transmission spectra, light output and response uniformity, γ-ray induced phosphorescence are measured.
Samples

LSO/LYSO samples: 2 x 2 x 20 cm

PWO samples: 2.85$^2$ x 22 x 3$^2$ cm
Instruments Used in This Study

Transmittance

Photo-luminescence

Light yield by $^{137}$Cs

Light Yield by $^{22}$Na

NSS09 Paper N32-5, Rihua Mao, Caltech

10/28/2009
No Damage on Photo-luminescence

No difference was found between spectra measured before and after irradiations for both PWO and LSO/LYSO

BTCP-PWO-2467

- before irradiation
- after 400 rad/h irradiation

Normalized area 360 - 500 nm

Average of |ΔI| 0.7% (360 - 500 nm)

SG-LSO-L 1

- before irradiation
- after 8500 rad/h irradiation

Normalized area 380 - 460 nm

Average of |ΔI| 0.6% (380 - 460 nm)
Very Different Damage Recovery

PWO: 3 components: a few tens hours, a few thousand hours and a longer one equivalent to no recovery. LSO/LYSO: no recovery at room temperature.

Dose rate dependent damage

Normalized T @ 440 nm

Time (hours)

Transmittance @ 420 nm

Time (hours)
Damage may Depend on Dose Rate

\[ dD = \sum_{i=1}^{n} \left\{ -a_i D_i dt + (D_i^{all} - D_i) b_i R dt \right\} \]

\[ D = \sum_{i=1}^{n} \left\{ \frac{b_i R D_i^{all}}{a_i + b_i R} \left[ 1 - e^{-(a_i + b_i R) t} \right] + D_i^0 e^{-(a_i + b_i R) t} \right\} \]

- \( D_i \): color center density in units of m\(^{-1}\);
- \( D_i^0 \): initial color center density;
- \( D_i^{all} \) is the total density of trap related to the color center in the crystal;
- \( a_i \): recovery constant in units of hr\(^{-1}\);
- \( b_i \): damage constant in units of kRad\(^{-1}\);
- \( R \): the radiation dose rate in units of kRad/hr.

\[ D_{eq} = \sum_{i=1}^{n} \frac{b_i R D_i^{all}}{a_i + b_i R} \]

A simple model was published in NIM A 332 (1993) 113-120 for the kinetics of radiation induced color center densities in crystal scintillators. It was used to explain the dose rate dependent damage for PWO crystals in a paper presented in NSS96 and published in IEEE Trans. Nucl. Sci., Vol. 44 (1997) 468-476.
PWO: dose rate dependent damage; LSO/LYSO: No dose rate dependence. Thermal annealing was found effective to remove γ-ray induced damages.

From top to bottom
- Before I.R.
- 15 rad/h (10^3 rad)
- 100 rad/h (7x10^3 rad)
- 400 rad/h (3x10^4 rad)
- 9000 rad/h (2.5x10^6 rad)
Emission weighted longitudinal transmittance:

\[
EWLT = \frac{\int LT(\lambda)Em(\lambda)d\lambda}{\int Em(\lambda)d\lambda}
\]
Damage on Optical Transmission-3

8-21% loss after $10^5$ rad @9 krad/h

5-9% loss after $10^6$ rad

![Graph showing damage on optical transmission](image-url)
Damage of Light Output

PWO: dose rate dependent damage; LSO/LYSO: No dose rate dependence

BTCP-PWO-2467
L.O. = 7.8 p.e./MeV (200 ns, 18.0°C)

SG-LYSO-L 3

L.O. = A_0 + A_1 (1 - e^{-\frac{t}{\tau_1}})

- 300°C ann.:
  - A_0: 0
  - A_1: 1290
  - \tau_1: 42.4

- 15 rad/h (10^2 rad):
  - A_0: 0
  - A_1: 1270
  - \tau_1: 42.9

- 100 rad/h (10^4 rad):
  - A_0: 0
  - A_1: 1210
  - \tau_1: 43.5

- 9000 rad/h (10^6 rad):
  - A_0: 0
  - A_1: 1120
  - \tau_1: 43.4

Normalized Light Output

Dose rate (rad/h):
- 15
- 100
- 400

Time (hours)

Light Output (p.e./MeV)

Time (ns)
Damage of Light Output

22-35% loss after $10^4$ rad @400 rad/h

About 10% loss after $10^6$ rad
Damage of Light Output - 3

25.6% loss after $10^4$ rad @ 400 rad/h

12.4% loss after $10^6$ rad

**PWO**

- Mean: 25.56
- RMS: 4.581

**LSO/LYSO**

- Mean: 12.43
- RMS: 1.143

L.O. Loss after 400 rad/h I.R. (%)

- SIC-PWO
- BTCP-PWO

L.O. Loss after $10^6$ rad I.R. (%)

- CTI-LSO
- SG-LYSO
- SIPAT-LYSO
No Damage in LRU if μ < 1 m⁻¹

Unchanged LRU maintains the constant term in resolution
**γ-ray Induced Phosphorescence**

PWO and BGO have small \(10^{-5}\) afterglow.

Afterglow for LSO/LYSO varies between \(10^{-3}\) to \(10^{-4}\). LYSO from Saint-Gobain has the lowest afterglow.
γ-ray induced anode current was measured for samples at different dose rate

PMT: R2059 (BA434), bias=2200V, T=66°F

- SIC-S392
- SIC-S412
- BTCP-2133
- BTCP-2162

- CPI-LSO-L
- SG-LSO-L
- CTI-LSO-L
- SIPAT-LSO-L
### γ-ray Induced Readout Noise in PbWO$_4$ Crystals

<table>
<thead>
<tr>
<th>Sample</th>
<th>L.Y. p.e./MeV</th>
<th>F µA rad$^{-1}$h</th>
<th>Q$_{\text{bar}}$ p.e.</th>
<th>Q$_{\text{end}}$ p.e.</th>
<th>$\sigma_{\text{bar}}$ MeV</th>
<th>$\sigma_{\text{end}}$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIC–S392</td>
<td>7.13</td>
<td>97.9</td>
<td>290.7</td>
<td>9690</td>
<td>2.39</td>
<td>13.8</td>
</tr>
<tr>
<td>SIC–S411</td>
<td>6.70</td>
<td>89.2</td>
<td>264.7</td>
<td>8822</td>
<td>2.43</td>
<td>14.0</td>
</tr>
<tr>
<td>BTCP–2133</td>
<td>5.79</td>
<td>82.1</td>
<td>243.6</td>
<td>8119</td>
<td>2.69</td>
<td>15.6</td>
</tr>
<tr>
<td>BTCP–2162</td>
<td>7.12</td>
<td>95.7</td>
<td>283.9</td>
<td>9466</td>
<td>2.37</td>
<td>13.7</td>
</tr>
</tbody>
</table>

- L.Y. is defined as the averaged light yield of nine points measured along crystals (to reduce systematic uncertainty of peak finding) in a gate of 100 ns at 66F.
- F is the gamma induced photoelectron coefficient, defined as gamma induced photoelectron number under unit dose rate.
- Q$_{\text{bar}}$ and Q$_{\text{end}}$ are the derived photoelectron number per 100 ns induced by LHC averaged dose rate in barrel (15 rad/h) and endcaps (500 rad/h) respectively.
- $\sigma_{\text{bar}}$ and $\sigma_{\text{end}}$ are the equivalent readout noise induced by LHC gamma radiation, derived as standard deviation of gamma induced photoelectrons in 100 ns.
### γ-ray Induced Readout Noise in LSO/LYSO Crystals

<table>
<thead>
<tr>
<th>Sample</th>
<th>L.Y. p.e./MeV</th>
<th>F (μA rad⁻¹h)</th>
<th>$Q_{\text{bar}}$ p.e.</th>
<th>$Q_{\text{end}}$ p.e.</th>
<th>$\sigma_{\text{bar}}$ MeV</th>
<th>$\sigma_{\text{end}}$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPI–LYSO–L</td>
<td>2606</td>
<td>4.8</td>
<td>3.44x10⁴</td>
<td>1.15x10⁶</td>
<td>0.13</td>
<td>0.74</td>
</tr>
<tr>
<td>SG–LYSO–L</td>
<td>2305</td>
<td>4.9</td>
<td>3.51x10⁴</td>
<td>1.17x10⁶</td>
<td>0.12</td>
<td>0.67</td>
</tr>
<tr>
<td>CTI–LSO–L</td>
<td>2020</td>
<td>5.2</td>
<td>3.75x10⁴</td>
<td>1.25x10⁶</td>
<td>0.14</td>
<td>0.79</td>
</tr>
<tr>
<td>SIPAT–LYSO–L</td>
<td>2155</td>
<td>4.9</td>
<td>3.56x10⁴</td>
<td>1.18x10⁶</td>
<td>0.12</td>
<td>0.72</td>
</tr>
</tbody>
</table>

- L.Y. is defined as the averaged light yield of nine points measured along crystals (to reduce systematic uncertainty of peak finding) in a gate of 100 ns at 66F.

- F is the gamma induced photoelectron coefficient, defined as gamma induced photoelectron number under unit dose rate.

- $Q_{\text{bar}}$ and $Q_{\text{end}}$ are the derived photoelectron number per 100 ns induced by LHC averaged dose rate in barrel (15 rad/h) and endcaps (500 rad/h) respectively.

- $\sigma_{\text{bar}}$ and $\sigma_{\text{end}}$ are the equivalent readout noise induced by LHC gamma radiation, derived as standard deviation of gamma induced photoelectrons in 100 ns.
Summary

- γ-ray induced radiation damage in large size PWO and LSO/LYSO crystals are evaluated. No damage in the scintillation mechanism was observed in both crystals. While PWO crystals recover at room temperature, leading to a dose rate dependent damage, LSO/LYSO shows no recovery so no dose rate dependence.

- Light output loss was found 26% after $10^4$ rad @400 rad/h for PWO, and 12.4% after $10^6$ rad for LSO/LYSO.

- γ-ray induced phosphorescence was found at $10^{-5}$ level for PWO, and was between $10^{-3}$ to $10^{-4}$ for LSO/LYSO. Saint-Gobain LYSO has the lowest afterglow.

- The equivalent readout noise induced by γ-ray dose at CMS Barrel and Endcap are about 2.5 MeV and 15 MeV, respectively, for PWO. The corresponding numbers for LSO/LYSO are 0.15 MeV and 0.8 MeV.