Gamma-ray Induced Radiation Damage up to 340 Mrad in Various Scintillation Crystals

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Introduction

• Gamma-ray induced radiation damage in large size crystal scintillators was investigated for BaF$_2$, BGO, CeF$_3$, pure CsI, LSO/LYSO/LFS and PWO.

• Irradiations were carried out at the total ionization dose (TID) facility of Jet Propulsion Laboratory (JPL) up to 340 Mrad with a dose rate up to 1 Mrad/h.

• Long crystal samples were hosted in an aluminum box of ten inch square. The box was inserted in a square throat of 10” x 10” x 13.5” facing a group of Co-60 $\gamma$-ray sources. The entire body of crystals was uniformly irradiated.
A group of high intensity $^{60}$Co sources provides a variable dose rate up to 1 Mrad/h in an opening throat of 10” x 10” x 13.5”.

Irradiation was carried out in step: 10 Mrad first, followed by several 100 Mrad steps over weekends.

The time between the end of each irradiation and the measurements at Caltech is less than 30 minutes.
### Crystals Irradiated at JPL

<table>
<thead>
<tr>
<th>ID</th>
<th>Dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CeF$_3$</td>
<td>33×32×191</td>
</tr>
<tr>
<td>BaF$_2$</td>
<td>20×20×250</td>
</tr>
<tr>
<td>PWO</td>
<td>28.5$^2$×30$^2$×220</td>
</tr>
<tr>
<td>BGO</td>
<td>25×25×200</td>
</tr>
<tr>
<td>LYSO</td>
<td>25×25×200</td>
</tr>
<tr>
<td>Pure CsI</td>
<td>50×50×200</td>
</tr>
</tbody>
</table>

### Experiments

Longitudinal Transmittance (LT) and Light Output (LO) were measured at room temperature before and after each irradiation step.
Gamma-Ray Induced Damage in 20 cm Long LYSO/LSO Crystals

No damage in scintillation mechanism

LYSO SG Photoluminescence

Before IR

IR $9 \times 10^7$ rad

FWHM: 380-450 nm

Average of |D| 0.45% (FWHM of Initial PL: 380-450 nm)

No recovery: dose rate independent

LYSO 25×25×200 mm$^3$

Recovery after 200 Mrad Irradiation

EWLT of SG LYSO

EWLT(t) = 29.0 + 7.4 (1 - $e^{-t/2361.8}$)

EWLT of SIC LYSO

EWLT(t) = 27.5 + 6.7 (1 - $e^{-t/3379.4}$)

Radiation damage in BaF$_2$ and pure CsI is also dose rate independent

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LYSO/LSO/LFS: Radiation Damage in Longitudinal Transmittance (LT)

The best sample: 77% EWLT after 100 Mrad

**EWLT or emission weighted longitudinal transmittance is defined as:**

\[
\text{EWLT} = \frac{\int \text{LT}(\lambda) \cdot \text{Em}(\lambda) \, d\lambda}{\int \text{Em}(\lambda) \, d\lambda}
\]

**RIAC or radiation induced absorption coefficient is defined as:**

\[
\text{RIAC} = \frac{1}{l} \ln \frac{T_0(\lambda)}{T(\lambda)}
\]

**EWRIAC or emission weighted radiation induced absorption coefficient is defined as:**

\[
\text{EWRIAC} = \frac{\int \text{RIAC}(\lambda) \cdot \text{Em}(\lambda) \, d\lambda}{\int \text{Em}(\lambda) \, d\lambda}
\]
LYSO/LSO/LFS: Normalized EWLT and LO vs. Dose and LO vs. EWLT

The best sample: 58% light output after 340 Mrad

Good correlation between LO and EWLT: LO loss is caused by absorption

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LYSO/LSO/LFS: EWRIAC vs. Dose and Normalized LO vs. EWRIAC

EWRIAC in the best sample is 0.62, 1.5 and 2.4 m\(^{-1}\) after 10, 120 and 340 Mrad.

- With EWRIAC of 3 m\(^{-1}\), LO losses in 14x14x1.5 mm plates and 20 cm long crystals are 4%/6% for direct/WLS readout and 50%.
BaF$_2$: Longitudinal Transmittance

Transmittance damage: 44% and 64% EWLT for the fast and slow scintillation component respectively after 120 Mrad
BaF$_2$: Normalized EWLT and LO

Consistent damage in crystals from three vendors

40%/45% LO for the fast/slow component after 120 Mrad
Pure CsI: Normalized EWLT/LO and RIAC @ Emission Peak

Consistent damage in crystals from two vendors

No significant damage in LO up to 100 krad
CeF$_3$: Damage & Recovery

Damage in CeF$_3$ recovers at room temperature, so is dose rate dependent.

Radiation damage in BGO and PWO is also dose rate dependent.
CeF$_3$: Normalized EWLT and LO

Irradiation carried out under a dose rate until reaching equilibrium
Dose rate dependent damage observed in both EWLT and LO

LO is too low to be measured under 1 Mrad/h in equilibrium

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BGO: Longitudinal Transmittance

Dose rate dependent damage in crystals from two vendors

BGO SIC-2011 25×25×200 mm³

Emission

EWLT:
- Before IR: 75.8%
- 2 rad/h: 72.8%
- 8 rad/h: 71.0%
- 30 rad/h: 69.6%
- 544 rad/h: 68.0%
- 1.8×10⁵ rad/h: 67.3%
- 1.0×10⁶ rad/h: 56.6%

75% EWLT under 1 Mrad/h

BGO NIIC-2013 25×25×200 mm³

Emission

EWLT:
- Before IR: 76.4%
- 2 rad/h: 75.2%
- 8 rad/h: 74.8%
- 30 rad/h: 74.0%
- 5444 rad/h: 64.0%
- 1.0×10⁶ rad/h: 57.5%
BGO: Normalized EWLT and LO

Dose rate dependent damage observed in both EWLT and LO

35% light output under 1 Mrad/h for both vendors
Dose rate dependent damage observed in both EWLT and LO

Recovery is not complete because of deep color centers
Damage in PWO crystals is diverse, so quality control is important

PWO-II for Panda and PWO 5 for JLAB are better than CMS PWO
Pure CsI is good below 100 krad; LYSO and BaF$_2$ are good beyond 1 Mrad
BGO shows small radiation induced absorption up to 1 Mrad/h

All Crystals: RIAC @ Emission Peak

No Recovery: Integrated Dose

With Recovery: Dose Rate
Ignoring dose rate dependence, the values of RIAC at the emission peak and normalized LO shown as a function of the integrated dose.

LYSO crystals show the best radiation hardness up to 340 Mrad.
Summary

- Gamma-ray induced damage in various scintillating crystals of about 20 cm long was investigated up to 340 Mrad.
- Damage in LYSO/LSO/LFS crystals from six vendors was measured. The best sample shows 58% light output after 340 Mrad.
- Damage in BaF$_2$ crystals from three vendors is consistent. 40%/45% LO is observed after 120 Mrad for the fast/slow component.
- Damage in pure CsI crystals from two vendors is consistent. Good radiation hardness is observed below 100 krad.
- Damage in CeF$_3$, BGO and PWO recovers at room temperature, so is dose rate dependent. The quality of the large size CeF$_3$ crystals grown 20 years ago is worse than PWO and BGO.
- Damage in BGO crystals from two vendors was measured. 35% light output is observed in both crystals under a dose rate of 1 Mrad/h.
- Damage in PWO crystals is diverse. Two PWO-II crystals for Panda and one PWO 5 crystal for JLAB are better than CMS PWO.
- LYSO/LSO/LFS crystals show the best radiation hardness among all scintillation crystals up to 340 Mrad.