Optical and Scintillation Properties of Heavy Crystal Scintillators

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Introduction

- This is a part of the work to improve the inorganic scintillator section in the particle data book (PDB). The crystal table in the PDB provides a comparison of light output measured by PMTs with a bi-alkali cathode for samples with undefined size and wrapping.

- To accommodate readout devices other than PMT with bi-alkali cathode, such as silicon photodiode (PD) and avalanche photodiode (APD), the quantum efficiencies (QE) of the PMT should be taken out. To reduce sample size and wrapping dependence samples should have defined dimension and wrapping.

- Properties investigated: UV excitation and emission spectra, optical transmittance, light output, decay kinetics and temperature coefficient.
# Inorganic Scintillators in the 2006 PDB

<table>
<thead>
<tr>
<th>Crystal</th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
<th>CsI</th>
<th>BaF$_2$</th>
<th>BGO</th>
<th>PbWO$_4$</th>
<th>LSO(Ce)</th>
<th>GSO(Ce)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm$^3$)</td>
<td>3.67</td>
<td>4.51</td>
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<td>4.89</td>
<td>7.13</td>
<td>8.3</td>
<td>7.40</td>
<td>6.71</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>651</td>
<td>621</td>
<td>621</td>
<td>1280</td>
<td>1050</td>
<td>1123</td>
<td>2050</td>
<td>1950</td>
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<tr>
<td>Radiation Length (cm)</td>
<td>2.59</td>
<td>1.86</td>
<td>1.86</td>
<td>2.03</td>
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<td>0.89</td>
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<td>2.00</td>
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<td>30.7</td>
<td>22.8</td>
<td>20.7</td>
<td>20.9</td>
<td>22.2</td>
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<td>Refractive Index $^a$</td>
<td>1.85</td>
<td>1.79</td>
<td>1.95</td>
<td>1.50</td>
<td>2.15</td>
<td>2.20</td>
<td>1.82</td>
<td>1.85</td>
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<tr>
<td>Hygroscopicity</td>
<td>Yes</td>
<td>Slight</td>
<td>Slight</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Luminescence $^b$ (nm) (at peak)</td>
<td>410</td>
<td>560</td>
<td>420</td>
<td>300</td>
<td>480</td>
<td>560</td>
<td>420</td>
<td>440</td>
</tr>
<tr>
<td>Decay Time $^b$ (ns)</td>
<td>230</td>
<td>1300</td>
<td>35</td>
<td>630</td>
<td>300</td>
<td>50</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Light Yield $^b,c$ (%)</td>
<td>100</td>
<td>45</td>
<td>5.6</td>
<td>21</td>
<td>13</td>
<td>0.1</td>
<td>75</td>
<td>30</td>
</tr>
<tr>
<td>d(LY)/dT $^b$ (%/ °C)</td>
<td>~0</td>
<td>0.3</td>
<td>-0.6</td>
<td>-2</td>
<td>-1.6</td>
<td>-1.9</td>
<td>~0</td>
<td>~0</td>
</tr>
</tbody>
</table>

$^a$ at peak of emission; $^b$ up/low row: slow/fast component; $^c$ measured by PMT of bi-alkali cathode.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Crystal</th>
<th>CLEO</th>
<th>BaBar</th>
<th>BELLE</th>
<th>BES III</th>
<th>KTeV</th>
<th>TAPS (L*) (GEM)</th>
<th>L3 BELLE</th>
<th>PANDA? (BTeV)…</th>
<th>CMS ALICE</th>
<th>PANDA?</th>
<th>CMS ALICE</th>
<th>PANDA?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ball</td>
<td>CLEO</td>
<td>BaBar</td>
<td>BELLE</td>
<td>BES III</td>
<td>KTeV</td>
<td>TAPS (L*) (GEM)</td>
<td>L3 BELLE</td>
<td>PANDA? (BTeV)…</td>
<td>CMS ALICE</td>
<td>PANDA?</td>
<td>CMS ALICE</td>
<td>PANDA?</td>
</tr>
</tbody>
</table>
Samples

Sample size: All are cube of 1.5 $X_0$. NaI(Tl) is a cylinder of 1.5 $X_0$ long and $1.5 \times 1.5 X_0^2$ area at two ends to match 2” PMT.

Sample Wrapping: All are wrapped with Tyvek paper. Hygroscopic samples (NaI and CsI) are sealed in 3 mm thick quartz window.
Excitation & Photo Luminescence

Emission measured with $\theta = 10^\circ$: No internal absorption

Hitachi F-4500

UV lamp and monochromator

Monochromator and PMT

Sample Orientation

Rotation stage
Transmittance Measurement

*Perkin Elmer* Lambda-950 spectrophotometer with double beam, double monochromator and GPOB

\[
T_s = (1 - R)^2 + R^2(1 - R)^2 + \ldots = (1 - R)/(1 + R), \text{ with}
\]

\[
R = \frac{(n_{\text{crystal}} - n_{\text{air}})^2}{(n_{\text{crystal}} + n_{\text{air}})^2}.
\]

Cubic sample placed inside a V-prism

Incident light shooting perpendicularly to one side of the prism

The refractive index is calculated according to the following equation:

\[ n = \left( N^2 + \sin \theta \sqrt{N^2 - \sin^2 \theta} \right)^{\frac{1}{2}} \]

<table>
<thead>
<tr>
<th>( \lambda ) (nm)</th>
<th>405</th>
<th>420</th>
<th>436</th>
<th>461</th>
<th>486</th>
<th>516</th>
<th>546</th>
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</thead>
<tbody>
<tr>
<td>R. I.</td>
<td>1.833</td>
<td>1.827</td>
<td>1.822</td>
<td>1.818</td>
<td>1.813</td>
<td>1.810</td>
<td>1.806</td>
</tr>
</tbody>
</table>
Excitation, Emission, Transmittance

Watch emission versus transmittance edge for self-absorption

**BGO**
- Em: 480 nm
- Ex: 304 nm

**LSO**
- Em: 402 nm
- Ex: 358 nm

**BaF₂**
- X-ray luminescence
- Peaks: 220 nm, 300 nm

**NaI(Tl)**
- Em: 410 nm
- Ex: 346 nm

**PWO**
- Em: 424 nm
- Ex: 310 nm

**LYSO**
- Em: 402 nm
- Ex: 358 nm

**CeF₃**
- Em: 301 nm
- Ex: 265 nm

**CsI(Tl)**
- Em: 540 nm
- Ex: 322 nm

**Wavelength (nm)**

**Intensity (a.u.)**

**Transmittance (%)**
Scintillation Light Decay Time

Recorded with an Agilent 6052A digital scope

Fast Scintillators

- \( \tau = 30/6 \text{ ns} \) CsI
- \( \tau = 35 \text{ ns} \) CeF₃
- \( \tau = 30/10 \text{ ns} \) PWO
- \( \tau = 40 \text{ ns} \) LSO

Slow Scintillators

- \( \tau = 1250 \text{ ns} \) CsI(Tl)
- \( \tau = 630 \text{ ns} \) CsI(Na)
- \( \tau = 230 \text{ ns} \) NaI(Tl)
- \( \tau = 300 \text{ ns} \) BGO
- \( \tau = 630/0.9 \text{ ns} \) BaF₂
Light Output Measurement

- Wrapping: Tyvek
- Source: Cs-137
- Gate: 45~4,000 ns
- System uncertainty <1%
- Temperature: 20°C
Light Output and Decay Kinetics

Photoelectron/MeV measured with a XP2254B PMT

Fast scintillators

Slow scintillators

\[ L.O = F + S \left( 1 - e^{-t/\tau_s} \right) \]

<table>
<thead>
<tr>
<th>Material</th>
<th>F</th>
<th>S</th>
<th>( \tau_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSO</td>
<td>0</td>
<td>2210</td>
<td>42</td>
</tr>
<tr>
<td>LYSO</td>
<td>0</td>
<td>2150</td>
<td>44</td>
</tr>
<tr>
<td>CeF₃</td>
<td>0</td>
<td>208</td>
<td>33</td>
</tr>
<tr>
<td>CsI</td>
<td>30</td>
<td>101</td>
<td>30</td>
</tr>
<tr>
<td>PWO</td>
<td>1.9</td>
<td>7.3</td>
<td>31</td>
</tr>
</tbody>
</table>

Main decay time

\[ L.O = F + S \left( 1 - e^{-t/\tau_s} \right) \]

<table>
<thead>
<tr>
<th>Material</th>
<th>F</th>
<th>S</th>
<th>( \tau_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI(Tl)</td>
<td>0</td>
<td>2604</td>
<td>245</td>
</tr>
<tr>
<td>CsI(Na)</td>
<td>0</td>
<td>2274</td>
<td>693</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>0</td>
<td>2093</td>
<td>1220</td>
</tr>
<tr>
<td>BaF₂</td>
<td>98</td>
<td>1051</td>
<td>655</td>
</tr>
<tr>
<td>BGO</td>
<td>0</td>
<td>350</td>
<td>302</td>
</tr>
</tbody>
</table>

Main decay time
Emission weighted QE used to calculate Photons/MeV

Emission weighted QE is calculated according to the following equation:

\[
\overline{QE} = \frac{\int QE(\lambda)Em(\lambda)d\lambda}{\int Em(\lambda)d\lambda}
\]

Where

- \(QE(\lambda)\): quantum efficiency of cathode
- \(Em(\lambda)\): scintillation intensity
# Light Output and Decay Kinetics

Light output, decay time & relative L.O. with PMT QE taken out

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>L.Y. (Fast)</th>
<th>EWQE</th>
<th>L.Y. (Slow)</th>
<th>EWQE</th>
<th>Decay time (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p.e./MeV</td>
<td>Photons/MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaI(Tl)</td>
<td>0</td>
<td>0</td>
<td>2604</td>
<td>100</td>
<td>0.072</td>
</tr>
<tr>
<td>CsI(Na)</td>
<td>0</td>
<td>0</td>
<td>2274</td>
<td>88</td>
<td>0.071</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>0</td>
<td>0</td>
<td>2093</td>
<td>165</td>
<td>0.035</td>
</tr>
<tr>
<td>BaF₂</td>
<td>98</td>
<td>1500</td>
<td>1051</td>
<td>36</td>
<td>0.081</td>
</tr>
<tr>
<td>BGO</td>
<td>0</td>
<td>0</td>
<td>350</td>
<td>21</td>
<td>0.047</td>
</tr>
<tr>
<td>LSO</td>
<td>0</td>
<td>0</td>
<td>2210</td>
<td>85</td>
<td>0.072</td>
</tr>
<tr>
<td>LYSO</td>
<td>0</td>
<td>0</td>
<td>2150</td>
<td>83</td>
<td>0.072</td>
</tr>
<tr>
<td>CeF₃</td>
<td>0</td>
<td>0</td>
<td>208</td>
<td>7.3</td>
<td>0.079</td>
</tr>
<tr>
<td>CsI</td>
<td>30</td>
<td>390</td>
<td>101</td>
<td>3.6</td>
<td>0.077</td>
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<tr>
<td>PWO</td>
<td>1.9</td>
<td>28</td>
<td>7.3</td>
<td>0.3</td>
<td>0.068</td>
</tr>
</tbody>
</table>

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*a* NaI(Tl) sample is cylinder with diameter of 44 mm and 39 mm long, while all other samples are 1.5 radiation length in cubic.

*b* By Photonis XP 2254b PMT.
Temperature Coefficient Measurement

A NESLAB circulator used to keep sample at a fixed temperature with precision 0.01°C

Sensitivity of PMT cathode versus temperature checked by LED

Circulation water
Copper clip
Sample crystal
Holder

PMT
NESLAB Circulator
T. Stability: 0.01°C

Channel Number

Temperature (°C)

Mean 81.4°C
PMS 0.1543
Light Output Temperature Coefficient

Temperature Range: 5 ~ 35 °C

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature Coefficient (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI(Tl)</td>
<td>T. C.: -0.2 ± 0.1 % / °C</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>T. C.: 0.3 ± 0.1 % / °C</td>
</tr>
<tr>
<td>CsI(Na)</td>
<td>T. C.: 0.4 ± 0.1 % / °C</td>
</tr>
<tr>
<td>CsI</td>
<td>T. C.: -1.3 ± 0.1 % / °C</td>
</tr>
<tr>
<td>BaF₂</td>
<td>T. C.: -1.3 ± 0.1 % / °C</td>
</tr>
<tr>
<td>CeF₃</td>
<td>T. C.: -0.1 ± 0.1 % / °C</td>
</tr>
<tr>
<td>LSO</td>
<td>T. C.: -0.2 ± 0.1 % / °C</td>
</tr>
<tr>
<td>LYSO</td>
<td>T. C.: -0.2 ± 0.1 % / °C</td>
</tr>
<tr>
<td>BGO</td>
<td>T. C.: -0.9 ± 0.1% / °C</td>
</tr>
<tr>
<td>PWO(Y)</td>
<td>T. C.: -2.7 ± 0.1 % / °C</td>
</tr>
</tbody>
</table>
BaF$_2$: Fast and Slow Components

Two filters used to select scintillation component

- Scintillation of BaF$_2$ has two components: the fast one peaked at 220 nm while the slow one peaked at 300 nm.

- Special band pass filters were used to measure the light output temperature coefficients for individual component.

Transmittance for filter BPF-214 (fast component)

Transmittance for filter BPF-300 (slow component)
BaF$_2$ Light Output Temperature Coefficient

Fast and slow components have very different temperature coefficient

**Fast**

BaF$_2$  
Em: 220 nm  
Temperature coefficient: $0.1 \pm 0.1 \% / ^\circ C$

**Slow**

BaF$_2$  
Em: 300 nm  
Temperature coefficient: $-1.9 \pm 0.1 \% / ^\circ C$
Light Output Temperature Coefficient

Temperature Range: 15 ~ 25 °C

- NaI(Tl): T.C.: -0.2 ± 0.1 % / °C
- CsI(Tl): T.C.: 0.4 ± 0.1 % / °C
- CsI(Na): T.C.: 0.4 ± 0.1 % / °C
- CsI - Pure: T.C.: -1.4 ± 0.1 % / °C
- BaF$_2$: T.C.(220 nm): 0.1 ± 0.1 % / °C, T.C.(300 nm): -1.9 ± 0.1 % / °C
- CeF$_3$: T.C.: 0.0 ± 0.1 % / °C
- LSO: T.C.: -0.2 ± 0.1 % / °C
- LYSO: T.C.: -0.2 ± 0.1 % / °C
- BGO: T.C.: -0.9 ± 0.1 % / °C
- PWO: T.C.: -2.5 ± 0.1 % / °C
# Table of Inorganic Scintillators

<table>
<thead>
<tr>
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<th>CsI(Tl)</th>
<th>CsI(Na)</th>
<th>CsI</th>
<th>CeF$_3$</th>
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</tr>
<tr>
<td>Hygroscopicity</td>
<td>Yes</td>
<td>Slight</td>
<td>Slight</td>
<td>Slight</td>
<td>No</td>
<td>No</td>
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<td>No</td>
<td>No</td>
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<td>340</td>
<td>300</td>
<td>480</td>
<td>425</td>
<td>402</td>
</tr>
<tr>
<td>Decay Time $^b$ (ns)</td>
<td>245</td>
<td>1220</td>
<td>690</td>
<td>30</td>
<td>30</td>
<td>650</td>
<td>300</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
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<td>88</td>
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<td>7.3</td>
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<td>21</td>
<td>0.3</td>
<td>85</td>
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<tr>
<td>$d$(LY)/dT $^b$ (%)/ ºC</td>
<td>-0.2</td>
<td>0.4</td>
<td>0.4</td>
<td>-1.4</td>
<td>0</td>
<td>-1.9</td>
<td>-0.9</td>
<td>-2.5</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

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$a$. at peak of emission; $b$. up/low row: slow/fast component; $c$. QE of readout device taken out.
Summary

- A comparative study on inorganic crystal scintillators commonly used in high energy physics experiments was carried out.

- Refractive indices for LSO/LYSO were measured by using a V-prism.

- Relative light output was measured for samples of 1.5 $X_0$ with Tyvek wrapping and with quantum efficiencies of the readout devices taken out.

- Light output temperature coefficients at room temperature were measured.

- Result presented here will be used in the inorganic scintillator section of the 2008 PDB.