Crystal Calorimeters in the Next Decade

Ren-Yuan Zhu

California Institute of Technology

June 8, 2009
Why Crystal Calorimeter in HEP?

• Photons and electrons are fundamental particles. Precision $e/\gamma$ measurements enhance physics discovery potential.

• Performance of total absorption crystal ECAL is well understood:
  – The best possible $e/\gamma$ energy resolution;
  – Good $e/\gamma$ position resolution;
  – Good $e/\gamma$ identification and reconstruction efficiency.

• Crystals may also provide a foundation for a total absorption HCAL to achieve good resolution for hadrons and jets. Dual readout with Cherenkov and scintillation light would further help.
## Crystals for HEP Calorimeters

<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>LYSO(Ce)</th>
<th>PWO</th>
<th>PbF$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm$^3$)</td>
<td>3.67</td>
<td>4.51</td>
<td>4.51</td>
<td>4.89</td>
<td>7.13</td>
<td>7.40</td>
<td>8.3</td>
<td>7.77</td>
</tr>
<tr>
<td>Melting Point ($^\circ$C)</td>
<td>651</td>
<td>621</td>
<td>621</td>
<td>1280</td>
<td>1050</td>
<td>2050</td>
<td>1123</td>
<td>824</td>
</tr>
<tr>
<td>Radiation Length (cm)</td>
<td>2.59</td>
<td>1.86</td>
<td>1.86</td>
<td>2.03</td>
<td>1.12</td>
<td>1.14</td>
<td>0.89</td>
<td>0.93</td>
</tr>
<tr>
<td>Molière Radius (cm)</td>
<td>4.13</td>
<td>3.57</td>
<td>3.57</td>
<td>3.10</td>
<td>2.23</td>
<td>2.07</td>
<td>2.00</td>
<td>2.21</td>
</tr>
<tr>
<td>Interaction Length (cm)</td>
<td>42.9</td>
<td>39.3</td>
<td>39.3</td>
<td>30.7</td>
<td>22.8</td>
<td>20.9</td>
<td>20.7</td>
<td>21.0</td>
</tr>
<tr>
<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>1.82</td>
<td>2.20</td>
<td>1.82</td>
</tr>
<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>550</td>
<td>420</td>
<td>300</td>
<td>480</td>
<td>402</td>
<td>425</td>
<td>420</td>
</tr>
<tr>
<td>Decay Time $^b$ (ns)</td>
<td>245</td>
<td>1220</td>
<td>30</td>
<td>6</td>
<td>650</td>
<td>300</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Light Yield $^{b,c}$ (%)</td>
<td>100</td>
<td>165</td>
<td>3.6</td>
<td>36</td>
<td>21</td>
<td>85</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>$d$(LY)/dT $^b$ ($%/ ^\circ$C)</td>
<td>-0.2</td>
<td>0.4</td>
<td>-1.4</td>
<td>-1.9</td>
<td>-0.9</td>
<td>-0.2</td>
<td>-2.5</td>
<td>?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Crystal Ball</th>
<th>BaBar</th>
<th>BELLE</th>
<th>BES III</th>
<th>KTeV</th>
<th>(L$^*$) (GEM) TAPS</th>
<th>L3 BELLE</th>
<th>SuperB</th>
<th>CMS ALICE PANDA</th>
<th>HHCAL?</th>
</tr>
</thead>
</table>

$a.$ at peak of emission; $b.$ up/lower row: slow/fast component; $c.$ QE of readout device taken out.
# Crystals for Homeland Security

<table>
<thead>
<tr>
<th>Crystal</th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
<th>CsI(Na)</th>
<th>LaCl₃(Ce)</th>
<th>Srl₂(Eu)</th>
<th>LaBr₃(Ce)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>3.67</td>
<td>4.51</td>
<td>4.51</td>
<td>3.86</td>
<td>4.59</td>
<td>5.29</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>651</td>
<td>621</td>
<td>621</td>
<td>859</td>
<td>538</td>
<td>788</td>
</tr>
<tr>
<td>Radiation Length (cm)</td>
<td>2.59</td>
<td>1.86</td>
<td>1.86</td>
<td>2.81</td>
<td>1.95</td>
<td>1.88</td>
</tr>
<tr>
<td>Molière Radius (cm)</td>
<td>4.13</td>
<td>3.57</td>
<td>3.57</td>
<td>3.71</td>
<td>3.40</td>
<td>2.85</td>
</tr>
<tr>
<td>Interaction Length (cm)</td>
<td>42.9</td>
<td>39.3</td>
<td>39.3</td>
<td>37.6</td>
<td>37.0</td>
<td>30.4</td>
</tr>
<tr>
<td>Refractive Index a</td>
<td>1.85</td>
<td>1.79</td>
<td>1.95</td>
<td>1.9</td>
<td>?</td>
<td>1.9</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>Yes</td>
<td>Slight</td>
<td>Slight</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Luminescence b (nm) (at peak)</td>
<td>410</td>
<td>550</td>
<td>420</td>
<td>335</td>
<td>435</td>
<td>356</td>
</tr>
<tr>
<td>Decay Time b (ns)</td>
<td>245</td>
<td>1220</td>
<td>690</td>
<td>570</td>
<td>1100</td>
<td>20</td>
</tr>
<tr>
<td>Light Yield b,c (%)</td>
<td>100</td>
<td>165</td>
<td>88</td>
<td>13</td>
<td>221</td>
<td>130</td>
</tr>
<tr>
<td>d(LY)/dT b (%)/ °C</td>
<td>-0.2</td>
<td>0.4</td>
<td>0.4</td>
<td>0.1</td>
<td>?</td>
<td>0.2</td>
</tr>
</tbody>
</table>

a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.
Crystal Density: Radiation Length

1.5 $X_0$ Cubic Samples:
- Hygroscopic: Sealed
- Non-hygro: Polished

Full Size Crystals:
- **BaBar CsI(Tl):** 16 $X_0$
- **L3 BGO:** 22 $X_0$
- **CMS PWO(Y):** 25 $X_0
Excitation, Emission, Transmission

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

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


No Self-absorption: BGO, PWO, BaF\(_2\), NaI(Tl) and CsI(Tl)
Scintillation Light Decay Time

Fast Scintillators

- CsI: $\tau = 30/6$ ns
- LaBr$_3$: $\tau = 20$ ns
- CeF$_3$: $\tau = 35$ ns
- PWO: $\tau = 30/10$ ns
- LSO: $\tau = 40$ ns

Slow Scintillators

- CsI(Tl): $\tau = 1250$ ns
- CsI(Na): $\tau = 630$ ns
- NaI(Tl): $\tau = 230$ ns
- BGO: $\tau = 300$ ns
- LaCl$_3$: $\tau = 600/25$ ns
- BaF$_2$: $\tau = 630/0.9$ ns

Recorded with an Agilent 6052A digital scope

T1-2, SCINT09 at Jeju, Korea, Ren-yuan Zhu, Caltech

June 8, 2009
Light Output & Decay Kinetics

Measured with Philips XP2254B PMT (multi-alkali cathode)

p.e./MeV: LSO/LYSO is 6 & 230 times of BGO & PWO respectively

### Fast Crystal Scintillators

- **LaBr$_3$**
- **LSO/LYSO**

### Slow Crystal Scintillators

- **LaCl$_3$**

<table>
<thead>
<tr>
<th>Crystal</th>
<th>F (p.e./MeV)</th>
<th>S (p.e./MeV)</th>
<th>$\tau_s$ (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaBr$_3$(Ce)</td>
<td>0</td>
<td>3810</td>
<td>19</td>
</tr>
<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>CeF$_3$</td>
<td>0</td>
<td>206</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>

<table>
<thead>
<tr>
<th>Crystal</th>
<th>F (p.e./MeV)</th>
<th>S (p.e./MeV)</th>
<th>$\tau_s$ (ns)</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>LaCl$_3$(Ce)</td>
<td>1190/360</td>
<td>24/570</td>
<td></td>
</tr>
<tr>
<td>BaF$_2$</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>
Emission Weighted QE

Taking out QE, L.O. of LSO/LYSO is 4/200 times BGO/PWO
Hamamatsu S8664-55 APD has QE 75% for LSO/LYSO

June 8, 2009
T1-2, SCINT09 at Jeju, Korea, Ren-yuan Zhu, Caltech
Large temperature coefficient: CsI, BGO, BaF$_2$ and PWO
$^{137}\text{Cs FWHM Energy Resolution}$

3% to 80% measured with Hamamatsu R1306 PMT with bi-alkali cathode

2% resolution and proportionality are important for $\gamma$–ray spectroscopy between 10 keV to 2 MeV
Low Energy Non Proportionality

D: deviation from linearity: 60 keV to 1.3 MeV
Good Crystals: LaBr$_3$, BaF$_2$, CsI(Na) and BGO

LaBr$_3$  D < 3%
BaF$_2$   D < 3%
CsI(Na)  D < 4%
BGO     D < 6%

CsI(Tl)  D < 9%
NaI(Tl)  D < 10%
LSO     D < 11%
CeF$_3$  D < 25%

L. O. (fraction of 662 KeV) (%)
Statistical & Intrinsic Resolutions

\[ \sigma^2 = \sigma^2_{\text{intrinsic}} + \sigma^2_{\text{statistical}}, \text{ ratio } = \frac{\sigma_{\text{intrinsic}}}{\sigma_{\text{statistical}}} \]

Good crystals: BGO and LaBr\(_3\)

---

**Energy Resolution (%)**

- LaBr\(_3\):
  - Ratio = 0.9

- CsI(Tl):
  - Ratio = 1.1

- NaI(Tl):
  - Ratio = 1.7

- LSO:
  - Ratio = 1.7

- BGO:
  - Ratio = 0.8

- BaF\(_2\):
  - Ratio = 1.1

- CsI(Na):
  - Ratio = 1.7

- LYSO:
  - Ratio = 1.8

---

Energy (KeV)

June 8, 2009
T1-2, SCINT09 at Jeju, Korea, Ren-yuan Zhu, Caltech
Crystal Calorimeters in HEP

<table>
<thead>
<tr>
<th>Date</th>
<th>75-85</th>
<th>80-00</th>
<th>80-00</th>
<th>80-00</th>
<th>90-10</th>
<th>94-10</th>
<th>94-10</th>
<th>95-20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>C. Ball</td>
<td>L3</td>
<td>CLEO II</td>
<td>C. Barrel</td>
<td>KTeV</td>
<td>BaBar</td>
<td>BELLE</td>
<td>CMS</td>
</tr>
<tr>
<td>Accelerator</td>
<td>SPEAR</td>
<td>LEP</td>
<td>CESR</td>
<td>LEAR</td>
<td>FNAL</td>
<td>SLAC</td>
<td>KEK</td>
<td>CERN</td>
</tr>
<tr>
<td>Crystal Type</td>
<td>NaI(Tl)</td>
<td>BGO</td>
<td>CsI(Tl)</td>
<td>CsI</td>
<td>CsI</td>
<td>CsI(Tl)</td>
<td>CsI(Tl)</td>
<td>PbWO$_4$</td>
</tr>
<tr>
<td>B-Field (T)</td>
<td>-</td>
<td>0.5</td>
<td>1.5</td>
<td>1.5</td>
<td>-</td>
<td>1.5</td>
<td>1.0</td>
<td>4.0</td>
</tr>
<tr>
<td>$r_{inner}$ (m)</td>
<td>0.254</td>
<td>0.55</td>
<td>1.0</td>
<td>0.27</td>
<td>-</td>
<td>1.0</td>
<td>1.25</td>
<td>1.29</td>
</tr>
<tr>
<td>Number of Crystals</td>
<td>672</td>
<td>11,400</td>
<td>7,800</td>
<td>1,400</td>
<td>3,300</td>
<td>6,580</td>
<td>8,800</td>
<td>76,000</td>
</tr>
<tr>
<td>Crystal Depth ($X_0$)</td>
<td>16</td>
<td>22</td>
<td>16</td>
<td>16</td>
<td>27</td>
<td>16 to 17.5</td>
<td>16.2</td>
<td>25</td>
</tr>
<tr>
<td>Crystal Volume (m$^3$)</td>
<td>1</td>
<td>1.5</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>5.9</td>
<td>9.5</td>
<td>11</td>
</tr>
<tr>
<td>Light Output (p.e./MeV)</td>
<td>350</td>
<td>1,400</td>
<td>5,000</td>
<td>2,000</td>
<td>40</td>
<td>5,000</td>
<td>5,000</td>
<td>2</td>
</tr>
<tr>
<td>Photosensor</td>
<td>PMT</td>
<td>Si PD</td>
<td>Si PD</td>
<td>WS$^a$+Si PD</td>
<td>PMT</td>
<td>Si PD</td>
<td>Si PD</td>
<td>APD$^a$</td>
</tr>
<tr>
<td>Gain of Photosensor</td>
<td>Large</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4,000</td>
<td>1</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>$\sigma_N$/Channel (MeV)</td>
<td>0.05</td>
<td>0.8</td>
<td>0.5</td>
<td>0.2</td>
<td>small</td>
<td>0.15</td>
<td>0.2</td>
<td>40</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>$10^4$</td>
<td>$10^5$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>

Future crystal calorimeters in HEP:
PWO for PANDA at GSI: R. Novotny T4-2
LSO/LYSO for a Super B Factory
Crystals for a total absorption HCAL: A. Para T4-1

June 8, 2009
T1-2, SCINT09 at Jeju, Korea, Ren-yuan Zhu, Caltech
L3 BGO Resolution

<table>
<thead>
<tr>
<th>Contribution</th>
<th>“Radiative”+Intrinsic</th>
<th>Temperature</th>
<th>Calibration</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>0.8%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>1.07%</td>
</tr>
<tr>
<td>Endcaps</td>
<td>0.6%</td>
<td>0.5%</td>
<td>0.4%</td>
<td>0.88%</td>
</tr>
</tbody>
</table>
BaBar CsI(Tl) Resolution

A crystal calorimeter at low energies

Good light yield of CsI(Tl) provides excellent energy resolution at low energies

\[ \frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt{E}} \oplus \sigma_2 \]

\[ \sigma_1 = (2.30 \pm 0.03 \pm 0.3)\% \]

\[ \sigma_2 = (1.35 \pm 0.08 \pm 0.2)\% \]
CMS PWO Resolution

Designed Resolution

Measured Resolution
$\sigma(E)/E < 1\%$ if $E > 25$ GeV
$\sigma(E)/E \sim 0.5\%$ at 120 GeV

76k PWO

CMS ECAL Test Beam Resolution in 3x3
PANDA at GSI, Germany

AntiProton

ANnihilations

at DArmstadt

8 - 12,000 modules

~ 20 $X_0$ deep

PWO at Low T

June 8, 2009

T1-2, SCINT09 at Jeju, Korea, Ren-yuan Zhu, Caltech
LYSO Endcap for SuperB

Aiming at $10^{36}/\text{cm}^2/\text{s}$ luminosity for rare B decays

Need fast detector with low noise at the endcap

LSO/LYSO
2.5 x 2.5 x 20 cm (18 X₀) Samples

SIC BGO

CPI LYSO

Saint-Gobain LYSO

CTI LSO
LSO/LYSO with PMT Readout

≈10% FWHM resolution for $^{22}\text{Na}$ source (0.51 MeV)
1,200 p.e./MeV, 5/230 times of BGO/PWO

SIC-BGO
PMT: R1306, HV=-1100V
Gate: 2000 ns
E.R.: 15.4±0.2%

CTI-LSO
PMT: R1306, HV=-1100V
Gate: 200 ns
E.R.: 11.3±0.2%

CPI-LSO
PMT: R1306, HV=-1100V
Gate: 200 ns
E.R.: 22.4±0.3%

SG-LYSO
PMT: R1306, HV=-1100V
Gate: 200 ns
E.R.: 10.8±0.2%
LSO/LYSO with APD Readout

L.O.: 1,500 p.e./MeV, 4/200 times of BGO/PWO
Readout Noise: < 40 keV

Pedestal
2 × Hamamatsu S8664-55
HV = 400 V, τ = 250 ns
pedestal = 46 ADC  σ = 34 ADC
noise = 57 electrons

Fe-55 Calibration
Fe-55: 1278 electrons
pedestal = 46 ADC
peak = 814 ADC
σ = 52 ADC
1.664 electrons/ADC

SIC-BGO-L
2 × Hamamatsu S8664-55
HV = 400 V, τ = 250 ns, M = 500
ped = 43, peak = 173
L.O. = 420 p.e./MeV

CTI-LSO-L
ped = 43, peak = 698
L.O. = 2130 p.e./MeV

CPI-LYSO-L
ped = 43, peak = 450
L.O. = 1330 p.e./MeV

SG-LYSO-L
ped = 43, peak = 504
L.O. = 1500 p.e./MeV
γ-Ray Induced Damage

No damage in Photo-Luminescence

Transmittance recovery slow

**Graphs:**
- **Left Graph:**
  - Title: SG-LYSO-L
  - X-axis: Wavelength (nm)
  - Y-axis: Intensity (a.u.)
  - Data points:
    - Before irradiation: Red line
    - After 8500 rad/h irradiation: Blue line
    - Normalized area: 380 - 460 nm
    - Average of |△I|: 0.6% (380 - 460 nm)

- **Right Graph:**
  - Title: Recovery after 8500 rad/h, 96 h irradiation
  - X-axis: Time (hours)
  - Y-axis: Transmittance @ 420 nm
  - Data points:
    - CTI-LYSO-L: $T_0 = 76.1$, $y = 68.46 \pm 0.0002x$
    - SG-LYSO-L: $T_0 = 74.1$, $y = 66.88 \pm 0.0000x$
    - CPI-LYSO-L: $T_0 = 70.2$, $y = 61.02 \pm 0.0008x$
\( \gamma \)-Ray Induced L.O. Damage

All samples show consistent radiation resistance

10% - 15% loss @ 1 Mrad by PMT

9% - 14% loss @ 1 Mrad by APD

Normalized Average Light output vs Irradiation Dose (rad) for different types of crystals coupled to PMT or APD.
LSO/LYSO ECAL Performance

• Less demanding to the environment because of small temperature coefficient.

• Radiation damage is less an issue as compared to other crystals.

• A better energy resolution, $\sigma(E)/E$, at low energies than L3 BGO and CMS PWO because of its high light output and low readout noise:

$$2.0\%/\sqrt{E} \oplus 0.5\% \oplus 0.001/E$$
A Fermilab team (A. Para et al.) proposed a total absorption homogeneous HCAL detector concept for the International Linear Collider to achieve good jet mass resolution. It eliminates dead materials between classical ECAL and HCAL. This is possible because of the latest development in compact readout devices, such as Si PMT. Readout with both Cherenkov and scintillation light would further help as demonstrated by the Dream collaboration (R. Wigwams et al.). It is an option in SiD Lol.
A. Para, ILCWS08, Chicago: GEANT simulation shows jet energy resolution of about $22\%/\sqrt{E}$ after corrections. This is much better than what has been achieved with PFA.

R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry.
Crystals of high density, good UV transmittance and some scintillation light, not necessary bright and fast, are required. The volume needed is 70 to 100 m$^3$: cost-effective material. Following 2/19/08 workshop at SICCAS, 5 x 5 x 5 cm samples evaluated.
Cherenkov Needs UV Transparency

Cherenkov figure of merit

Using UG11 optical filter, Cherenkov light can be effectively selected with negligible contamination from scintillation.
Scintillation Selected with Filter

GG400 optical filter effectively selects scintillation light with very small contamination from Cherenkov

Transmittance (%)  
Wavelength (nm)

Em BGO (a.u.)
(θ = 10°)
Cosmic Setup with Dual Readout

- **Agilent 6052A (500 MHZ) DSO** with rise time 0.7 ns
- **Hamamatsu R2059 PMT (2500 V)** with rise time 1.3 ns

UG11 and GG 400 used to select Cherenkov & scintillation
No Discrimination in Front Edge

Consistent timing and rise time for all Cherenkov and scintillation light pulses observed.
Slow Scintillation Decay May be Used

After 15 ns no Cherenkov contamination

BGO

τ: 302 ns
t_f: 0.7 μs

PWO

τ: 3.0/26.6 ns
t_f: 18 ns
Ratio of Cherenkov/Scintillation

1.6% for BGO and 22% for PWO with UG11/GG400 filter and R2059 PMT

\[ R = \text{Ch./Scint.} = 1.55\% \]

\[ R = \text{Ch./Scint.} = 22\% \]
Green Slow Scintillation in PWO

A factor of ten intensity of slow ($\mu$s) green scintillation light (560 nm) was observed in PbF$_2$/BaF$_2$ doped PWO.

R.H. Mao at al., in Calor2000 proceedings
Scintillation was Observed in PbF$_2$(Gd)

Scintillation of PbF$_2$(Gd)


PbF$_2$(Gd) Response to MIP of 1 GeV/c

Fast Scintillation of 6.5 p.e./MeV with decay time of less than 10 ns
Scintillation Observed in PbF₂

Consistent Photo- and X-luminescence observed in doped PbF₂ samples grown by Prof. Dingzhong Shen of SIC/Scintibow.

June 8, 2009
T1-2, SCINT09 at Jeju, Korea, Ren-yuan Zhu, Caltech
Set-up Verified with BGO & CsI(Tl)

Decay time consists with well known values

BGO

\[ I = A \exp \left(-\frac{x}{\tau}\right) \]
\[ A = 1.0 \]
\[ \tau = 289.2 \]
\[ \chi^2/DOF = 1.3 \]

290 ns

CsI(Tl)

\[ I = A \exp \left(-\frac{x}{\tau}\right) \]
\[ A = 1.0 \]
\[ \tau = 1280.0 \]
\[ \chi^2/DOF = 1.4 \]

1280 ns
Eu and Sm Doped PbF$_2$

Red emission with multi-ms decay time observed

\[ I = A \exp\left(-\frac{x}{\tau}\right) \]

- \( A = 1.0 \)
- \( \tau = 8.52 \) ms
- \( \chi^2/\text{DOF} = 1.9 \)

\[ I = A \exp\left(-\frac{x}{\tau}\right) \]

- \( A = 1.0 \)
- \( \tau = 7.02 \) ms
- \( \chi^2/\text{DOF} = 1.3 \)
Tb and Er Doped PbF$_2$

Green emission with ms decay time observed

PbF:Tb
Laser excited

$I = A \exp (-x/\tau)$
$A = 1.0$
$\tau = 4.95$

$\chi^2$/DOF = 1.7

5.0 ms

PbF:Er
Laser excited

$I = A \exp (-x/\tau)$
$A = 1.0$
$\tau = 1.52$

$\chi^2$/DOF = 1.7

1.5 ms
Ho Doped PbF$_2$

PbF:Ho

Laser excited

\[ I = A \exp \left(-\frac{t}{\tau}\right) \]

\[ A = 1.0 \]

\[ \tau = 1.33 \]

\[ \chi^2/DOF = 2.2 \]

1.3ms
Summary

• Historically homogeneous ECAL provides good resolutions for e/\(\gamma\) measurements. An LSO/LYSO crystal calorimeter may provide excellent energy resolution over a large dynamic range down to MeV level for future HEP experiments, such as SuperB.

• The proposed homogeneous hadronic calorimeter (HHCAL) detector concept would provide good resolution for hadron and jet measurements. Because of the huge volume needed development of cost-effective UV transparent material is crucial. Our initial investigation indicates that scintillating PbF\(_2\) seems the best choice. BSO, PWO and BGO may also serve as candidate. The SCINT community may help this development.