Fast Crystal Scintillators for Future HEP Experiments

Ren-Yuan Zhu

California Institute of Technology

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Why Crystal Calorimeter in HEP?

• Precision $e/\gamma$ measurements enhance physics discovery potential.

• Performance of homogeneous crystal calorimeter for $e/\gamma$ measurements is well understood:
  – The best possible energy resolution;
  – Good position resolution;
  – Good $e/\gamma$ identification and reconstruction efficiency.

• Challenges at future HEP Experiments:
  – Radiation hard calorimeter for HL-LHC;
  – Good jet mass resolution for ILC/CLIC;
  – Ultra-fast rate and $\gamma$-pointing at the intensity frontier.
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>

45.6 GeV < $E_{beam}$ < 94.3 GeV

- **Barrel**
  - $\sigma = 1.06\%$
  - Events / 0.0025
  - BGO energy / Beam energy

- **Endcaps**
  - $\sigma = 0.86\%$
  - Events / 10
  - BGO energy / Beam energy

12k BGO

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Neutrino Counting in Z Decay

\[ N_\nu = 2.98 \pm 0.06 \]

SUSY Breaking with Gravitino

\[ e^+e^- \rightarrow \tilde{G}\tilde{\chi}_1^0 \rightarrow \tilde{G}\tilde{G}\gamma \]

\[ 189 \text{ GeV} \leq \sqrt{s} \leq 208 \text{ GeV} \]
Charmonium system observed by CB through Inclusive photons

Higgs -> $\gamma\gamma$ by CMS through reconstructing photon pairs

CB NaI(Tl)

CMS PWO

$\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$ $\sqrt{s} = 8$ TeV, $L = 5.3$ fb$^{-1}$
2013 Nobel Price for Physics?
**H→γγ Search Needs Precision ECAL**

**Natural width (GeV)**

<table>
<thead>
<tr>
<th>Higgs Mass (GeV)</th>
<th>0</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>800</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.001</td>
<td>0.004</td>
<td>1.4</td>
<td>30</td>
<td>250</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **LEP**
- **LHC**

**Narrow width and large background**

- **H → γγ**
- **H → ZZ → 4 leptons**
- **H → ZZ → 4 leptons**
- **H → WW or ZZjj**

**CMS PWO**

\[\sigma / m = 0.5 [\sigma E_1 / E_1 \oplus \sigma E_2 / E_2 \oplus \sigma \theta / \tan(\theta/2)],\]

where \(\sigma E / E = a / \sqrt{E} \oplus b \oplus c / E\) and \(E\) in GeV.

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### Existing 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(Tl)</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:
- LSO/LYSO for Mu2e, (Super B), and HL-LHC (Sampling)
- PbF$_2$, PbFCl, BSO for Homogeneous HCAL
- BaF$_2$ for fast calorimeters at the intensity frontier
CMS Experiment at LHC
History of Scintillating Crystals


- **Fifties**: NaI and CsI
- **Seventies**: BGO
- **Nineties**: PWO, LSO
- **21 Century**: LaBr$_3$

Invention of the photomultiplier tube

- Cs$_2$LiYCl$_6$:Ce 2003
- LuI$_3$:Ce 2003
- K$_2$LaI$_5$:Ce 2002
- LaBr$_3$:Ce 2001
- LaCl$_3$:C 2000
- Lu$_2$O$_3$:Eu, Tb 2000
- Lu$_2$Si$_2$O$_7$:Ce 2000
- RbGd$_2$Br$_7$:Ce 1997
- $^6$Li$_6$Gd(BO$_3$)$_3$:Ce 1996

Fast UV response

Trigger

HPGe

Ge:Li

Fifties: NaI and CsI
# Crystals for HEP Calorimeters

<table>
<thead>
<tr>
<th>Crystal</th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
<th>CsI</th>
<th>BaF₂</th>
<th>BGO</th>
<th>LYSO(Ce)</th>
<th>PWO</th>
<th>PbF₂</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density (g/cm³)</strong></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><strong>Melting Point (°C)</strong></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><strong>Radiation Length (cm)</strong></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><strong>Molière Radius (cm)</strong></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><strong>Interaction Length (cm)</strong></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><strong>Refractive Index a</strong></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><strong>Hygroscopicity</strong></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><strong>Luminescence b (nm) (at peak)</strong></td>
<td>410</td>
<td>550</td>
<td>420</td>
<td>300</td>
<td>480</td>
<td>402</td>
<td>425</td>
<td>?</td>
</tr>
<tr>
<td><strong>Decay Time b (ns)</strong></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><strong>Light Yield b,c (%)</strong></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>?</td>
</tr>
<tr>
<td><strong>d(LY)/dT b (%/ °C)</strong></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>
<tr>
<td><strong>Experiment</strong></td>
<td>Crystal Ball</td>
<td>BaBar</td>
<td>BELLE</td>
<td>KTeV</td>
<td>L3</td>
<td>Mu2e (SuperB)</td>
<td>CMS</td>
<td>ALICE</td>
</tr>
</tbody>
</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>SrI₂ (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 (ºC)</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 (%)/ ºC</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 $X_0$ Samples:
Hygroscopic: Sealed
Surfaces: Polished

Full Size Crystals:
BaBar CsI(Tl): 16 $X_0$
L3 BGO: 22 $X_0$
CMS PWO(Y): 25 $X_0$
$T_s = (1 - R)^2 + R^2 (1 - R)^2 + \ldots = \frac{1 - R}{1 + R}$, 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)
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

<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$_3$</td>
<td>3810</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>LSO</td>
<td>2210</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>LYSO</td>
<td>2150</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>CeF$_3$</td>
<td>206</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>CsI</td>
<td>101</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>PWO</td>
<td>7.3</td>
<td>31</td>
<td></td>
</tr>
</tbody>
</table>

Slow Crystal Scintillators

<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>BaF$_2$</td>
<td>1190/360</td>
<td>24/570</td>
<td></td>
</tr>
<tr>
<td>BGO</td>
<td>350</td>
<td>302</td>
<td></td>
</tr>
<tr>
<td>NaI(Tl)</td>
<td>2604</td>
<td>245</td>
<td></td>
</tr>
<tr>
<td>CsI(Na)</td>
<td>2274</td>
<td>693</td>
<td></td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>2093</td>
<td>1220</td>
<td></td>
</tr>
</tbody>
</table>

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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

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L.O. Temperature Coefficient

Temperature Range: 15 - 25°C

Large coefficient: CsI, BGO, slow component of BaF₂ 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

D < 3%
D < 3%
D < 4%
D < 6%
D < 9%
D < 10%
D < 11%
D < 25%

L. O. (fraction of 662 KeV) (%)

Energy (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)

- Logarithmic scale from $10^2$ to $10^3$.

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CMS PWO Monitoring Response

The observed degradation is well understood

CMS Preliminary 2011-2012

relativresponse

|η| < 1.4  
1.5 < |η| < 1.8  
1.8 < |η| < 2.1  
2.1 < |η| < 2.4  
2.4 < |η| < 2.7  
2.7 < |η|

LHC luminosity

10^{33} cm^{-2} s^{-1}

05/11 07/11 09/11 11/11 01/12 03/12 05/12 07/12 09/12 11/12
date (month/year)
Dose Rate Dependent EM Damage

The LO reached equilibrium during irradiations under a defined dose rate, showing dose rate dependent radiation damage

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

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

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

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

BTCP-2162R
L.O. = 9.3 p.e./MeV (200 ns, 20.0°C)

Normalized Light Output

- [Graph showing normalized light output over time with dose rate (rad/h) indicated at various points: 15, 100, 500, 1000, recovery...]

Time (hours)
Oxygen Vacancies Identified by TEM/EDS

TOPCON-002B scope, 200 kV, 10 uA, 5 to 10 nm black spots identified
JEOL JEM-2010 scope and Link ISIS EDS localized Stoichiometry Analysis

NIM A413 (1998) 297

Atomic Fraction (%) in PbWO$_4$

As Grown Sample

<table>
<thead>
<tr>
<th>Element</th>
<th>Black Spot</th>
<th>Peripheral</th>
<th>Matrix$_1$</th>
<th>Matrix$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>1.5</td>
<td>15.8</td>
<td>60.8</td>
<td>63.2</td>
</tr>
<tr>
<td>W</td>
<td>50.8</td>
<td>44.3</td>
<td>19.6</td>
<td>18.4</td>
</tr>
<tr>
<td>Pb</td>
<td>47.7</td>
<td>39.9</td>
<td>19.6</td>
<td>18.4</td>
</tr>
</tbody>
</table>

The Same Sample after Oxygen Compensation

<table>
<thead>
<tr>
<th>Element</th>
<th>Point$_1$</th>
<th>Point$_2$</th>
<th>Point$_3$</th>
<th>Point$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>59.0</td>
<td>66.4</td>
<td>57.4</td>
<td>66.7</td>
</tr>
<tr>
<td>W</td>
<td>21.0</td>
<td>16.5</td>
<td>21.3</td>
<td>16.8</td>
</tr>
<tr>
<td>Pb</td>
<td>20.0</td>
<td>17.1</td>
<td>21.3</td>
<td>16.5</td>
</tr>
</tbody>
</table>
Prediction of PWO Radiation Damage


Talk in CMS Forward Calorimeter Taskforce Meeting, CERN, 12/10/2010

Predicted EM dose induced damage agrees well with the LHC data. In addition, there is cumulative hadron induced damage in PWO.
Proton Induced Damage

The proton induced absorption in LYSO is 1/5 of PWO.

Damage may also be reduced by short light path.

Expected resolution @ $\eta = 2.2$

3,000/fb
Bright, Fast & Rad Hard LSO/LYSO

LSO/LYSO is a bright (200 times of PWO), fast (40 ns) and radiation hard crystal scintillator. The longitudinal non-uniformity issue caused by tapered crystal geometry, self-absorption and cerium segregation can be addressed by roughening one side surface. The material is widely used in the medical industry. Existing mass production capability would help in crystal cost control.
Excellent Radiation Hardness in LT

Consistent & Small Damage in LT

Larger variation @ shorter $\lambda$

CPI-LYSO-L 25\times25\times200 mm$^3$

Before IR: 52.5%

$10^2$ rad: 52.2%

$10^4$ rad: 50.5%

$10^6$ rad: 48.4%

CTI-LSO-L 25\times25\times200 mm$^3$

Before IR: 55.3%

$10^2$ rad: 55.1%

$10^4$ rad: 52.5%

$10^6$ rad: 50.6%

SG-LYSO-L 25\times25\times200 mm$^3$

Before IR: 56.4%

$10^2$ rad: 56.1%

$10^4$ rad: 53.8%

$10^6$ rad: 51.8%

SIPAT-LYSO-L 25\times25\times200 mm$^3$

Before IR: 59.9%

$10^2$ rad: 59.8%

$10^4$ rad: 57.7%

$10^6$ rad: 53.7%

SIC-LYSO-L 25\times25\times200 mm$^3$

Before IR: 55.4%

$10^2$ rad: 55.3%

$10^4$ rad: 54.9%

$10^6$ rad: 53.3%
Excellent Radiation Hardness in LO

About 12% LO loss observed after 1 Mrad irradiation in all samples with LRU maintained. It can be corrected by light monitoring.
28 cm Long LYSO Under γ-Rays

1st 30 cm Ingot grown at SIPAT, Sep, 2009

SIPAT-LYSO-L7: 2.5 x 2.5 x 28 cm, Nov, 2009
Damage in 25x25x5 mm LYSO Plates

Two 5 mm thick LYSO plates went through $\gamma$-ray irradiation to 10 Mrad with degradation in both EWLT and LO less than 10%.
Mu2e Experiment at Fermilab

Production Solenoid
- Production target
- Graded field

Production Target Tracker Calorimeter

Transport Solenoid
- Collimation system selects muon charge and momentum range
- Pbar window in middle of central collimator

Delivers $\sim 0.0015$ stopped $\mu^{-}$ per incident proton
5 x $10^{10}$ Hz of stopped muons

Detector Solenoid
- Muon stopping target
- Tracker
- Calorimeter
- Warm bore evacuated to $10^{-4}$ Torr

Cosmic Ray Veto not shown

LYSO CAL

Physics/Theory colloquium Presented at Los Alamos National Laboratory by Ren-Yuan Zhu, Caltech

October 3, 2013
Mu2e LYSO Calorimeter

An array of hexagonal LYSO crystals arranged in two disks
25 LYSO test beam crystals are uniformized to $|\delta| < 3\%$ by roughening the smallest side surface.
LYSO Test Beam Result


198 MeV beam
With 1/2/3 e⁻
CMS Forward Calorimeter Upgrade

CMS ECAL endcap: Single Crystal: 160 cm$^3$
Total number: 16,000 Total Volume: 3 m$^3$

Issues: Radiation hardness of the photo-detector and Cost

Crystal Cost: ~$18M@$30/cc

Issue: Radiation hardness of the photo-detector

Expected Crystal Cost: ~$90M@$30/cc

Talk in CMS FCAL Taskforce Meeting at CERN, 6/30/2011

October 3, 2013 Physics/Theory colloquium Presented at Los Alamos National Laboratory by Ren-Yuan Zhu, Caltech 35
## LYSO Based Shashlik Cell Design

### Absorber

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHCb Lead (Pb)</th>
<th>Plan-1 Lead (Pb)</th>
<th>Plan-2 Tungsten (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>11.4</td>
<td>11.4</td>
<td>19.3</td>
</tr>
<tr>
<td>Radiation Length (cm)</td>
<td>0.56</td>
<td>0.56</td>
<td>0.35</td>
</tr>
<tr>
<td>Moliere Radius (cm)</td>
<td>1.60</td>
<td>1.60</td>
<td>0.93</td>
</tr>
<tr>
<td>dE/dX (MeV/cm)</td>
<td>12.74</td>
<td>12.74</td>
<td>22.1</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>2</td>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td>Plates number</td>
<td>66</td>
<td>28</td>
<td>28</td>
</tr>
</tbody>
</table>

### Scintillator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BASF-165 Polystyrene (Sc)</th>
<th>LYSO</th>
<th>LYSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>1.06</td>
<td>7.4</td>
<td>7.4</td>
</tr>
<tr>
<td>Light Yield (photons/MeV)</td>
<td>5200</td>
<td>30000</td>
<td>30000</td>
</tr>
<tr>
<td>Radiation Length (cm)</td>
<td>41.31</td>
<td>1.14</td>
<td>1.14</td>
</tr>
<tr>
<td>Moliere Radius (cm)</td>
<td>9.59</td>
<td>2.07</td>
<td>2.07</td>
</tr>
<tr>
<td>dE/dX (MeV/cm)</td>
<td>2.05</td>
<td>9.55</td>
<td>9.55</td>
</tr>
<tr>
<td>Plate Thickness (mm)</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Plates number</td>
<td>67</td>
<td>29</td>
<td>29</td>
</tr>
</tbody>
</table>

### WLS Fiber

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Number /Cell</td>
<td>16</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

### Cell Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHCb</th>
<th>Plan-1</th>
<th>Plan-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Depth (X₀)</td>
<td>24.22</td>
<td>25.09</td>
<td>25.09</td>
</tr>
<tr>
<td>Sampling Fraction (MIPs)</td>
<td>0.25</td>
<td>0.28</td>
<td>0.26</td>
</tr>
<tr>
<td>Total Physical Length (cm)</td>
<td>40</td>
<td>17</td>
<td>12.8</td>
</tr>
<tr>
<td>Total Sc Length (cm)</td>
<td>26.8</td>
<td>5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Absorber Weight Ratio</td>
<td>0.84</td>
<td>0.75</td>
<td>0.76</td>
</tr>
<tr>
<td>Scintillator Weight Ratio</td>
<td>0.16</td>
<td>0.25</td>
<td>0.24</td>
</tr>
<tr>
<td>Average Density (g/cm³)</td>
<td>4.47</td>
<td>10.04</td>
<td>13.91</td>
</tr>
<tr>
<td>Average Radiation Length (cm)</td>
<td>1.65</td>
<td>0.68</td>
<td>0.51</td>
</tr>
<tr>
<td>Average Moliere Radius (cm)</td>
<td>3.6</td>
<td>1.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Transverse Dimension (cm)</td>
<td>4.1</td>
<td>1.9</td>
<td>1.4</td>
</tr>
<tr>
<td>Sc-depth/Total-depth in X₀</td>
<td>0.0268</td>
<td>0.2028</td>
<td>0.2028</td>
</tr>
<tr>
<td>WLS Fiber Density (N/cm²)</td>
<td>0.97</td>
<td>1.06</td>
<td>2.07</td>
</tr>
</tbody>
</table>

### MIPs Energy Deposition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHCb</th>
<th>Plan-1</th>
<th>Plan-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sc plates (MeV)</td>
<td>54.94</td>
<td>55.39</td>
<td>55.39</td>
</tr>
</tbody>
</table>

### Light Yield using MIPs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHCb</th>
<th>Plan-1</th>
<th>Plan-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon Electrons/GeV</td>
<td>3077</td>
<td>17897</td>
<td>17897</td>
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</tbody>
</table>

### Signal of MIPs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHCb</th>
<th>Plan-1</th>
<th>Plan-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon Electrons / MIP</td>
<td>169</td>
<td>991</td>
<td>991</td>
</tr>
</tbody>
</table>

### Module Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHCb</th>
<th>Plan-1</th>
<th>Plan-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Resolution (a, %)</td>
<td>8.2</td>
<td>9.0*</td>
<td>9.0*</td>
</tr>
</tbody>
</table>

*Based on the simulation of Zhigang Wang, IHEP, Beijing.*
Three LYSO Plates with Holes

25 × 25 × 5, 3 and 1.5 mm³
Two Measurement Setups

1) LYSO plates with Tyvek wrapping are readout directly by a R1306 PMT using a Cs-137 $\gamma$-ray source.

2) LYSO plates with Tyvek wrapping are readout with four Y11 WLS fibers of 40 cm long and a R2059 PMT using a Na-22 $\gamma$-ray source and coincidence.
**PHS of 3 mm LYSO Plate**

**LYSO 25 × 25 × 3 mm³**

LYSO SIPAT-07116a-51 25×25×3 mm³  
Source: Cs-137, Gate = 200 ns  
R1306 PMT, HV = -850 V  
Light Yield: 3970 p.e./MeV  
E.R. = 11.8%

**3 mm plate & 4 x 40 cm Y11 fiber**

25×25×3 mm³ LYSO plate  
40 cm WLS (Y11) fiber  
Source: Na-22, Gate = 200 ns  
R2059 PMT, HV = -2700 V  
Net peak: 174 ch, Light Yield: 24.3 p.e./MeV

γ-ray peaks are clearly visible
PMT Quantum Efficiency

Light Output (LO) measured in p.e./MeV are converted to Light Yield (LY) in photons/MeV by taking out the QE of the PMT:

\[ LY = \frac{LO}{QE} \]
# Light Collection Efficiencies

<table>
<thead>
<tr>
<th>Samples</th>
<th>5 mm LYSO</th>
<th>3 mm LYSO</th>
<th>1.5 mm LYSO</th>
<th>LHCb cell*</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO₁ (p.e. /MeV)</td>
<td>3760</td>
<td>3970</td>
<td>4370</td>
<td></td>
</tr>
<tr>
<td>LY₁ (Photons /MeV)</td>
<td>29,150</td>
<td>30,780</td>
<td>33,880</td>
<td>5,200</td>
</tr>
<tr>
<td>LO₂ (p.e./MeV)</td>
<td>20.7</td>
<td>24.3</td>
<td>17.9</td>
<td>3.1</td>
</tr>
<tr>
<td>LY₂ (Photons /MeV)</td>
<td>479</td>
<td>563</td>
<td>414</td>
<td></td>
</tr>
<tr>
<td>MIP (p.e./55 MeV)</td>
<td>1,140</td>
<td>1,340</td>
<td>990</td>
<td>169</td>
</tr>
<tr>
<td>LO₂/LO₁ (%)</td>
<td>0.55</td>
<td>0.61</td>
<td>0.41</td>
<td></td>
</tr>
<tr>
<td>LO₂/LY₁ (%)</td>
<td>0.07</td>
<td>0.08</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>LY₂/LY₁ (%)</td>
<td>1.64</td>
<td>1.83</td>
<td>1.22</td>
<td></td>
</tr>
</tbody>
</table>


Measured light collection efficiencies consist with the LHCb data
A. Para, H. Wenzel, and S. McGill, Callor2012: GEANT simulations show a jet energy resolution at a level of 20%/\sqrt{E} after corrections.

R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry.
## Candidate Crystals for HHCAL

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Bi$_4$Ge$<em>3$O$</em>{12}$ (BGO)</th>
<th>PbWO$_4$ (PWO)</th>
<th>PbF$_2$</th>
<th>PbClF</th>
<th>Bi$_4$Si$<em>3$O$</em>{12}$ (BSO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (g/cm$^3$)</td>
<td>7.13</td>
<td>8.29</td>
<td>7.77</td>
<td>7.11</td>
<td>6.8</td>
</tr>
<tr>
<td>$\lambda_i$ (cm)</td>
<td>22.8</td>
<td>20.7</td>
<td>21.0</td>
<td>24.3</td>
<td>23.1</td>
</tr>
<tr>
<td>$n$ @ $\lambda_{\text{max}}$</td>
<td>2.15</td>
<td>2.20</td>
<td>1.82</td>
<td>2.15</td>
<td>2.06</td>
</tr>
<tr>
<td>$\tau_{\text{decay}}$ (ns)</td>
<td>300</td>
<td>30/10</td>
<td>?</td>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>$\lambda_{\text{max}}$ (nm)</td>
<td>480</td>
<td>425/420</td>
<td>?</td>
<td>400</td>
<td>470</td>
</tr>
<tr>
<td>Cut-off $\lambda$ (nm)</td>
<td>310</td>
<td>350</td>
<td>250</td>
<td>280</td>
<td>300</td>
</tr>
<tr>
<td>Light Output (%)</td>
<td>100</td>
<td>1.4/0.37</td>
<td>?</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>1050</td>
<td>1123</td>
<td>842</td>
<td>608</td>
<td>1030</td>
</tr>
<tr>
<td>Raw Material Cost (%)</td>
<td>100</td>
<td>49</td>
<td>29</td>
<td>29</td>
<td>47</td>
</tr>
</tbody>
</table>
Search for Scintillation in Doped PbF$_2$

116 samples tested

Will look performance at low temperature with the FLS920 fluorescence lifetime spectrometer

Doped PbF$_2$  Gamma ray excited (Gs-137)

Average value = 31 nA
Average value = 43 nA
Average value = 30 nA
Average value = 25 nA
Average value = 34 nA
Average value = 38 nA
Average value = 40 nA
Other Materials: PbFCl & BSO

<table>
<thead>
<tr>
<th>ID</th>
<th>PbFCl-1</th>
<th>PbFCl-2</th>
<th>PbFCl-3</th>
<th>PbFCl-4</th>
<th>PbFCl-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doping</td>
<td>--</td>
<td>Na 0.5at%</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Dimension (mm)</td>
<td>10x10x2</td>
<td>10x10x2</td>
<td>30x10x5</td>
<td>20x10x3</td>
<td>~10x10x9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ID</th>
<th>PWO</th>
<th>PbFCl-1</th>
<th>PbFCl-2</th>
<th>PbFCl-3</th>
<th>PbFCl-4</th>
<th>PbFCl-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-luminescence</td>
<td>Peaked @ 420 nm</td>
<td>100</td>
<td>14</td>
<td>64</td>
<td>33</td>
<td>35</td>
</tr>
<tr>
<td>L.O. (% PWO)</td>
<td>1.8</td>
<td>0.25</td>
<td>1.1</td>
<td>0.59</td>
<td>0.63</td>
<td>0.56</td>
</tr>
</tbody>
</table>

PbFCl Pure
PMT-R2059, HV = 2400 V, Gate = 50 ns
Na-22 Source

PbFCl Pure
PMT-R2059, HV = 2400 V, Gate = 50 ns
Na-22 Source

BGO
Source: Co-137
Gate = 1000 ns
Ped = 150 ch
Net peak = 500 ch
R.L.O. = 100%

Bi$_4$Si$_2$O$_{12}$ (1.5 X$_g$)

Light Output (p.e./MeV)

PWO ST
PMT-R2059, HV = 2400 V, Gate = 50 ns
Na-22 Source

Ped = 65, Net peak = 143

| LO = A_2 + A_1 (1 - e^{-t_2}) |
| A_2 | A_1 | t_2 |
| 0   | 11.6| 3.1 |

| LO = A_2 + A_1 (1 - e^{-t_1}) |
| A_2 | A_1 | t_1 |
| 0.0 | 65.1| 104 |
Future Calorimeter at the IF

Excellent energy resolution: a total absorption crystal calorimeter.

Good photon pointing for $\pi^0$ reconstruction: a longitudinally segmented crystal calorimeter.

A fast calorimeter with ten times rate capability as compared to existing calorimeters: crystals with sub nanosecond scintillation decay time. The figure of merit is the light in the 1st ns.
A Long. Segmented Crystal ECAL

May provide needed resolutions for energy, position and photon angle

With compact readout devices embedded in the detector
**Fast Scintillator: BaF$_2$ (ZnO:Ga, PbFCl, YAP:Yb, CuI)**

<table>
<thead>
<tr>
<th></th>
<th>LYSO:Ce</th>
<th>CsI</th>
<th>BaF$_2$</th>
<th>CeF$_3$</th>
<th>CeBr$_3$</th>
<th>LaBr$_3$:Ce</th>
<th>ZnO:Ga</th>
<th>PbFCl</th>
<th>Y$<em>{0.55}$Yb$</em>{0.45}$AlO$_3$</th>
<th>CuI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm$^3$)</td>
<td>7.40</td>
<td>4.51</td>
<td>4.89</td>
<td>6.16</td>
<td>5.23</td>
<td>5.29</td>
<td>5.67</td>
<td>7.11</td>
<td>6.59</td>
<td>5.61</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>2050</td>
<td>621</td>
<td>1280</td>
<td>1460</td>
<td>722</td>
<td>783</td>
<td>1975</td>
<td>608</td>
<td>1870</td>
<td>602</td>
</tr>
<tr>
<td>Radiation Length (cm)</td>
<td>1.14</td>
<td>1.86</td>
<td>2.03</td>
<td>1.70</td>
<td>1.96</td>
<td>1.88</td>
<td>2.51</td>
<td>1.05</td>
<td>1.67</td>
<td>1.71</td>
</tr>
<tr>
<td>$Z_{\text{eff}}$</td>
<td>64.8</td>
<td>54.0</td>
<td>51.6</td>
<td>50.8</td>
<td>45.6</td>
<td>45.6</td>
<td>27.7</td>
<td>75.8</td>
<td>52.6</td>
<td>47.1</td>
</tr>
<tr>
<td>$dE/dX$ (MeV/cm)</td>
<td>9.55</td>
<td>5.56</td>
<td>6.52</td>
<td>8.42</td>
<td>6.65</td>
<td>6.90</td>
<td>8.42</td>
<td>8.68</td>
<td>9.27</td>
<td>7.35</td>
</tr>
<tr>
<td>Emission Peak (nm)</td>
<td>420</td>
<td>420</td>
<td>300</td>
<td>340</td>
<td>371</td>
<td>356</td>
<td>389</td>
<td>400</td>
<td>350</td>
<td>410</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>1.82</td>
<td>1.95</td>
<td>1.50</td>
<td>1.62</td>
<td>1.9</td>
<td>1.9</td>
<td>2.1</td>
<td>2.1</td>
<td>1.96</td>
<td>2.1</td>
</tr>
<tr>
<td>Relative Light Yield</td>
<td>100</td>
<td>4.2</td>
<td>42.1</td>
<td>8.6</td>
<td>141</td>
<td>153</td>
<td>?</td>
<td>0.5</td>
<td>0.6 ?</td>
<td>2.2 ?</td>
</tr>
<tr>
<td>LY in 1st ns (photons)</td>
<td>740</td>
<td>100</td>
<td>960</td>
<td>85</td>
<td>2420</td>
<td>2240</td>
<td>?</td>
<td>51</td>
<td>497 ?</td>
<td>?</td>
</tr>
<tr>
<td>Decay Time (ns)</td>
<td>40</td>
<td>30</td>
<td>6</td>
<td>30</td>
<td>17</td>
<td>20</td>
<td>&lt;1</td>
<td>3</td>
<td>2.2 &lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>$d(LY)/dT$ (%/°C)</td>
<td>-0.2</td>
<td>-1.4</td>
<td>-1.9</td>
<td>~0</td>
<td>-0.1</td>
<td>0.2</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>40 keV Att. $\lambda$ (mm)</td>
<td>0.185</td>
<td>0.097</td>
<td>0.106</td>
<td>0.428</td>
<td>0.277</td>
<td>0.131</td>
<td>0.407</td>
<td>0.122</td>
<td>0.245</td>
<td>0.108</td>
</tr>
<tr>
<td>40 keV $\delta$ 90% (mm)</td>
<td>0.425</td>
<td>0.222</td>
<td>0.244</td>
<td>0.987</td>
<td>0.637</td>
<td>0.301</td>
<td>0.938</td>
<td>0.281</td>
<td>0.564</td>
<td>0.248</td>
</tr>
<tr>
<td>40 keV $\delta$ 95% (mm)</td>
<td>0.553</td>
<td>0.289</td>
<td>0.317</td>
<td>1.284</td>
<td>0.829</td>
<td>0.392</td>
<td>1.220</td>
<td>0.365</td>
<td>0.734</td>
<td>0.323</td>
</tr>
<tr>
<td>40 keV $\delta$ 99% (mm)</td>
<td>0.850</td>
<td>0.444</td>
<td>0.488</td>
<td>1.973</td>
<td>1.274</td>
<td>0.602</td>
<td>1.876</td>
<td>0.561</td>
<td>1.128</td>
<td>0.497</td>
</tr>
</tbody>
</table>

Rising Time for 1.5 $X_0$ Samples

Talk in the time resolution workshop at U. Chicago, 4/28/2011: Agilent MSO9254A (2.5 GHz) DSO with 0.14 ns rise time Hamamatsu R2059 PMT (2500 V) with rise time 1.3 ns

Measured rising time is dominated by photo-detector response, and is affected by light propagation in crystal.
BaF$_2$ for Very Fast Calorimeter

The fast component of BaF$_2$ crystals at 220 nm has a sub-ns decay time.

The slow component at 300 nm may be reduced by selective doping, such as La.

Spectroscopic selection of fast component may be achieved with solar blind photo-detectors or filters.

APD with built-in filter
BaF$_2$

BaF$_2$-ST

Transmittance (%)

Wavelength (nm)

BaF$_2$-ST 30×30×30 mm$^3$

PMT: XP2254B, HV = -1800 V, Gate = 50 ns,
Na-22 source, Coincidence Trigger
Ped = 63, Net peak = 58
LO = 175 p.e./MeV

BaF$_2$-ST 30×30×30 mm$^3$

Cs-137 Excited
PMT: R2059, HV = 2000 V
Readout by DSO
Agilent 9254

Pulse Height (V)

Time (ns)

Light Output (p.e./MeV)

Time (ns)

PH = $A_1e^{(-\nu_1t)} + A_2e^{(-\nu_2t)}$

$A_1 = 5.5$, $\tau_1 = 0.9$, $A_2 = 0.1$, $\tau_2 = 649$
PbFCl

PbFCl Pure
X-ray excited luminescence 295K
Em=400 nm

PbFCl Pure
PMT: R2059, HV = -2400 V, Gate = 50 ns
Na-22 Source
Ped = 65, Net peak = 129
LO = 14 p.e./MeV

PbFCl Pure
PMT: R2059, HV = -2400 V, Gate = 50 ns
Na-22 Source
Ped = 65, Net peak = 110
LO = 12 p.e./MeV

Ex = 368 nm  Em = 420 nm
τ = 1.30 ± 0.49 ns

PbFCl Pure
PMT: R2059, HV = -2400 V
Na-22 Source, Coincidence Trigger
Readout by DSO Agilent 9254

PbFCl Pure
PMT: R2059, HV = -2400 V, Na-22 source, PTFE Wrapped

Pulse Height (V)

Light Output (p.e./MeV)

Physics/Theory colloquium Presented at Los Alamos National Laboratory by Ren-Yuan Zhu, Caltech
M. Nikl et al, Appl. Phys. Lett., Vol. 84, No. 6,

Fast (0.87/2.2 ns) scintillation found in YAP:Yb with low light output

FIG. 1. Radioluminescence of Yb:YAP and BGO at RT. Excitation by x-ray tube, 35 kV, 15 mA. Quantitative comparison with respect to BGO is provided by the calculation of spectra integrals.

FIG. 3. Scintillation decay of Yb-0.45 at room temperature. Excitation by 511 keV photons of $^{22}$Na radioisotope, spectrally unresolved. The two-exponential approximation is given by a solid line: convolution of the two-exponential function in the figure with the instrumental response given by a dashed line. The coefficient alpha related to the relative amplitude of the superslow components calculated according Ref. 12 is also given.
YAP:Yb DJ20

- YAP:Yb 25% DJ20 20×20×20 mm³
  - Transmittance (%)
  - Theoretical limit of transmittance
  - Measured transmittance
  - Wavelength (nm)

- Counts
  - Channel Number

- YAP:Yb 25% DJ20 20×20×20 mm³
  - Raw data
  - Instrument Response
  - Fitted line
  - Ex = 260 nm  Em = 350 nm
  - $\tau = 1.09 \pm 0.41$ ns

- YAP:Yb 25% DJ20 20×20×20 mm³
  - Cosmic Ray Excited
  - PMT:R2059, HV=-2200 V
  - Readout by DSO Agilent 9254
  - PH = $A_0 + A_1 e^{(-t/\tau)}$
  - $A_0$, $A_1$, $\tau$ values provided
Summary

• Precision ECAL with good e/γ resolution may be built for CMS forward calorimeter upgrade at the HL-LHC by using blight, fast and rad hard LYSO crystals.

• Homogeneous hadron calorimeter with good jet mass resolution may be built for future lepton colliders by reading both Cherenkov and scintillation light for PbF$_2$, PbFCl and BSO.

• Crystal calorimeters with more than ten times faster rate/timing capability may be built for future HEP experiments at the intensity frontier by using the sub-ns decay time of BaF$_2$.

• Investigations on novel fast crystal scintillators, such as PbFCl, YAP:Yb, ZnO:Ga and CuI, may play important role for future HEP experiments.