Why Crystal Calorimeter in HEP?

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

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

• Crystals may also provide a foundation for a homogeneous hadron calorimeter with dual readout of Cherenkov and scintillation light to achieve good resolution for hadrons and jets.

• Crystals are also being considered to build sampling calorimeter for applications resolution is less crucial.
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>Density (g/cm³)</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>
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<td>Melting Point (°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>
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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>
<td>1.12</td>
<td>1.14</td>
<td>0.89</td>
<td>0.93</td>
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<tr>
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<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>
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<tr>
<td>Interaction Length (cm)</td>
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<td>39.3</td>
<td>39.3</td>
<td>30.7</td>
<td>22.8</td>
<td>20.9</td>
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<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>
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<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>?</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>1.1</td>
<td>36</td>
<td>21</td>
<td>85</td>
<td>0.3</td>
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<tr>
<td>d(LY)/dT b (%/ °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>

Experiment

<table>
<thead>
<tr>
<th>Crystal</th>
<th>BaBar</th>
<th>BELLE</th>
<th>BES III</th>
<th>KTeV (L*) (GEM)</th>
<th>L3 TAPS</th>
<th>BELLE KLOE-2 SuperB SLHC?</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>
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<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>
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<tr>
<td>Interaction Length (cm)</td>
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<td>39.3</td>
<td>37.6</td>
<td>37.0</td>
<td>30.4</td>
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<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>
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<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.

June 9, 2011
Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
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

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

with

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


No Self-absorption: BGO, PWO, BaF\textsubscript{2}, NaI(Tl) and CsI(Tl)
Scintillation Light Decay Time

Recorded with an Agilent 6052A digital scope

**Fast Scintillators**

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

**Slow Scintillators**

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

Slow Crystal Scintillators

LaBr₃

LaCl₃

LSO/LYSO

June 9, 2011

Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
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

- **Hamamatsu PMT, R1306**
  - BGO: QE=8.0 ± 0.4%
  - LSO/LYSO: QE=12.9 ± 0.6%
  - CsI(Tl): QE=5.0 ± 0.3%

- **Photonis PMT, XP2254B**
  - BGO: QE=4.7 ± 0.2%
  - LSO/LYSO: QE=7.2 ± 0.4%
  - CsI(Tl): QE=3.5 ± 0.2%

- **Hamamatsu APD, S8664-55**
  - BGO: QE=82 ± 4%
  - LSO/LYSO: QE=75 ± 4%
  - CsI(Tl): QE=84 ± 4%

- **Hamamatsu PD, S2744**
  - BGO: QE=75 ± 4%
  - LSO/LYSO: QE=59 ± 3%
  - CsI(Tl): QE=80 ± 4%
L.O. Temperature Coefficient

Temperature Range: 15 - 25ºC

Large temperature coefficient: CsI, BGO, 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

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

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

Energy (KeV)

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

Good crystals: BGO and LaBr\(_3\)
### Crystal Calorimeters in HEP

#### Future crystal calorimeters in HEP:
- PWO for PANDA at GSI
- LYSO for Mu2e, Super B and HL-LHC, also a Shashlic
- PbF$_2$, PbFCl, BSO for Homogeneous HCAL

<table>
<thead>
<tr>
<th>Date</th>
<th>75-85</th>
<th>80-00</th>
<th>80-00</th>
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<th>90-10</th>
<th>94-10</th>
<th>94-10</th>
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<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>
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<td>Accelerator</td>
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<td>LEP</td>
<td>CESR</td>
<td>LEAR</td>
<td>FNAL</td>
<td>SLAC</td>
<td>KEK</td>
<td>CERN</td>
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<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>
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<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>
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<td>$r_{inner}$ (m)</td>
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<td>0.55</td>
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<td>0.27</td>
<td>-</td>
<td>1.0</td>
<td>1.25</td>
<td>1.29</td>
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<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>
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<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>
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<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>
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<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>
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<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>
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<td>Gain of Photosensor</td>
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<td>1</td>
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<td>1</td>
<td>4,000</td>
<td>1</td>
<td>1</td>
<td>50</td>
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<td>$\sigma_N$/Channel (MeV)</td>
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<td>0.8</td>
<td>0.5</td>
<td>0.2</td>
<td>small</td>
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<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>
Crystal Calorimeter Resolution

6.6k CsI(Tl)

12k BGO

$$\frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt{E}} \oplus \sigma_2$$

$$\sigma_1 = (2.30 \pm 0.03 \pm 0.3)\%$$

$$\sigma_2 = (1.35 \pm 0.08 \pm 0.2)\%$$

June 9, 2011

Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
CMS PWO Calorimeter

Measured Resolution

\[ \sigma(E)/E < 1\% \text{ if } E > 25 \text{ GeV} \]

\[ \sigma(E)/E \sim 0.5\% \text{ at } 120 \text{ GeV} \]

Designed Resolution

76k PWO

Measured Resolution

\[ \sigma(E)/E < 1\% \text{ if } E > 25 \text{ GeV} \]

\[ \sigma(E)/E \sim 0.5\% \text{ at } 120 \text{ GeV} \]
PANDA at GSI, Germany

AntiProton annihilations at DArmstadt

8 - 12,000 modules
~ 20 X₀ deep

1400 220 50 1 m

17,000 PWO

June 9, 2011

Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
LYSO ECAL for Mu2e

Four-vane calorimeter, comprised of 2400 LYSO crystals of 30 x 30 x 130 mm
LYSO Endcap for SuperB

The proposed SuperB ECAL endcap comprising 4400 LYSO crystals in projective geometry

Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
A large size ingot of $\Phi 60 \times 310$ mm was grown at SIPAT in 2009 and a $2.5 \times 2.5 \times 28$ cm LYSO sample was obtained.

- Photo-luminescence, transmission, light output and light response uniformity (LRU) were evaluated.
- Radiation hardness against $^{137}\text{Cs}$ $\gamma$-rays up to 1 Mrad @ 7.5k rad/h were measured.
- Progress on optical transmittance for large size LYSO will be addressed.
Light response uniformity at a few percents observed for both PMT and APD readouts.
Energy Resolution for 0.511 MeV γ-rays

Corresponding FWHM energy resolution at seven points along the crystal was measured by using an R1306 PMT to be 12.4% in average.

June 9, 2011
Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
\( ^{137}\text{Cs} \) \( \gamma \)-rays up to 1 Mrad @ 7.5k rad/h: 9.6%

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

**SIPAT-LYSO-L7**

From top to bottom:
- 0 rad
- \(10^2\) rad
- \(10^4\) rad
- \(10^6\) rad

**Transmittance (%)**

**Wavelength (nm)**

**SIPAT-LYSO-L7**

**Transmittance (%)**

**Wavelength (nm)**

**EWLT (from top to bottom):**
- As, 48.8%
- \(10^5\) rad, 47.7%
- \(10^4\) rad, 46.9%
- \(10^6\) rad, 44.1%
Damage in L.O. and Uniformity

$^{137}$Cs $\gamma$-rays up to 1 Mrad @ 7.5k rad/h: 12 ~ 14%
Light response uniformity is maintained

Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
LYSO is Radiation Hard against Charged Hadrons

G. Dissertori, D. Luckey, P. Lecomte, Francesca Nessi-Tedaldi, F. Pauss, IEEE NSS09, N32-3

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

June 9, 2011
Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
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:

\[
2.0\%/\sqrt{E} \oplus 0.5\% \oplus 0.001/E
\]
Encouraging resolution measured at BTF, Frascati, with non uniformized LYSO crystals. Another test beam is planned at MAINZ after crystal uniformization.

E. Monoli, SuperB Elba Meeting, 5/28/11
An LYSO Shashlic ECAL

R.-Y. Zhu, CMS Forward Calorimetry Meeting at CERN, 6/17/10

Issues: Radiation hardness of the photo-detector and the WLS fiber

Energy resolution

\[ \sigma = \frac{10\%}{E} \oplus 1\% \]
Homogeneous Hadron Calorimeter

A Fermilab team (A. Para et al.) proposed a total absorption homogeneous HCAL detector concept to achieve good jet mass resolution by measuring both Cherenkov and Scintillation light. It also eliminates the dead materials between classical ECAL and HCAL. This longitudinal segmented crystal HCAL is possible because of the latest development in large area compact readout devices.

Requirements for the materials to be used for HHCAL:

- Short nuclear interaction length: ~ 20 cm.
- Good UV transmittance: UV cut-off < 350 nm.
- Some scintillation light, not necessary bright and fast.
- Cost-effective material: < $2/cc for 100 m³!
- Radiation hardness is not crucial at the ILC/CLIC.

A series of workshops on material development for HHCAL:

1st 2/19/2008 at SIC, Shanghai, 2nd 5/9/2010 at IHEP, Beijing, 3rd 10/30/2010 at Knoxville, will go with SCINT, CALOR & IEEE NSS.
HHCAL Design

Corrected jet response and energy resolution, energy dependence

Corrected energy, 20 GeV
Corrected energy, 50 GeV

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.

Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech

R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry, 11/18/08
# Candidate Crystals for HHCAL

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Bi₄Ge₃O₁₂ (BGO)</th>
<th>PbWO₄ (PWO)</th>
<th>PbF₂</th>
<th>PbClF</th>
<th>Bi₄Si₃O₁₂ (BSO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p (g/cm³)</td>
<td>7.13</td>
<td>8.29</td>
<td>7.77</td>
<td>7.11</td>
<td>6.8?</td>
</tr>
<tr>
<td>λ₁ (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 @ λ_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>τ_decy (ns)</td>
<td>300</td>
<td>30/10</td>
<td>?</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>λ_max (nm)</td>
<td>480</td>
<td>425/420</td>
<td>?</td>
<td>420</td>
<td>470</td>
</tr>
<tr>
<td>Cut-off λ (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>17</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>
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

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

Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
Scintillation Selected with Filters

UG11/GG400 optical filter effectively selects Cherenkov/scintillation light

Transmittance (%)

Wavelength (nm)

Em BGO (a.u.)

(θ = 10°)

Em PWO (a.u.)

(θ = 10°)

June 9, 2011

Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
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.
1.6% for BGO and 22% for PWO with UG11/GG400 filter and R2059 PMT, which is configuration dependent.
A total of 116 samples with various rare earth doping were grown by vertical Bridgman method at SIC and Scintibow.

- SIC samples: grown in platinum crucible, 1.5 \( X_0 \) (14 mm) cube.
- Scintibow samples: grown in graphite crucible, \( \Phi \) 22 x 15 mm.
Luminescence Observed in PbF$_2$

Consistent Photo- and X-luminescence observed in doped PbF$_2$ samples grown by Prof. Dingzhong Shen of SIC/Scintibow.
Rare Earth Doped PbF$_2$

Multi-ms decay time observed, indicating f-f transitions of these rare earth elements which is too slow to be useful.

Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
Anode current measured for doped PbF2 samples is at the same level as undoped crystals, indicating weak light.
BSO Crystals

Hu Yuan of SIC: Talk at the 2nd Workshop for HHCAL

Nov. 2008: Φ2.5 x 12 cm

Feb. 2009 Φ2 x 17 cm

May 2009 Φ5.5 x 12 cm

Oct. 2009: 2 x 18 cm

Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
A $\Phi 22 \times 105$ mm BSO shows good UV absorption edge and about 12% light output of a BGO cube with decay time 100 ns.
PbClF Crystals

Guohao Ren of SIC: Talk at the 2nd Workshop for HHCAL

Crystal structure of PbClF

D = 7.11g/cm³
Melting point = 608°C
Space group = P/4nmm
a = 4.10Å; c = 7.22Å

PbClF Crystal samples grown at SICCAS
## PbFCl Samples

<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><strong>Doping</strong></td>
<td>--</td>
<td>Na 0.5at%</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td><strong>Dimension (mm)</strong></td>
<td>10x10x2</td>
<td>10x10x2</td>
<td>30x10x5</td>
<td>20x10x3</td>
<td>~10x10x9</td>
</tr>
</tbody>
</table>

### X-luminescence

<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><strong>X-luminescence</strong></td>
<td></td>
<td>Peaked @ 420 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L.O. (% PWO)</td>
<td>100</td>
<td>14</td>
<td>64</td>
<td>33</td>
<td>35</td>
<td>31</td>
</tr>
<tr>
<td>L.O. (% BGO)</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>
Consistent X-luminescence peaked at 420 nm observed in all PbFCl samples.

Transmittance cut-off at 300 nm.

Weak scintillation light with decay time of 24 ns observed in all PbFCl samples.

June 9, 2011
Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
Scintillating Ceramics at SICCAS

Highly transparent RAG-based scintillation ceramics were prepared and their properties characterized.

The scintillation properties of these ceramics may be optimized to fit the concept of the HHCAL detector.

XEL Spectra, Decay curve and Transmittance of YAG based ceramics

June 9, 2011

Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
Highly transparent BSO-based glasses were prepared and their properties characterized.

The scintillation properties of BSO glasses may be modified and optimization are undergoing to fit the concept of the HHCAL detector.
Summary

- Homogeneous crystal ECAL provides good resolutions for $e/\gamma$ measurements. An LSO/LYSO ECAL may provide excellent energy resolution over a large dynamic range down to MeV level.

- Homogeneous hadronic calorimeter (HHCAL) 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 $\text{PbF}_2$, $\text{PbClF}$ and BSO are the best crystal candidates. Scintillating glasses and ceramics are also being considered.

- LSO/LYSO plates have also be proposed for a Shashlic type sampling calorimeter for HL-LHC. Scintillating glasses and ceramics may also fit in this application if radiation hard.
1) HHCAL and General Requirement:

Gene Fisk, FNAL: “Fermilab's History in the Development of Crystals, Glasses and Si Detector Readout for Calorimetry”
Adam Para, FNAL: “Scintillating Materials for Homogeneous Hadron Calorimetry”
Steve Derenzo, LBL: “Search for Scintillating Glasses and Crystals for Hadron Calorimetry”
Paul Lecoq, CERN: “A CERN Contribution to the Dual Readout Calorimeter Concept”

2) Materials for HHCAL (I):

Alex Gektin, SCI: “Crystal Development for HHCAL: Physics and Technological Limits”
Liyuan Zhang, Caltech: “Search for Scintillation in Doped Lead Fluoride for the HHCAL Detector Concept”
Guohao Ren, SIC: “Development of Halide Scintillation Crystals for the HHCAL Detector Concept”
Hui Yuan, SIC: “BSO Crystals Development with the Modified Multi-crucible Bridgman Method for the HHCAL Detector Concept”

3) Materials for the HHCAL (II) followed by discussions

Mingrong Zhang, BGRI: “R&D on Scintillation Crystals and Special Glasses at BGRI”
Tiachi Zhao, U Washington/IHEP and Ningbo University: “Study of Dense Scintillating Glass Samples”
Jing Tai Zhao, SIC: “Status of Scintillating Ceramics and Glasses at SIC and Their Potential Applications for the HHCAL Detector Concept”
Richard, Wigmans, Texas Tech University: “Some thoughts about homogeneous dual-readout calorimeters”
3rd Workshop for the HHCAL

October 31, 2010, Knoxville: http://www.nss-mic.org/2010/program/ListProgram.asp?session=HC1,2,3,4

1. A. Para, Prospects for High Resolution Hadron Calorimetry
2. G. Mavromanolakis, Studies on Dual Readout Calorimetry with Meta-Crystals
3. D. Groom, Degradation of resolution in a homogeneous dual readout hadronic calorimeter
4. S. Derenzo, High-Throughput Synthesis and Measurement of Candidate Detector Materials for Homogeneous Hadronic Calorimeters
6. I. Dafinei, High Density Fluoride Glasses, Possible Candidates for Homogeneous Hadron Calorimetry
7. P. Hobson, Prospects for Dense Glass Scintillators for Homogeneous Calorimeters
8. G. Dosovitski, Potential of Crystalline, Glass and Ceramic Scintillation Materials for Future Hadron Calorimetry
9. Tianchi Zhao, Study on Dense Scintillating Glasses
10. Jin-tai Zhao, BSO-Based Crystal and Glass Scintillators for Homogeneous Hadronic Calorimeter
11. Guohao Ren, Development of RE-Doped Cubic PbF2 and PbClF Crystals for HHCAL
12. N. Cherepy, Transparent Ceramic Scintillators for Hadron Calorimetry
13. J. Dong, Experimental Study of Large Area GEM
14. H. Frisch, The Development of Large-Area Flat-Panel Photodetectors with Correlated Space and Time Resolution