Towards a Large Calorimeter based on LYSO Crystals for Future High Energy Physics

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Overview

1. Introduction
2. Simulation
3. Results
4. Conclusion
The Need for High Precision Calorimetry

... to find evidence for BSM physics in testing SM predictions to an unprecedented accuracy.

Charged Lepton Flavour Violation

- Looking for decays like $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$ etc.
- Prohibited by the SM, predicted by some BSM theories.

The Legendary Needle in the Haystack: $\mu \rightarrow e\gamma$ [1, 2]

Signal

![Signal Diagram]

Prompt Background

![Prompt Background Diagram]

Accidental Background

![Accidental Background Diagram]

Is the branching ratio $BR(\mu \rightarrow e\gamma) > 6 \times 10^{-14}$?

$R_{acc} \propto R_{\mu}^2 \cdot \Delta E_{\gamma}^2 \cdot \Delta P_{e} \cdot \Delta \Theta_{e\gamma}^2 \cdot \Delta t_{e\gamma}$

Affected by calorimeter performance
LYSO vs. Lanthanum Bromide
Short Radiation Length vs. High Light Yield and Fast Decay

### Selection of Scintillating Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $\rho$ (g/cm$^3$)</th>
<th>Light Yield $LY$ (ph/keV)</th>
<th>Decay Time $\tau$ (ns)</th>
<th>Radiation Length $X_0$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaBr$_3$(Ce)</td>
<td>5.08</td>
<td>63</td>
<td>16</td>
<td>2.1</td>
</tr>
<tr>
<td>LYSO</td>
<td>7.1</td>
<td>27</td>
<td>41</td>
<td>1.21</td>
</tr>
<tr>
<td>NaI(Tl)</td>
<td>3.67</td>
<td>38</td>
<td>245</td>
<td>2.59</td>
</tr>
<tr>
<td>BGO</td>
<td>7.13</td>
<td>9</td>
<td>300</td>
<td>1.12</td>
</tr>
</tbody>
</table>

### Crystal Sizes Previously Investigated [3, 4, 5]

| Material  | LYSO | | LaBr$_3$(Ce) |
|-----------|------||---------------|
|           | Diameter | Length | Diameter | Length |
| “Available” | 7 cm    | 16 cm   | 9 cm     | 20 cm  |
| “Large”    | 15 cm   | 16 cm   | 15 cm    | 20 cm  |
| “Ultimate” | 40 cm   | 17 cm   | 46 cm    | 31.5 cm|
Prototype Configuration

- Goal: Detect Photons of $O(50\,\text{MeV})$
- Attach SiPMs to LYSO or LaBr$_3$(Ce) to build calorimeter.
- Thin SiPMs allow readout on front and back.
- Use granularity for geometrical reconstruction.
Better charge resolution for LYSO due to larger energy leakage through lateral side in LaBr₃(Ce).
- Time resolution around 30 ps for both.
- Position resolution around 3 mm perpendicular to the crystal axis for both.

⇒ Prefer LYSO over LaBr₃(Ce)
Potential Use of Larger Crystals
Towards future High Precision Calorimeters

Combine multiple large crystals (e.g. 25 cm × 25 cm × 15 cm)
Tracking Optical Photons

Photons detected per SiPM on the inner surface of a crystal

$x = -81.1, y = 87.9$
Variable Estimation Algorithms

**Time:** Estimate from front and back times $t_f, t_b$

$$t = \frac{(n - 1)t_f + (n + 1)t_b - L/c(n^2 + n)}{2n}$$

**Position:** Estimate from granular charge collection and time

$$x, y : \text{Gaussian Fit}$$

$$z = \frac{1}{2} \left( \frac{c}{n} * (t_f - t_b) + L \right)$$

**Charge:** Sum integrated charge over all channels

$$Q_{tot} = \sum q_i$$

$$Q_{tot}^{(2)} = \frac{Q_{tot}}{1 - a(x^2 + y^2)}$$
Charge Reconstruction

Before Correction

Charge vs. Position

Q (a.u.)

Pos
Charge Reconstruction

After Correction

Charge vs. Position

1.2
1.25
1.3
1.35
1.4
1.45
1.5
1.55
1.6
1.65
1.7
(a.u.)

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

Q\textsuperscript{(2)} (a.u.)

Pos
Charge Resolution

Charge

\[ Q(2) \text{ (a.u.)} \]

- Photons: \( \sigma/\mu = 0.768(14) \% \)
- Positrons: \( \sigma/\mu = 1.25(2) \% \)
Geometrical Cuts

![Plot showing the relationship between efficiency and resolution for two different calculations, Qtot and Qtot2.](image-url)
Position Resolution

![X Reconstruction Diagram]

Photons: \( \sigma = 3.95(4) \text{ mm} \)
Positrons: \( \sigma = 5.44(5) \text{ mm} \)
Time Resolution

![Time Resolution Graph]

- Photons
  - \( \sigma = 0.0321(2) \) ns
- Positrons
  - \( \sigma = 0.0321(2) \) ns
## Conclusion

### Promising Results
- Energy resolution below 1% for 55 MeV photons.
- Position resolution below 5 mm
- Time resolution below 40 ps

### Far Future Plans
There is still a long way to go until such crystals can be grown.

### Not so Far Future Plans
Instead of large single crystals, build a calorimeter from smaller, tapered crystals. [6]
Acknowledgements

Co-Authors

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Xenon Calorimeter Calibration by Charge Exchange

**Configuration**

**Charge Exchange Reaction**

\[ \pi^- \text{beam on LH2 target} \]

\[ \pi^- p \rightarrow \pi^0 n \]

\[ \pi^0 \text{decays in flights} \]

\[ \pi^0 \rightarrow \gamma \gamma \]

\[ 54.9 \text{ MeV} \leq E_\gamma \leq 82.9 \text{ MeV} \]

Extremal for \( \Theta_{\gamma\gamma} = 180^\circ \)

Require AUX detector to assert \( \Theta_{\gamma\gamma} = 180^\circ \) and thus 55 MeV (83 MeV) \( \gamma \) in calorimeter. Opportunity to test prototypes.
Applying Geometrical Cuts

Charge

Counts (a.u.)

- Uncut
- $\sigma/\mu = 2.67(12)\%$
- MC Truth Cut
- $\sigma/\mu = 2.06(10)\% \quad \varepsilon = 0.402$
- Rec. Pos Cut
- $\sigma/\mu = 2.13(11)\% \quad \varepsilon = 0.400$
- Skewness Cut
- $\sigma/\mu = 2.06(10)\% \quad \varepsilon = 0.438$
- Unspread (scaled)
- $\sigma/\mu = 1.69(6)\%$

$q$ (a.u.) $\times 10^3$
Better energy resolution for larger diameters.
Ultimate Crystals

**Charge**

<table>
<thead>
<tr>
<th>Crystal Configuration</th>
<th>Charge Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LYSO (R = 20 cm, L = 17 cm) + sensL</td>
<td>0.242(4) %</td>
</tr>
<tr>
<td>LYSO (R = 20 cm, L = 17 cm) + Hamamatsu</td>
<td>0.334(5) %</td>
</tr>
<tr>
<td>LaBrCe (R = 23 cm, L = 31.5 cm) + sensL</td>
<td>0.196(4) %</td>
</tr>
<tr>
<td>LaBrCe (R = 23 cm, L = 31.5 cm) + Hamamatsu</td>
<td>0.304(5) %</td>
</tr>
</tbody>
</table>

Time resolution $\mathcal{O}(30\text{ ps})$, Position resolution $\mathcal{O}(5\text{ mm})$. 
Summary of LYSO Prototype Studies

Resolutions

<table>
<thead>
<tr>
<th></th>
<th>LaBr₃(Ce)</th>
<th>LYSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (%)</td>
<td>2.5 / 0.9 / 0.3</td>
<td>1.7 / 0.4 / 0.3</td>
</tr>
<tr>
<td>Time (ps)</td>
<td>28 / 30 / 39</td>
<td>26 / 28 / 36</td>
</tr>
<tr>
<td>x Position (mm)</td>
<td>3 / 3.7 / 5.7</td>
<td>2.4 / 3.0 / 3.6</td>
</tr>
<tr>
<td>z Position (mm)</td>
<td>4 / 4.8 / 5.4</td>
<td>4.4 / 5 / 6</td>
</tr>
</tbody>
</table>

Values refer to available/ large/ ultimate crystals.

Conclusion

- Light yield is not the limiting factor for the resolutions.
- LYSO performs better due to higher density.

Prototype using a LYSO crystal with 10 cm length and 7 cm diameter is under construction.
SiPMs

<table>
<thead>
<tr>
<th></th>
<th>Hamamatsu</th>
<th>sensL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>S13360-6025PE</td>
<td>MicroFJ-60035TSV</td>
</tr>
<tr>
<td>Size (mm$^2$)</td>
<td>7.35 × 6.85</td>
<td>6.13 × 6.13</td>
</tr>
<tr>
<td>Active Area (mm$^2$)</td>
<td>6.0 × 6.0</td>
<td>6.07 × 6.07</td>
</tr>
<tr>
<td>Number of Pixels</td>
<td>57 600</td>
<td>22 292</td>
</tr>
<tr>
<td>Fill Factor (%)</td>
<td>47</td>
<td>75</td>
</tr>
<tr>
<td>PDE (%)</td>
<td>25</td>
<td>38 to 50</td>
</tr>
</tbody>
</table>
"Available" LYSO crystal has defects ...

Closest size: 7.5 cm diam., 10 cm length.
No significant decrease in performance.
Further Reading I


Development of new large calorimeter prototypes based on LaBr₃(Ce) and LYSO crystals coupled to silicon photomultipliers: A direct comparison. 

Study of 3D calorimetry based on LYSO or LaBr₃:Ce crystals for future high energy precision physics. 

PSI Ring Cyclotron Proposal R-22-01.1. 