Development of a new large calorimeter prototypes based on LaBr$_3$(Ce) and LYSO crystals coupled to silicon-photomultipliers

Monte Carlo simulations: A direct comparison

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Content

• Introduction

• Crystal main properties

• Photosensors: MPPC/SiPM

• Detector layout

• Monte Carlo simulation predictions: from point-like to extended impinging radiation. Part I and Part II
Motivations

• The aim of this study is to explore the possibility of a new calorimetry based on new crystals coupled to MPPC/SiPM able to work at relative high energy $\mathcal{O}(50-100)$ MeV and to sustain high rate (regime: Intensity Frontiers) for simultaneously:

  • Excellent energy resolution ($\sigma_E/E \leq 1\% @ E \sim 50$ MeV)

  • Ultra-precise timing resolution ($\sigma_t. \leq 50$ ps)

  • 3D event reconstruction ($\sigma_{tx,y,z} \leq 10$ mm)
A new calorimetry for future cLFV researches

- The MEGII experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of $\sim 6 \times 10^{-14}$ (previous upper limit $\text{BR}(\mu^+ \rightarrow e^+ \gamma) \leq 4.2 \times 10^{-13}$ at 90 C.L. by MEG experiment)

- Five observables ($E_g$, $E_e$, $t_{eg}$, $\theta_{eg}$, $\phi_{eg}$) to characterize $\mu \rightarrow e \gamma$ events
MEGII: The upgraded LXe calorimeter

- Increased uniformity/resolutions
- Increased pile-up rejection capability
- Increased acceptance and detection efficiency
- Assembly: Completed
- Detector filled with LXe
- Purification: Ongoing
- Monitoring and calibrations with sources: Ongoing

<table>
<thead>
<tr>
<th></th>
<th>MEG</th>
<th>MEGII</th>
</tr>
</thead>
<tbody>
<tr>
<td>u [mm]</td>
<td>5</td>
<td>2.4</td>
</tr>
<tr>
<td>v [mm]</td>
<td>5</td>
<td>2.2</td>
</tr>
<tr>
<td>w [mm]</td>
<td>6</td>
<td>3.1</td>
</tr>
<tr>
<td>E [w&lt;2cm]</td>
<td>2.4%</td>
<td>1.1%</td>
</tr>
<tr>
<td>E [w&gt;2cm]</td>
<td>1.7%</td>
<td>1.0%</td>
</tr>
<tr>
<td>t [ps]</td>
<td>67</td>
<td>60</td>
</tr>
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</table>

900 L of Xe
MEGII: A new auxiliary detector for the LXe calibration

- Two folded aims:
  - Auxiliary detector for selecting back-to-back gammas at 55 and 83 MeV for the full characterisation of the MEGII LXe calorimeter at the MEGII signal
  - Prototype for larger based crystal calorimeter for future cLFV and muon physics searches
The LaBr₃(:Ce) and LYSO main properties

- LaBr₃(:Ce): Ideal medium due to ultra high light yield LY (1.65 x LY(NaI)), ultra-fast response, high density (relative compact size)

- LYSO: Very attractive medium (excellent alternative to LaBr₃(:Ce)). The very-high density and the fast response compensate for the reduced LY (0.70 x LY(NaI))

- Comparison with other scintillators via the figure of merite F.o.M. = \( \sqrt{\frac{\rho \cdot LY}{\tau}} \)

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Density ( \rho ) [g/cm(^3)]</th>
<th>Light Yield LY [ph/keV]</th>
<th>Decay time ( \tau ) [ns]</th>
<th>F.o.M. ( \sqrt{\frac{\rho \cdot LY}{\tau}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaBr₃(:Ce)</td>
<td>5.08</td>
<td>63</td>
<td>16</td>
<td>4.55</td>
</tr>
<tr>
<td>LYSO</td>
<td>7.1</td>
<td>27</td>
<td>41</td>
<td>2.17</td>
</tr>
<tr>
<td>YAP</td>
<td>5.35</td>
<td>22</td>
<td>26</td>
<td>2.13</td>
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<tr>
<td>LXe</td>
<td>2.89</td>
<td>40</td>
<td>45</td>
<td>1.61</td>
</tr>
<tr>
<td>NaI(Tl)</td>
<td>3.67</td>
<td>38</td>
<td>250</td>
<td>0.75</td>
</tr>
<tr>
<td>BGO</td>
<td>7.13</td>
<td>9</td>
<td>300</td>
<td>0.46</td>
</tr>
</tbody>
</table>
The LaBr₃(:Ce) for high energy gamma calorimetry

Status:
• Well established low energy gamma calorimetry with detector sizes of (Diameter x Length): 1”x1”, 2”x2” and 3”x3”
• In rapid development for PET applications

Prospects for high energy gamma calorimetry O(50 MeV) at high rate (intensity frontiers):
• Challenge: **Large size crystals**
  Desired: 5” x 8-10”, recently commercially available: 3.5” x 8” (Saint Gobain), under test: 3.5” x 9”
• Photosensors: multi-pixel photon counter/silicon photomultiplier (MPPC/SiPM)
• **For the first time** a large crystal coupled to MPPC to fully exploit the detector performances at high gamma energy

**Detector:**
3” x 3” LaBr₃(:Ce) coupled to a Photomultiplier PM XP53A2B

**i.e. 2” x 2”**
M. Ciemał et al. NIMA 608 (2009) 76–79

**i.e. 3” x 3”**
L. Galli et al. NIMA 718 (2013) 48-51

**Energy spectra**

**Energy response Linearity**
The Photosensors

- The high LY and the short radiation length $X_0$ point towards relative small pixel size ($< 50$ um)
- Trade-off between DAQ channels and granularity: sensor size
- Two candidates: Hamamatsu S13360-6025 and SensL MicroFJ-60035TSV; active area 6 x 6 mm$^2$, pixel size respectively 25 um and 35 um

<table>
<thead>
<tr>
<th></th>
<th>Package [mm$^2$]</th>
<th>Active area [mm$^2$]</th>
<th>No. Of pixels</th>
<th>Fill factor [%]</th>
<th>PDE [%]</th>
<th>PCB cov. [%]</th>
<th>F.o.M*</th>
</tr>
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<tbody>
<tr>
<td>Hamamatsu</td>
<td>7.35 x 6.85</td>
<td>6.0 x 6.0</td>
<td>57600</td>
<td>47</td>
<td>20-25</td>
<td>69</td>
<td>8.9</td>
</tr>
<tr>
<td>sensL</td>
<td>6.13 x 6.13</td>
<td>6.07 x 6.07</td>
<td>22292</td>
<td>75</td>
<td>40-50</td>
<td>91</td>
<td>9.1</td>
</tr>
</tbody>
</table>

(*) F.o.M. = \( \frac{\text{No pixel} \times \text{PDE} \times \text{PCB cov.}}{1000} \)

LaBr₃(Ce) emission spectrum
LYSO emission spectrum
Detector layout

The first large crystal assembly for high energy gamma detection 0(50) MeV with a MPPC/SiPM (d) double readout scheme for:

- Maximal photosensor coverage area
- Optimal geometrical acceptance
- Very high photosensor granularity
- High rate sustainability
- Optimum energy, timing and position resolutions: 5D kinematical variable reconstruction
- Insensitive to magnetic field
- LaBr3(Ce) 4.45 (R) x 20.32 (L) cm or LYSO 3.5 (R) x 16 (L) cm
- Photosensors: Hamamatsu 240/152; sensL 336/214

FR4 PCB feedthroughs equipped with MCX connectors

200 um thick carbon fiber

Flex-print cables to connect the MPPC board to the feedthroughs

2.5 mm thick quartz window

1.5 mm thick Al2O3 PCB where the MPPC/SiPM are soldered
The Double readout out scheme with MPPC/SiPM

- The advent of the MPPC open the door to a more performing detector with a double readout
  - Larger photocathode coverage wrt single readout (i.e. old scheme with PMT)
  - Further benefit: Energy deposit near the front/entrance face
- For hygroscopic crystals (LaBr₃(Ce)): double quartz window sealed inside a thin Al case

![Diagram showing Front and Back Readout](image)

(a) Hit in Central Region: \((x, y) = (-10 \text{ mm}, 3 \text{ mm})\)
Part I: Intrinsic kinematical variable resolutions

- Basic Monte Carlo simulation input
- Point-like impinging source: 55 MeV gammas
- Crystal sizes:
  - Available on the market (custom production)
    - $\text{LaBr}_3(\text{Ce})$ (R,L) = (4.45, 20.32) cm [R = Radius, L = Length]
    - LYSO (R,L) = (3.5, 16) cm
  - Ideal
    - $\text{LaBr}_3(\text{Ce})$ (R,L) = (7.62, 22.86) cm
    - LYSO (R,L) = (6.5, 20) cm
- Photosensors:
  - Hamamatsu S13360-6025PE and SensL MicroFJ-60035TSV
The Double readout: The photon collection

- Crystal: LaBr3(Ce), radius (R) 4.45 cm x length (L) 20.32 cm
- Photosensor: Hamamatsu S13360-6025PE
- Radiation: point-like 55 MeV gammas

\[ f(x|N, \mu, \sigma_1, \sigma_2, \sigma_3) = \begin{cases} N \exp \left( -\frac{(x-\mu)^2}{2(\sigma_1)^2} \right) & \text{if } x > \mu \\ N \exp \left( -\frac{(x-\mu)^2}{2(\sigma_1+\sigma_2(x-\mu)+\sigma_3(x-\mu)^2)^2} \right) & \text{if } x < \mu \end{cases} \]

Energy deposit: unaffected
Number of photons and energy resolution: affected
The Size of the crystal: The shower containment

- Crystal: LaBr3(Ce), variable sizes - see legend
- Photosensor: Hamamatsu S13360-6025PE
- Radiation: point-like 55 MeV gammas

Energy deposit

Number of photons and energy resolution

\[ \sigma\sqrt{N} \% = 2.4 \Rightarrow 1.0 \]
The Crystal type: The energy resolution

- Crystal: LaBr3(Ce) and LYSO, variable sizes: What available in the market and desirable - see legend
- Photosensor: Hamamatsu S13360-6025PE
- Radiation: point-like 55 MeV gammas
- Although LaBr3(Ce) ( ■ and ■ ) has x2 LY of LYSO ( ■ and ■ ) and provides better photon statistics the resolution of LaBr3(Ce) is limited by the energy leakage. Available LYSO crystals perform better than available LaBr3(Ce) crystals.
The Photosensor type: The energy resolution

- Crystal: LaBr3(Ce) with size (R,L) = (4.45, 20.32) and LYSO with size (R,L) = (3.5, 16) cm
- Photosensor: Hamamatsu S13360-6025PE and SensL MicroFJ-60035TSV
- Radiation: point-like 55 MeV gammas
- **Hamamatsu vs SensL**: The first offers x2 pixels than the second (i.e. smaller size) yet the second has a significantly increased (x2) PDE and a smaller support structure. This suggests that sensL MPPC/SiPM will collect more photons yet more susceptible to saturation effect due to the larger pixel size.

LaBr3(Ce) vs LYSO:

\[
\frac{\sigma_E}{E} \text{ [\%]} = 2.4 \Rightarrow 2.3
\]

\[
\frac{\sigma_E}{E} \text{ [\%]} = 1.5 \Rightarrow 1.3
\]
The Photosensor type: The pixel saturation

- Crystal: LaBr3(Ce) with size \((R,L) = (4.45, 20.32)\) cm and LYSO with size \((R,L) = (3.5, 16)\) cm
- Photosensor: Hamamatsu S13360-6025PE and SensL MicroFJ-60035TSV
- Radiation: point-like 55 MeV gammas
- Saturation effect: LYSO \(\text{vs}\) , LaBr3(Ce) \(\text{vs}\)
The timing resolution

- Crystal: LaBr$_3$(Ce) with size (R,L) = (4.45, 20.32) and LYSO with size (R,L) = (3.5, 16) cm
- Photosensor: Hamamatsu S13360-6025PE and SensL MicroFJ-60035TSV
- Radiation: point-like 55 MeV gammas
- Input: Waveform analysis
- Variable: Time at which the gamma enters inside the detector $t_0$
- Algorithm: The average among the timing calculated with the constant fraction (threshold = 15%) of the most intense amplitude and its neighbours: Cons. Frac. Ave. To distinguish it from the timing of the most intense amplitude only

\[ t_0 = \frac{(n - 1)t_f + (n + 1)t_b - \frac{L}{c}(n^2 + n)}{2n} \]

Where:
- $t_f$ and $t_b$ are the reconstructed time on the front and back face
- $n$ and $L$ the refractive index and length of the crystal respectively
- $c$ the speed of light
The position resolutions

- Crystal: LaBr3(Ce) with size \((R,L) = (4.45, 20.32)\) and LYSO with size \((R,L) = (3.5, 16)\) cm
- Photosensor: Hamamatsu S13360-6025PE and SensL MicroFJ-60035TSV
- Radiation: point-like 55 MeV gammas

\[
x_{\text{rec}} = a x_f + b x_b + c
\]

\[
z_{\text{rec}} = a (t_f - t_b) + b
\]

\[
z_{\text{rec}} = a \ln \left( \frac{N_f}{N_b} \right) + b
\]

\[\text{LYSO, Hamamatsu S13360-6025PE}\]
\[\sigma = 3.56(4) \text{ mm}\]
\[\text{LYSO, sensL MicroFJ-60035TSV}\]
\[\sigma = 3.52(3) \text{ mm}\]

\[\text{LYSO, Hamamatsu S13360-6025PE}\]
\[\sigma = 3.75(4) \text{ mm}\]
\[\text{LYSO, sensL MicroFJ-60035TSV}\]
\[\sigma = 3.52(3) \text{ mm}\]

\[\text{LYSO, Hamamatsu S13360-6025PE}\]
\[\sigma = 5.99(6) \text{ mm}\]
\[\text{LYSO, sensL MicroFJ-60035TSV}\]
\[\sigma = 5.26(6) \text{ mm}\]
Part II: Effective kinematical variable resolutions

- Basic Monte Carlo simulation input
- Extended impinging source: 55 MeV gammas
- Geometrical cut
- Crystal sizes:
  - Available on the market (custom production)
    - LaBr3(Ce) (R,L) = (4.45, 20.32) cm \([R = \text{Radius}, L = \text{Length}]\)
    - LYSO (R,L) = (3.5, 16) cm
  - Ideal
    - LaBr3(Ce) (R,L) = (7.62, 22.86) cm
    - LYSO (R,L) = (6.5, 20) cm
- Photosensors:
  - Hamamatsu S13360-6025PE and SensL MicroFJ-60035TSV
Shower inside the crystal

- LaBr$_3$(Ce); crystal size (R,L) = (4.45, 20.32) cm; 55 MeV gamma with different impinging conditions
Shower inside the crystal

- LYSO; crystal size (R,L) = (3.5, 16) cm; 55 MeV gamma with different impinging conditions
Extended source: Geometrical cut

- Two type of events: inner and border line events - simplified view
- Detector performances spoiled by border line events
- High segmented photosensor coverage: A powerful tool for geometrical cut
  - Optimal trade-off between kinematical variable resolutions and event selection efficiency
- Valid in view of a segmented/multi-element scalable big calorimeter for increasing the detector uniformity - i.e. parallelepiped elements

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figures.png}
\caption{(a) Hit in Central Region: \((x, y) = (10 \text{ mm}, 3 \text{ mm})\) \hspace{1cm} (b) Hit in Outer Region: \((x, y) = (23 \text{ mm}, -21 \text{ mm})\)}
\end{figure}
Extended source: Geometrical cut

- Two type of events: inner and border line events - simplified view
- Detector performances spoiled by border line events
- High segmented photosensor coverage: A powerful tool for geometrical cut
  - Optimal trade-off between kinematical variable resolutions and event selection efficiency
  - Valid in view of a segmented/multi-element scalable big calorimeter for increasing the detector uniformity - i.e. parallelepiped elements
- Two methods:
  - Reconstructed radius cut
  - Skewness cut
  - Both compared to the simulated radius cut
- Effective kinematical variable resolutions
Extended source: Geometrical cut

- Small crystal case
- Crystal: LYSO with size (R,L) = (3.5, 16) cm
- Photosensor: Hamamatsu S13360-6025PE
- Radiation: 55 MeV gammas

- $\sqrt{(x^2 + y^2)} < 20$ mm
- Radial Skewness (F,B) > -0.6

- $\sigma_N/N$ [%] = 3.3 $\Rightarrow$ 2.5, (reconstructed radius cut)
- $\sigma_N/N$ [%] = 3.3 $\Rightarrow$ 2.1, (skewness cut)
- $\sigma_N/N$ [%] = 3.3 $\Rightarrow$ 2.0 (simulated radius cut)
- For all cases: $\varepsilon_{sel} \sim 30\%$
Extended source: Geometrical cut

- Large crystal case
- Crystal: LYSO with size \((R,L) = (7.5, 16)\) cm
- Photosensor: Hamamatsu S13360-6025PE
- Radiation: 55 MeV gammas

- \(\sqrt{x^2 + y^2} < 65\) mm
- Radial Skewness \((F,B) > -0.6\)

- \(\sigma_{N/N} [%] = 0.9 \Rightarrow 0.7\), (reconstructed radius cut)
- \(\sigma_{N/N} [%] = 0.9 \Rightarrow 0.7\), (skewness cut)
- \(\sigma_{N/N} [%] = 0.9 \Rightarrow 0.7\) (simulated radius cut)
- For all cases: \(\epsilon_{\text{sel}} > 75\%\)
Extended source: Energy resolution

- **Crystals:**
  - LaBr3(Ce) with size \((R,L) = (4.45, 20.3)\) cm
  - LYSO with size \((R,L) = (3.5, 16)\) cm
- **Photosensors:**
  - SensL MicroFJ-60035TSV
  - Hamamatsu S13360-6025PE
- **Radiation:** 55 MeV gammas
- **Geometrical cut:** \(\sqrt{x^2 + y^2} < 20\) mm
- **LYSO + Hamamatsu:** best \(\sigma_{N/N} [%] = 2.4\)
- **LaBr3(Ce) + sensL:** best \(\sigma_{N/N} [%] = 3.3\)
Extended source

- Crystals:
  - LaBr₃(Ce) with size (R,L) = (4.45, 20.3) cm
  - LYSO with size (R,L) = (3.5, 16) cm
- Photosensors:
  - SensL MicroFJ-60035TSV
  - Hamamatsu S13360-6025PE
- Radiation: 55 MeV gammas
- Geometrical cut: \( \sqrt{x^2 + y^2} < 20 \text{ mm} \)
- LYSO + sensL: best \( \sigma_\text{t} [\text{ps}] = 51 \pm \text{ few ps} \)
- LaBr₃(Ce) + sensL/Hamamatsu: best \( \sigma_\text{t} [\text{ps}] = 46 \pm \text{ few ps} \)
Extended source

- Crystals:
  - LaBr3(Ce) with size (R,L) = (4.45, 20.3) cm
  - LYSO with size (R,L) = (3.5, 16) cm
- Photosensors:
  - SensL MicroFJ-60035TSV
  - Hamamatsu S13360-6025PE
- Radiation: 55 MeV gammas
- Geometrical cut: $\sqrt{x^2 + y^2} < 20$ mm

- LYSO + Hamamatsu/sensL: $\sigma_{X,Y} [\text{mm}] = 3.5 \pm 0.5$
- LaBr3(Ce) + Hamamatsu/sensL: $\sigma_{X,Y} [\text{mm}] = 4.8 \pm 0.5$
Extended source

- Crystals:
  - LaBr3(Ce) with size (R,L) = (4.45, 20.3) cm
  - LYSO with size (R,L) = (3.5, 16) cm
- Photosensors:
  - SensL MicroFJ-60035TSV
  - Hamamatsu S13360-6025PE
- Radiation: 55 MeV gammas
- Geometrical cut: $\sqrt{x^2 + y^2} < 20$ mm

- LYSO + sensL: best $\sigma_z$ [mm] = 5.3 $\pm$ 0.5
- LaBr3(Ce) + Hamamatsu/sensL: best $\sigma_z$ [mm] = 5.5 $\pm$ 0.5
Summary and Outlook

- LaBr$_3$(:Ce) and LYSO are a very attractive media for gamma calorimetry not only for low energy physics but also for high energy physics and in particular for the energy range of interest in charged Lepton Flavour Violation searches - O(50-100) MeV at the intensity frontier

- The well established MPPC/SiPM technology open the road to geometrical configurations never considered before (i.e. multiple readout scheme, with sensors along the path of the incident radiation, high granularity, geometrical cut for the best detector acceptance etc.) allowing to fully exploit the scintillation crystal characteristics [i.e. for LaBr$_3$(:Ce) 4.45 (R) x 20.32 (L) cm the energy resolution for single readout (back), single readout (front) and double readout are respectively: 7.8(2)%, 5.6(1)% and 2.25(7)%]

- Detailed Monte Carlo simulations including nowadays - available and custom size - and future cases of a single big crystal showed very promising results:
  - LaBr$_3$(:Ce) 4.45 (R) x 20.32 (L) cm
    - $\sigma_{N/N} [%] \sim 2.2$ [3.2 ext.] [3.8 ext. + waveform] $\Rightarrow 1.0$ [7.6(R) x 22.7 (L) cm crystal], $\sigma_t [ps] \sim 35$ [46 ext.], $\sigma_{x,y} [mm] \sim 3.5$, $\sigma_z [mm] \sim 6$ mm
  - LYSO 3.5 (R) x 16 (L) cm
    - $\sigma_{N/N} [%] \sim 1.3$ [2.4 ext.] [3.5 ext. + waveform] $\Rightarrow 0.7$ [7.5(R) x 16(L) cm crystal], $\sigma_t [ps] \sim 40$ [51 ext.], $\sigma_{x,y} [mm] \sim 3.5$, $\sigma_z [mm] \sim 6$ mm

- Calorimeters with such performances are at the detector technology frontiers

- A first large LaBr$_3$(:Ce)/LYSO detector prototype coupled to MPPC /SiPM for high energy gamma calorimetry is under construction
Acknowledgements

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• Grants: Italian Ministry of Education University and Research, Montalcini D.M. 2014 n. 975 and Swiss National Foundation n. 200020_172706
Backup
MPPC/SiPM characterisation

- Photosensors:
  - SensL MicroFJ-60035TSV
  - Hamamatsu S13360-6025PE

![Graphs showing gain and current as a function of bias voltage.]