Timing resolution measurement of a 3” Lanthanum Bromide detector

INFN Pisa, INFN Genova, PSI Villigen
LaBr$_3$:Ce as a detector

Recent dense, luminous and fast scintillator

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<tr>
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<td>63000</td>
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<tr>
<td>Decay Time (ns)</td>
<td>16</td>
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<td>$\lambda$ emission (nm)</td>
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<td>Refractive index</td>
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Unprecedented energy resolution: 3% FWHM @ 611 keV (1”×1” crystal)

Usage:
- nuclear spectroscopy
- nuclear imaging: TOF PET, SPET
- geophysics and astrophysics

HEP experiments in the high intensity frontier, in particular for cLFV searches:
- energy in the [50,100] MeV region
- excellent energy resolution is crucial for background rejection
- promising time resolution, to be investigated!
LaBr$_3$:Ce as a detector

LaBr$_3$(Ce) recent dense, luminous and fast scintillator

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Comparison with NaI

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HEP segmented detector

- 100 MeV gamma
- 6x6 array of crystals, each 1” x 1” x 50 cm
- 100 MeV containment with depth = 50 cm
- ~1.5 MeV self-activity line
- Online equalization of all channels
- Online calibration and monitoring of energy scale

Energy deposit in single crystal O(10) MeV
Brillance 380 detector

Customized detector from Saint Gobain

- largest crystal available: $3'' \times 3''$
  - good containment @ $\mathcal{O}(10 \text{ MeV})$
- time measurement
  - fast PMT with low TTS according to our specifications
- energy/gain linearity (crystal sanity check)
  - monitored with last dynode output
  - PMT in “low gain mode” (HV = 1100 V)
Confirm energy resolution

Our results consistent with previous measurements on 1”x1” and 2”x2” crystals even with a not optimized set-up

- Energy resolution
  - 3” NaI
  - Brillance

- Self radioactivity 1.45 MeV

- AmBe in a CH₂-Ni moderator-absorber
  - 4.4 MeV
  - Ni(n,γ) 9MeV
  - 2.2 MeV

- Spectra taken with a PC-based Multi Channel Analyzer

- \( \sigma_E \) more than a factor 2 better than NaI

- Linearity better than 1% up to 9 MeV
The characterization of the Brillance time resolution was the aim of our measurement campaign.

**RECIPE:** compare photon time between at least two coincident particles, with different devices.

**Implementation:**

1) Physical sources
   - production of two coincident photons from either $^{60}$Co source:
     \[ E_\gamma 1.17 \text{ & } 1.33 \text{ MeV} \]
   - or nuclear reaction $^{11}$B(p,$\gamma$)$^{12}$C:
     \[ E_\gamma 4.4 \text{ & } 11.7 \text{ MeV} \]
   - This gives us the possibility to explore different energy range, in the region of interest.

2) Instrumentation
   - Ideal case: 2 identical Brillance crystals
   - Real case: a set of different reference counters
   - Together with a suitable DAQ architecture optimized for reliable and high quality data-taking.
1) Gamma production

- Coincident $E_{\gamma} = 4.4, 11.7$ MeV from $^{11}\text{B}(p,\gamma)^{12}\text{C}$
- Cockcroft-Walton accelerator @ Paul Scherrer Institut (Villigen) $p$-beam on $\text{Li}_2\text{B}_4\text{O}_7$ target
- Working point $E_p = 700$ keV, $I_p = 1$ $\mu$A
- Coincidence rate $\sim 20$ Hz
- $< 1$ cm$^2$ beam spot

CW target used also as support for $^{60}\text{Co}$ source

\[\sigma_{\text{beam spot}} \approx 15 \text{ ps}(5\text{mm})\]
2) Resolution extraction

With 4 detectors and 2 monochromatic photons a system of 6 equations constraint the 4 unknown quantities

\[
\begin{align*}
\sigma_{ab}^2 &= \sigma_a^2 + \sigma_b^2 \\
\sigma_{ac}^2 &= \sigma_a^2 + \sigma_c^2 \\
\sigma_{ad}^2 &= \sigma_a^2 + \sigma_d^2 \\
\sigma_{bc}^2 &= \sigma_b^2 + \sigma_c^2 \\
\sigma_{bd}^2 &= \sigma_b^2 + \sigma_d^2 \\
\sigma_{cd}^2 &= \sigma_c^2 + \sigma_d^2
\end{align*}
\]

In the real case the equations take into account the different photon energies and the systematics such as electronics and beam spot contribution.
Need 3 reference detectors:

- 1 YAP crystal 2”x2” (cylindrical)
- 2 BC404 cubes 4x4x4 cm

All detectors were read out by very fast Hamamatsu PMT R5924 (2” fine mesh, TTS ~450 ps)

Symmetrical geometry

- Maximizes coincidence rate
- All detectors subtend ~same solid angle
- Allows fast calibration & cross-check with $^{60}$Co
- Two identical counters to check systematics
Experimental set-up: pictures
Experimental set-up: pictures
Electronics

Maximum care of the electronics chain: waveform digitizer to preserve the maximum information from the detectors, QDC CAEN V465 and TDC CAEN V488 for redundancy

- **CAEN V1729** waveform digitizer
  - 4 channels, 12 bit, 2 Gsamples, 300MHz BW
- **DAQ**
  - root-based front-end: online monitor and well defined data structure
  - ~50 Hz maximum rate

\[
\sigma_{ele} \approx 20 \text{ps}
\]
Data analysis

Select coincidences of detector pairs
- energy deposit on the detectors
- QDC and the waveform charge

Time for each detector from waveform fit
- \( f(t) = A \times ERF(t - t_0, \sigma) \times e^{-t/\tau} + C \)

- Correct residual time-amplitude correlations
- Gaussian fit of detector pair distributions
  - Compute detector offsets
  - Initialize global fit
Resolution extraction

The number of $\Delta T$ combinations is larger than the number of variables:

- simultaneous fit of all combinations to extract all the time resolutions.
- Systematic contributions taken into account in the fit.

\[ f(\sigma_{ij}) = \sum_{i,j} C_{i,j} \text{Gaus}(x - \mu_{i,j}, \sigma_{i,j}) \]

\[ \sigma_{i,j} = \sqrt{\sigma_i^2 + \sigma_j^2 + \sigma_{\text{ele}}^2 + \sigma_{\text{beamspot}}^2} \]
Results

The time resolution ~85 ps @ 11.7 MeV, promising for time reconstruction in a large volume calorimeter.

Sanity check result consistent with PARIS experiment at the $^{60}$Co energy.

http://paris.ifj.edu.pl/
Conclusions

Are LaBr₃(Ce) segmented detectors ready for HEP experiments?

- (Energy resolution/linearity)
- Easy inter-calibration - energy scale
- Excellent single crystal timing resolution @12 MeV

Work ongoing

- New measurements in preparation:
  - Energy resolution and linearity with 17.6 MeV from \(^{11}\text{Li}(p,\gamma)^{12}\text{Be}\) with CW
  - Time resolution with 55 MeV photons from \(\pi^0\) decays from \(\pi^- p\) CEX @ PSI

Preliminary studies encourage further investigations
Backup
## LaBrCe characteristics

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Density (g/cm³)</th>
<th>LY (pho/keV)</th>
<th>Decay Time (ns)</th>
<th>Wavelength of max emission (nm)</th>
<th>Refractive Index @max</th>
<th>Energy Resolution (% fwhm @ 662 keV)</th>
<th>F.O.M. √(τ/LY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC 404</td>
<td>1.03</td>
<td>12</td>
<td>1.8</td>
<td>408</td>
<td>1.58</td>
<td>-</td>
<td>0.39</td>
</tr>
<tr>
<td>BrLaCe 380 (5% Ce)</td>
<td>5.08</td>
<td>63</td>
<td>16</td>
<td>380</td>
<td>1.9</td>
<td>2.9%</td>
<td>0.5</td>
</tr>
<tr>
<td>YAP</td>
<td>5.35</td>
<td>22</td>
<td>26</td>
<td>347</td>
<td>1.95</td>
<td>4.38%</td>
<td>1.09</td>
</tr>
<tr>
<td>LYSO</td>
<td>7.1</td>
<td>27</td>
<td>41</td>
<td>425</td>
<td>1.82</td>
<td>~8%</td>
<td>1.23</td>
</tr>
<tr>
<td>NaI(Tl)</td>
<td>3.67</td>
<td>38</td>
<td>250</td>
<td>415</td>
<td>1.85</td>
<td>7.0%</td>
<td>2.6</td>
</tr>
<tr>
<td>BGO</td>
<td>7.13</td>
<td>9</td>
<td>300</td>
<td>480</td>
<td>2.15</td>
<td>9.05%</td>
<td>5.8</td>
</tr>
</tbody>
</table>
Conversion point uncertainty

\[ \sigma_t = \sigma_x / c \]

\[ \sigma_{t_{1.25\,MeV}} = 51\,ps \]

\[ \sigma_{t_{4.4\,MeV}} = 57\,ps \]

\[ \sigma_{t_{11.7\,MeV}} = 54\,ps \]

Example

\[ E_Y = 4.4\,MeV \]
BrLaCe self-activity

Activity $\sim 1 \text{ Bq/cm}^3$ [70 keV, 5 MeV]

$La + e^- \rightarrow Ba + \nu_e + \gamma$