Characterization of new crystals for X-rays detection

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* speaker
Properties of PrLuAg crystals

Physical and Scintillation Properties

<table>
<thead>
<tr>
<th>Scintillators</th>
<th>PrLuAG</th>
<th>Ce:LYSO</th>
<th>BGO</th>
<th>Ce:LaBr₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>6.73</td>
<td>7.1</td>
<td>7.13</td>
<td>5.08</td>
</tr>
<tr>
<td>Light yield (photon/MeV)</td>
<td>22,000</td>
<td>34,000</td>
<td>8,000</td>
<td>75,000</td>
</tr>
<tr>
<td>Decay time (ns)</td>
<td>20</td>
<td>40</td>
<td>300</td>
<td>30</td>
</tr>
<tr>
<td>Peak emission (nm)</td>
<td>310</td>
<td>420</td>
<td>480</td>
<td>360</td>
</tr>
<tr>
<td>Energy resolution (%@662keV)</td>
<td>4.2</td>
<td>10</td>
<td>12</td>
<td>2.6</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Cleavage</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>2,043</td>
<td>2,150</td>
<td>1,050</td>
<td>783</td>
</tr>
</tbody>
</table>

- High density, non-hygroscopic
- Short decay time; good light yield
- BUT: peak emission in UV -> problems with photodetectors
- and slightly radioactive: 36 Bq/g due to Pr

Emission and absorption spectra of PrLuAG

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Intrinsic activity of PrLuAg crystals

- Measured with a HpGE detector
- Total activity due to Lu$^{176}$ 36 Bq/g

![Graph showing energy vs counts per KeV hour with labels for detector, pre-amp, spectroscopy amplifier Ortec 672, and MCA.]
Properties of CeCAAG crystals

**Physical and Scintillation Properties**

<table>
<thead>
<tr>
<th>Scintillators</th>
<th>Ce:Gd$_3$Al$_2$Ga$_3$O$_12$ (CerGAGG)</th>
<th>Ce:Lu$<em>{1.4}$Y$</em>{0.6}$SiO$_5$ (CerLYSO)</th>
<th>Bi$_4$Ge$_3$O$_12$ (BGO)</th>
<th>Ce:LaBr$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm$^3$)</td>
<td>6.63</td>
<td>7.1</td>
<td>7.13</td>
<td>5.08</td>
</tr>
<tr>
<td>Light yield (photon/Mev)</td>
<td>57,000</td>
<td>34,000</td>
<td>8,000</td>
<td>75,000</td>
</tr>
<tr>
<td>Decay time (ns)</td>
<td>88 (91%)</td>
<td>40</td>
<td>300</td>
<td>30</td>
</tr>
<tr>
<td>Peak emission (nm)</td>
<td>520</td>
<td>420</td>
<td>480</td>
<td>375</td>
</tr>
<tr>
<td>Energy resolution (%@662keV)</td>
<td>5.2 (3x250mm$^2$ with APD)</td>
<td>10</td>
<td>12</td>
<td>2.6</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Cleavage</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>1,850</td>
<td>2,150</td>
<td>1,050</td>
<td>783</td>
</tr>
</tbody>
</table>

- **Natural radioactivity of CeCAAG crystals**
  - **LiveTime**: 355h
  - **Activity [Bq/kg]**
    - $^{232}$Th: <0.6
    - $^{228}$Ac: <0.6
    - $^{208}$Tl: <0.5
    - $^{238}$U: <5
    - $^{226}$Ra: <0.6
    - $^{214}$Bi: <0.6
    - $^{235}$U: <0.4
    - $^{40}$K: <6
    - $^{60}$Co: <0.2
    - $^{137}$Cs: <0.2

- **High density, non hygroscopic**
- **No intrinsic activity (<15 Bq/kg)**
- **Short decay time, high yield**
- **Emission peak ~520 nm well matched to SiPMT and SiPMT arrays**
Possible applications

**TOF PET imaging (Medical Physics)**

- Measurement of transfer functions from $\mu^-p + Z \rightarrow \mu^Z^* + p$ ($Z=O_2, Ar, Ne, CH_4, C_2H_6, CO_2$) at RiKEN-RAL, preliminary to experiment for $R_p$ measurement (FAMU experiment at RAL). Needs to detect low-energy X-rays (Nuclear Physics)

- large soft photon yield per MeV
- high density crystals (stopping power)
- soft photon detection in magnetic fields
- compact design
- high granularity
- non-hygroscopic
- affordable
Detector requirements

- High photon yield + good timing resolution (some tens of ns)
- Good energy resolution at low X-rays energy (~ 100 KeV)
- Low cost
- Simple photon readout

<table>
<thead>
<tr>
<th></th>
<th>Ge</th>
<th>NaI</th>
<th>LaBr3</th>
<th>CeCAAG</th>
<th>PrLuAg</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 keV</td>
<td>0.9 cm</td>
<td>0.5 cm</td>
<td>0.5 cm</td>
<td>0.3 cm</td>
<td>0.2 cm</td>
</tr>
<tr>
<td>500 keV</td>
<td>2.8 cm</td>
<td>3.5 cm</td>
<td>2.6 cm</td>
<td>1.8 cm</td>
<td>1.6 cm</td>
</tr>
<tr>
<td>800 keV</td>
<td>3.5 cm</td>
<td>4.9 cm</td>
<td>3.6 cm</td>
<td>2.6 cm</td>
<td>2.4 cm</td>
</tr>
</tbody>
</table>

Crystal thickness for 70% X-rays detection efficiency

A simple solution is a crystal read out by a SiPMT array, where cells outputs are summed up. Analogue signal may then be digitized by a fast (> 500 MHz) digitizer. As an alternative crystals may be read by a suitable PMT (R11065 with MgF$_2$ window for X-rays detection)
Used SiPMT arrays

Tested SiPMT arrays use 3x3 mm$^2$ macro-cells arranged in 4x4 arrays.

- **SENSL ArraySB-4-30035-CER** arrays with 3x3 mm$^2$ macrocells, $V_{op} \sim 27$ V
- **Hamamatsu S13361** arrays with 3x3 mm$^2$ macrocells, $V_{op} \sim 53.8$ V, TSV technology
- **Advansid ASD-SiPM3S-4x4T (RGB)** arrays with 3x3 mm$^2$ macrocells, $V_{bkw} \sim 28.5$ V

PDE for Hamamatsu TSV SiPMT (suitable for UV detection)

PDE for RGB Advansid SiPMT (well suited for RGB detection)

PDE for B-extended SENSLSiPMT

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Some more details on Hamamatsu TSV arrays

- TSV (``through Silicon Via'') technology used to eliminate the need of a wire bonding pad, that creates dead spaces problems
- The anode of each channel is traced to the backside pad by TSV
- In principle better for timing application (smaller timing jitter)

**Example: Hamamatsu S13361**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>S12642-060PA-50</th>
<th>S12642-064PB-50</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral response range</td>
<td>λ</td>
<td>320 to 900</td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td>Peak sensitivity wavelength</td>
<td>λp</td>
<td>450</td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td>Photon detection efficiency at λp</td>
<td>PDE</td>
<td>35</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Dark count 1</td>
<td>Typ.</td>
<td>2</td>
<td>20×10⁴</td>
<td>1/s</td>
</tr>
<tr>
<td></td>
<td>Max.</td>
<td>3</td>
<td>pps</td>
<td></td>
</tr>
<tr>
<td>Terminal capacitance</td>
<td>C1</td>
<td>320</td>
<td>pF</td>
<td></td>
</tr>
<tr>
<td>Gain 2</td>
<td>M</td>
<td>1.25x10⁶</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breakdown voltage</td>
<td>Vbr</td>
<td>65</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Recommended operating voltage 3</td>
<td>Vop</td>
<td>90</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Vop variation between channels (\text{%})</td>
<td>Typ.</td>
<td>0.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max.</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature coefficient of reverse voltage</td>
<td>AT(Top)</td>
<td>50</td>
<td>mW/°C</td>
<td></td>
</tr>
</tbody>
</table>

1: Photon detection efficiency does not include crosstalk and afterpulses.
2: The data will be measured by current.
3: Characteristics change with applied over voltage. Please refer to next section in detail.
4: Refer to the data attached for each product.

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Readout chain for SiPMT arrays

- SiPMT array custom mount
- 16 3x3 mm$^2$ cells signals are summed up in the basette and then amplified (parallel readout): it may be optimized

**Schematic of one "basette"**

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Tests with PMT readout (Hamamatsu R11065, suitable for UV light) and different SiPMT arrays from Hamamatsu, SENSEL, Advansid

Different crystal wrapping for crystals (Teflon, Aluminized Mylar, \( \text{BaSO}_4 \))

Standard spectroscopic readout chain. Ortec 570, 579 or 672 amplifiers + CAEN N951 MCA or ORTEC EasyMCA

Different calibrated X-rays sources from Spectrum Techniques

In some tests a Voetsch VT7004 climatic chamber was used

Inside ARMFLEX insulation (at room temperature) or climatic chamber
Results with CeCAAG crystals and SiPMT array readout

<table>
<thead>
<tr>
<th></th>
<th>Vop</th>
<th>Amplifier gain</th>
<th>MCA mean at Cs$^{137}$ peak</th>
<th>Resolution at Cs$^{137}$ peak (FWHM/E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SENS L B-extended</td>
<td>-27 V</td>
<td>150 x (*)&amp;</td>
<td>2048</td>
<td>10.4%</td>
</tr>
<tr>
<td>Advansid 4x4 RGB</td>
<td>29.5 V</td>
<td>125 x (0)</td>
<td>653.6</td>
<td>9.9%</td>
</tr>
<tr>
<td>Hama S13361 TSV</td>
<td>53.8 V</td>
<td>50 x (0)</td>
<td>1606</td>
<td>7.7%</td>
</tr>
</tbody>
</table>

- Tests done in “realistic experimental conditions” without a climatic chamber, but with ARMFLEX insulation (thermal excursion ~1-2 degs)
- Tests with Ortec 579 fast amplifier [0] (always same settings, aside gain to avoid signal saturation) or Ortec spectroscopy amplifier 672 [*]
- Results compare well with previous ones with MPPC readout (~12% or worse), but still worse with PMT readout
- Better results with Hamamatsu S13361 TSV 4x4 arrays (total area 14x14 mm²) are probably due to better matched PDE (l) and reduced noise in nearby cells. No clear improvements increasing V$_{op}$ in a sensible range (+ 1-2 V).
- Studies at room conditions (~25°C with ± 1°C excursions)
- In the resolution are folded: crystal intrinsic resolution and dimensions, effect of thermal excursions on SiPMT arrays, electronic noise (signals from cell SiPMT array are simply summed up), optical coupling, ...
- Results are obtained with an Ortec 579 Fast amplifier, but they do not change with dedicated spectroscopy amplifiers as Ortec 672
Tests in a climatic chamber

- Climatic chamber Voetsch VT7004: stability ~1K
- Same setup as before
- Effects may be explained with decrease of $V_{brk}$ with temperature lowering

![Graph showing current vs. voltage with different temperatures](image)

SENSSL B-series SiPMT

- $V_{op} = 53.8 \text{ V}$
Results with PrLuAG crystals and SiPMT array readout

- Teflon wrapping and optical grease (BC600) to make contact between crystal and SiPMT Array
- Studies at room temperature ~25 °C
- Hamamatsu TSV array S13361 with silicon epoxy window (UV extended)
- With Ortec 672 spectroscopy amplifier FWHM/E ~ 10% ; with Ortec 579 Fast Amplifier ~12%
- worse than published results with UV-extended PMTs or single SiPMT (but area much bigger than 3x3 mm²)
- Needs additional work on coating (BaSO₄)
Different reflectors for PrLuAG

- PrLuAG emission ~310 nm (UV). Reflectors may influence results.
- Tests with 14x14x13 mm³ crystal, with PMT’s readout. Polished-only, Teflon-wrapped, Al mylar wrapped and BaSO4 coated crystals. Improvement seen with BaSO4 coating.
- Signal amplitude increases of ~15% and resolution of ~50% with BaSO4 reflector.
- For CeCAAG (peak emission ~520 nm) reflector problem less relevant.

Studies are under way to improve BaSO4 coating.
PrLuAG and CeCAAG large area crystals (~1/2 '') are promising crystals for X-rays detection: low cost, dense, not hygroscopic, fast.

A solution with SiPMT array readout has been shown and is feasible.

But to have a real working detector, a lot of points must be clarified:
- Crystal wrapping/coating (especially for PrLuAG that emits in near UV)
- Noise reduction using SiPMT arrays
- Factors that affect resolution at low X-rays energy (O(100 KeV))
- ...

Performances (energy resolution) still worse than LaBr3

In conclusions: STILL A LOT OF WORK NEEDED (THEY ARE NOT OFF_THE_SHELL DETECTORS)

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