Ultrafast and Radiation Hard
Inorganic Scintillators
for Future HEP Experiments

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California Institute of Technology
May 24, 2018

Talk in the XVIII International Conference on Calorimetry in Particle Physics, Eugene
Why Ultrafast Crystals?

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

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

• Challenges at future HEP & other Applications:
  – Ultrafast and rad hard crystals at the energy frontier (HL-LHC);
  – Ultrafast crystals at the intensity frontier (Mu2e-II);
  – Ultrafast crystals for GHz hard X-ray imaging (Marie).
The Mu2e Undoped CsI Calorimeter

- Crystal lateral dimension: ±100 μ, length: ±100 μ.
- Scintillation properties at seven points along the crystal wrapped by two layers of Tyvek paper of 150 μm for alternative end coupled to a bi-alkali PMT with an air gap. Light output and FWHM resolution are the average of seven points with 200 ns integration time. The light response uniformity is the rms of seven points. F/T is measured at the point of 2.5 cm to the PMT.
  - Light output (LO): > 100 p.e./MeV with 200 ns gate, will be compared to reference for cross-calibration;
  - FWHM Energy resolution: < 45% for Na-22 peak;
  - Light response uniformity (LRU, rms of seven points): < 5%;
  - Fast (200 ns)/Total (3000 ns) Ratio: > 75%.

- Radiation related spec::
  - Normalized LO after 10/100 krad: > 85/60%;
  - Radiation Induced noise @ 1.8 rad/h: < 0.6 MeV.

1,348 CsI crystals of 34 x 34 x 200 mm under production

See also presentations by L. Morescalchi, R. Zhu, E. Diociaiuti & R. Donghia
Future Application of Ultrafast Crystals

Ultrafast and radiation hard inorganic scintillators have broad applications


BaF$_2$:Y, ZnO:Ga and others are attractive for an ultrafast front imager for the FEL based GHz hard x-ray imaging

1,940 BaF$_2$:Y crystals
30 x 30 x 218 mm

Marie Project

Optical-Based Rad Hard Calorimeter
Sensor for GHz Hard X-Ray Imaging

High-Energy and Ultrafast X-Ray Imaging Technologies and Applications

Organizers: Peter Denes, Sol Gruner, Michael Stevens & Zhehui (Jeff) Wang
(Location/Time: Santa Fe, NM, USA / Aug 2-3, 2016)

The goals of this workshop are to gather the leading experts in the related fields, to prioritize tasks for ultrafast hard X-ray imaging detector technology development and applications in the next 5 to 10 years, see Table 1, and to establish the foundations for near-term R&D collaborations.

Table I. High-energy photon imagers for MaRIE XFEL

<table>
<thead>
<tr>
<th>Performance</th>
<th>Type I imager</th>
<th>Type II imager</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray energy</td>
<td>30 keV</td>
<td>42-126 keV</td>
</tr>
<tr>
<td>Frame-rate/inter-frame time</td>
<td>0.5 GHz/2 ns</td>
<td>3 GHz / 300 ps</td>
</tr>
<tr>
<td>Number of frames</td>
<td>10</td>
<td>10 - 30</td>
</tr>
<tr>
<td>X-ray detection efficiency</td>
<td>above 50%</td>
<td>above 80%</td>
</tr>
<tr>
<td>Pixel size/pitch</td>
<td>≤ 300 μm</td>
<td>&lt; 300 μm</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>$10^3$ X-ray photons</td>
<td>$\geq 10^4$ X-ray photons</td>
</tr>
<tr>
<td>Pixel format</td>
<td>64 x 64 (scalable to 1 Mpix)</td>
<td>1 Mpix</td>
</tr>
</tbody>
</table>

2 ns and 300 ps inter-frame time requires very fast sensor
Fast & Radiation Hard Scintillators

- Supported by the DOE ADR program we are developing fast and radiation hard scintillators to face the challenge for future HEP and GHz hard x-ray applications.

- LYSO:Ce, BaF$_2$ and LuAG:Ce will survive the radiation environment expected at HL-LHC with 3000 fb$^{-1}$. LYSO will be used for a MIP Timing Detector (MTD) for CMS upgrade:
  - Absorbed dose: up to 100 Mrad,
  - Charged hadron fluence: up to $6\times10^{14}$ p/cm$^2$,
  - Fast neutron fluence: up to $3\times10^{15}$ n/cm$^2$.

- Ultra-fast scintillators with excellent radiation hardness is also needed to face the challenge of unprecedented event rate expected at future HEP experiments at the intensity frontier, such as Mu2e-II and the proposed Marie project at Los Alamos. BaF$_2$:Y and other ultrafast crystals with sub-ns decay time and suppressed slow scintillation component is a leading candidate for all applications.
# Inorganic Scintillators for HEP Calorimetry

<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>
</tr>
<tr>
<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>
</tr>
<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>
</tr>
<tr>
<td>Molière Radius (cm)</td>
<td>4.13</td>
<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>
</tr>
<tr>
<td>Interaction Length (cm)</td>
<td>42.9</td>
<td>39.3</td>
<td>39.3</td>
<td>30.7</td>
<td>22.8</td>
<td>20.9</td>
<td>20.7</td>
<td>21.0</td>
</tr>
<tr>
<td>Refractive Index a</td>
<td>1.85</td>
<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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<tr>
<td>Hygroscopicity</td>
<td>Yes</td>
<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>310</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>26</td>
<td>650</td>
<td>300</td>
<td>40</td>
<td>30</td>
<td>?</td>
</tr>
<tr>
<td>Light Yield b,c (%)</td>
<td>100</td>
<td>165</td>
<td>4.7</td>
<td>36</td>
<td>21</td>
<td>85</td>
<td>0.3</td>
<td>?</td>
</tr>
<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>
<tr>
<td>Experiment</td>
<td>Crystal Ball</td>
<td>BaBar BELLE BES-III</td>
<td>KTeV S.BELLE Mu2e-I</td>
<td>(GEM) TAPS Mu2e-II</td>
<td>L3 BELLE HHCAL</td>
<td>COMET &amp; CMS (Mu2e &amp; SperB)</td>
<td>CMS ALICE PANDA</td>
<td>A4 g-2 HHCAL</td>
</tr>
</tbody>
</table>

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a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.
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
- LSO/LYSO
- LaBr₃
- CsI

Slow Crystal Scintillators
- BaF₂

May 24, 2018 Presented by Ren-Yuan Zhu of Caltech in 2018 Calor Conference at Eugene, Oregon
Fast Signals with $1.5 X_0$ Samples

Hamamatsu R2059 PMT (2500 V)/Agilent MSO9254A (2.5 GHz) DSO with 1.3/0.14 ns rise time

The 3 ns width of BaF$_2$ pulse may be reduced by a faster photodetector. LYSO, LaBr$_3$ & CeBr$_3$ have tail, which would cause pile-up for GHz readout.
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>7.4</td>
<td>7.4</td>
<td>6.76</td>
<td>6.76</td>
<td>6.5</td>
<td>4.51</td>
<td>4.89</td>
<td>4.89</td>
<td>5.23</td>
</tr>
<tr>
<td>Melting points (°C)</td>
<td>2050</td>
<td>2050</td>
<td>2060</td>
<td>2060</td>
<td>1850d</td>
<td>621</td>
<td>1280</td>
<td>1280</td>
<td>722</td>
</tr>
<tr>
<td>X₀ (cm)</td>
<td>1.14</td>
<td>1.14</td>
<td>1.45</td>
<td>1.45</td>
<td>1.63</td>
<td>1.86</td>
<td>2.03</td>
<td>2.03</td>
<td>1.96</td>
</tr>
<tr>
<td>Rₘ (cm)</td>
<td>2.07</td>
<td>2.07</td>
<td>2.15</td>
<td>2.15</td>
<td>2.20</td>
<td>3.57</td>
<td>3.1</td>
<td>3.1</td>
<td>2.97</td>
</tr>
<tr>
<td>λ₁ (cm)</td>
<td>20.9</td>
<td>20.9</td>
<td>20.6</td>
<td>20.6</td>
<td>21.5</td>
<td>39.3</td>
<td>30.7</td>
<td>30.7</td>
<td>31.5</td>
</tr>
<tr>
<td>Zeff</td>
<td>64.8</td>
<td>64.8</td>
<td>60.3</td>
<td>60.3</td>
<td>51.8</td>
<td>54.0</td>
<td>51.6</td>
<td>51.6</td>
<td>45.6</td>
</tr>
<tr>
<td>λpeak (nm)</td>
<td>420</td>
<td>420</td>
<td>520</td>
<td>310</td>
<td>540</td>
<td>310</td>
<td>300</td>
<td>220</td>
<td>300</td>
</tr>
<tr>
<td>PL Emission Peak (nm)</td>
<td>402</td>
<td>402</td>
<td>500</td>
<td>308</td>
<td>540</td>
<td>310</td>
<td>300</td>
<td>220</td>
<td>300</td>
</tr>
<tr>
<td>PL Excitation Peak (nm)</td>
<td>358</td>
<td>358</td>
<td>450</td>
<td>275</td>
<td>445</td>
<td>256</td>
<td>&lt;200</td>
<td>&lt;200</td>
<td>330</td>
</tr>
<tr>
<td>Absorption Edge (nm)</td>
<td>170</td>
<td>170</td>
<td>160</td>
<td>160</td>
<td>190</td>
<td>200</td>
<td>140</td>
<td>140</td>
<td>n.r.</td>
</tr>
<tr>
<td>Refractive Indexb</td>
<td>1.82</td>
<td>1.82</td>
<td>1.84</td>
<td>1.84</td>
<td>1.92</td>
<td>1.95</td>
<td>1.50</td>
<td>1.50</td>
<td>1.9</td>
</tr>
<tr>
<td>Normalized Light Yielda,c</td>
<td>100</td>
<td>116e</td>
<td>35f</td>
<td>44</td>
<td>40</td>
<td>4.2</td>
<td>42</td>
<td>1.7</td>
<td>99</td>
</tr>
<tr>
<td>Total Light yield (ph/MeV)</td>
<td>30,000</td>
<td>34,800e</td>
<td>25,000f</td>
<td>25,800</td>
<td>34,700</td>
<td>1,700</td>
<td>13,000</td>
<td>2,100</td>
<td>30,000</td>
</tr>
<tr>
<td>Decay timea (ns)</td>
<td>40</td>
<td>31e</td>
<td>981f</td>
<td>1208</td>
<td>319</td>
<td>101</td>
<td>600</td>
<td>0.5</td>
<td>600</td>
</tr>
<tr>
<td>Light Yield in 1st ns (photons/MeV)</td>
<td>740</td>
<td>950</td>
<td>240</td>
<td>520</td>
<td>260</td>
<td>100</td>
<td>1200</td>
<td>1200</td>
<td>1,700</td>
</tr>
</tbody>
</table>

**Issues**
- neutron x-section
- slightly hygroscopic
- slow component
- DUV PD
- hygroscopic

May 24, 2018
Presented by Ren-Yuan Zhu of Caltech in 2018 Calor Conference at Eugene, Oregon
Fast Inorganic Scintillators (II)

a. Top line: slow component, bottom line: fast component;
b. At the wavelength of the emission maximum;
c. Excited by Gamma rays;
d. For Gd₃Ga₃Al₂O₁₂:Ce

e. For 0.4 at% Ca co-doping
f. Ceramic with 0.3 Mg at% co-doping

LuAG:Ce Ceramic Samples

- LuAG S1 and LuAG S2 samples are shown.
- Cerium concentrations of 0.1, 0.2, and 0.3 are displayed.
- Transmittance and emission spectra for LuAG:Ce S1 and S2 samples are presented.
- Number of Events and Light Output graphs are provided for both S1 and S2 samples.

Additional data and analysis are included in the presentation.
Excellent Radiation Hardness

No damage observed in both transmittance and light output after 220 Mrad ionization dose and $3 \times 10^{14}$ p/cm$^2$ of 800 MeV.

Very promising for optical-based radiation hard calorimeter.

Key issue: slow scintillation component.
The fast component at 220 nm with 0.6 ns decay time has a similar LO as undoped CsI.

Spectroscopic selection of fast component may be realized by solar blind photocathode and/or selective doping.
Slow Suppression: Doping & Readout

Slow component may be suppressed by RE doping: Y, La and Ce

Solar-blind cathode (Cs-Te) + La doping achieved high F/S


Presented by Ren-Yuan Zhu of Caltech in 2018 Calor Conference at Eugene, Oregon
Yttrium Doping in $\text{BaF}_2$

Significant increase in F/S ratio observed

May 24, 2018
Presented by Ren-Yuan Zhu of Caltech in 2018 Calor Conference at Eugene, Oregon
Pulse Shape: PbF\(_2\) and BaF\(_2\)

BaF\(_2\) cylinders of \(\Phi 10 \times 10\) cm\(^3\) shows \(\gamma\)-ray response: 0.26/0.55/0.94 ns of rising/decay/FWHM width
Tail Reduced in BaF$_2$:Y

Slow tail observed in BaF$_2$, much reduced in BaF$_2$:Y

BaF$_2$, φ10×10 mm, Na-22
Photek PMT240, HV=-4800V
Tektronix MSO 72304DX

BaF$_2$(Y), φ10×10 mm, Na-22
Photek PMT240, HV=-4800V
Tektronix MSO 72304DX
BGRI/Incrom/SIC BaF$_2$ Samples

<table>
<thead>
<tr>
<th>ID</th>
<th>Vendor</th>
<th>Dimension (mm$^3$)</th>
<th>Polishing</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIC 1-20</td>
<td>SICCAS</td>
<td>30x30x250</td>
<td>Six faces</td>
</tr>
<tr>
<td>BGRI-2015 D, E, 511</td>
<td>BGRI</td>
<td>30x30x200</td>
<td>Six faces</td>
</tr>
<tr>
<td>Russo 2, 3</td>
<td>Incrom</td>
<td>30x30x200</td>
<td>Six faces</td>
</tr>
</tbody>
</table>
Ionization Dose: BaF$_2$ and PWO

Dose rate dependent damage in PWO
Good radiation hardness in BaF$_2$ up to 100 Mrad

40% fast scintillation light remains after 120 Mrad ionization dose

Fan Yang et al., IEEE TNS 64 (2017) 665-672
A Hellma BaF$_2$ of 2 cm and a SIC PWO of 5 mm were irradiated up to 1.2×10$^{15}$ p/cm$^2$ by 800 MeV protons at the blue room of LANSCE with transmittance measured in-situ.

LYSO, BaF$_2$ and PWO plates of 3, 5 and 5 mm were also irradiated up to 1×10$^{15}$ p/cm$^2$.

Excellent radiation hardness observed in LYSO and BaF$_2$, but not PWO.

Proton-Induced Radiation Damage in BaF$_2$, LYSO and PWO Crystal Scintillators, IEEE TNS 65 (2018)
Digital Object Identifier 10.1109/TNS.2018.2808841
Neutrons: LYSO/BaF₂/PWO at LANSCE

LYSO, BaF₂ and PWO plates of 5 mm were irradiated up to $2 \times 10^{15}$ n/cm² in three steps at the East Port of LANSCE.

Excellent radiation hardness observed in LYSO and BaF₂, but not PWO.

See talk by L. Zhang in this conference.
LYSO, BaF$_2$ crystals and LuAG ceramics show excellent radiation hardness beyond 100 Mrad, 1 x 10$^{15}$ p/cm$^2$ and 2 x 10$^{15}$ n/cm$^2$. They promise a very fast and robust detector in a severe radiation environment, such as HL-LHC.

Commercially available undoped BaF$_2$ crystals provide sufficient fast light with sub-ns decay time. Yttrium doping in BaF$_2$ crystals increases its F/S ratio significantly while maintaining the intensity of the sub-ns fast component. This material is promising for Mu2e-II and GHz X-ray imaging.

Results of the LANL experiments 6991 and 7332 show fast neutrons up to 2 x 10$^{15}$ n/cm$^2$ do not cause significant damage LYSO and BaF$_2$, qualitatively confirming early observation at the Saclay reactor.

Our plan is to investigate novel ultrafast crystals and radiation hardness of BaF$_2$:Y crystals. Will also test TPBD WLS with R. Ruchiti et al. for BaF$_2$:Y, and pay an attention to photodetector with DUV response: LAPPD, Si or diamond etc.
Hamamatsu S13371-6050CQ-02

SiPM with VUV response is available: QE = 22% at 220 nm

PDE measurement data
Vover = 4V, in vacuum

S13371-6050CQ-02 PDE (Vover = 4V)
Diamond Photodetector


**Figure 6.** Quantum efficiency of diamond photoconductors at different temperatures and Arrhenius plot of the peak value (inset). (From [Sal00].)

**Fig. 4.** External quantum efficiency extended to visible and near infrared wavelength regions. The