Comparing BSO and BGO with different surface finishes as cost-effective, hybrid scintillation/Cherenkov detectors for TOF-PET

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Motivation: TOF-PET

For $\Delta d = 1\text{cm}$ a $\Delta t$ of 66 ps is required!

<table>
<thead>
<tr>
<th>Time resolution (ns)</th>
<th>$\Delta x$ (cm)</th>
<th>TOF NEC gain</th>
<th>TOF SNR gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.5</td>
<td>26.7</td>
<td>5.2</td>
</tr>
<tr>
<td>0.3</td>
<td>4.5</td>
<td>8.9</td>
<td>3.0</td>
</tr>
<tr>
<td>0.6</td>
<td>9.0</td>
<td>4.4</td>
<td>2.1</td>
</tr>
<tr>
<td>1.2</td>
<td>18.0</td>
<td>2.2</td>
<td>1.5</td>
</tr>
<tr>
<td>2.7</td>
<td>40.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Conti 2011

State-of-the-art:
- Systems: CRT 300 ps to 400 ps FWHM (LSO:Ce based)
- Preclinical systems: 200 ps to 250 ps FWHM (LSO:Ce based)
- Lab: 70 ps to 80 ps FWHM (Ca codoped LSO:Ce, 3x3x5mm$^3$)
The Cherenkov effect

- Photons emitted almost \textit{instantaneously} (< 10 ps)
- Emission increases towards \textcolor{blue}{blue/UV} (prop \(1/\lambda^2\))
- Emission increases with increasing refractive index
- Only \textbf{a few Cherenkov photons} are emitted at \textcolor{red}{511 keV} (10-20 photons)

\[
\frac{dN^2}{dx d\lambda} = \frac{2\pi \alpha}{\lambda^2} \left( 1 - \frac{1}{n(\lambda)^2 \beta^2} \right)
\]
Annihilation photon induced Cherenkov emission

Based on: Vasil’ev, SCINT99
Annihilation photon induced Cherenkov emission

Based on: Vasil’ev, SCINT99

Talk: S. Omelkov, Do 8:45
Investigating materials

Problem: How to discriminate photoelectric events from Compton scattering?

A1: Energy after Compton scattering is not sufficient for Cherenkov emission - pure Cherenkov radiator ($\beta_{\text{thr}} > 1/n$)

A2: Use of combined scintillation and Cherenkov emission - hybrid Cherenkov radiator / scintillator

- Simulation study using Geant4
- Figure of merit: ratio of Cherenkov/scintillation emission in first 100 ps
- LSO:Ce, LuAG:Ce, BGO, PbWO, Pb-glass

![Graph showing the ratio of Cherenkov to scintillation photons over time.]

**Ratio Cherenkov/scintillation photon yield**

<table>
<thead>
<tr>
<th>Material</th>
<th>&lt; 25 ps</th>
<th>&lt; 100 ps</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSO:Ce</td>
<td>1.78</td>
<td>0.16</td>
</tr>
<tr>
<td>LuAG:Ce</td>
<td>41.5</td>
<td>3.4</td>
</tr>
<tr>
<td>BGO</td>
<td>364</td>
<td>28</td>
</tr>
<tr>
<td>PWO</td>
<td>134</td>
<td>21</td>
</tr>
</tbody>
</table>

Brunner et al., IEEE TNS 61-1 (2014)
Comparing LSO:Ce with BGO/BSO

BGO/BSO compared to LSO:Ce
- higher stopping power
- higher photo-fraction
- no intrinsic radiation
- is inexpensive

BSO compared to BGO
- improved detection rate cap.
- is inexpensive

<table>
<thead>
<tr>
<th>Property</th>
<th>Lu$_2$SiO$_5$:Ce</th>
<th>Bi$_4$Ge$<em>3$O$</em>{12}$</th>
<th>Bi$_4$Si$<em>3$O$</em>{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive index (420nm)</td>
<td>1.83$^a$</td>
<td>2.2$^b$</td>
<td>2.06 (480 nm)$^c$</td>
</tr>
<tr>
<td>Light yield [phot x MeV$^{-1}$]</td>
<td>30000$^d$</td>
<td>8200$^e$</td>
<td>1200$^f$</td>
</tr>
<tr>
<td>Scint. rise time [ps]</td>
<td>69$^g$</td>
<td>30$^h$, 50$^p$</td>
<td>&lt; 50 ps$^f$</td>
</tr>
<tr>
<td>Decay time [ns]</td>
<td>40$^g$</td>
<td>300 + fast$^h,i,j$</td>
<td>100 + fast$^c$</td>
</tr>
<tr>
<td>Density [g x cm$^{-3}$]</td>
<td>7.4$^d$</td>
<td>7.13$^m$</td>
<td>6.8$^c$</td>
</tr>
<tr>
<td>$Z_{\text{eff}}$</td>
<td>66$^n$</td>
<td>75.2$^e$</td>
<td>74.4$^l$</td>
</tr>
<tr>
<td>Photo fraction</td>
<td>0.31$^o$</td>
<td>0.41$^o$</td>
<td>0.43$^o$</td>
</tr>
<tr>
<td>Intrinsic radiation</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

a) Spurrier 2008  
b) Williams 1996  
c) Ishii 2008  
d) Humm 2003  
e) Holl 1988  
f) Shulgin 1991  
g) Gundacker 2016  
h) Derenzo 2000  
i) Moszynski 1981  
j) Wolszczak 2014  
k) Kobayashi 1983  
l) Harada 2002  
m) Weber 1973  
n) Welcher 1995  
o) NIST XCOM  
p) Brunner 2017  
q) this work
A simple, digital SiPM based setup for high precision TCSPC on scintillators using e+/e- annihilation photons

Motivation: Measure rise time of scintillators including Cherenkov emission \( \rightarrow \) need 511keV for excitation (\(^{22}\text{Na}\)).

Detector: Philips Digital Photon Counter (DPC)
- 16 DPC dies \( \rightarrow \) 16 timestamps
- 64 DPC pixels \( \rightarrow \) 64 photon counts
- 3200 SPADs per pixel \( \rightarrow \) > 200 kSPADs
- each SPAD individually addressable

The SPAD with the lowest DCR is selected for the TCSPC measurements.
BGO: 511 keV excited luminescence spectra

\[ \tau_{\text{rise}} = 10 \text{ ps} \pm 10 \text{ ps} \]

\[ \tau_{\text{rise}} = 15 \text{ ps} \pm 15 \text{ ps} \]

Within first 10 ns:
- Exp1: 93.7%
- Exp2: 1.8%
- Prompt: 4.5%

Within first 10 ns:
- Exp1: 92.9%
- Exp2: 3.6%
- Prompt: 3.5%

\[ p_\text{c}(t|\Theta) = \sum_{i=1}^{N} \frac{p_i}{\tau_{ij} - \tau_{ij}} \left( e^{-\frac{t}{\tau_{ij}}} - e^{-\frac{t}{\tau_{ij}}} \right) \cdot \Theta(t - \theta) + \delta(t - \theta). \]

\[ f_{\text{te}}(t|\Theta) = p_{\text{te}}(t|\Theta) \ast \text{IRF}(t). \]
Adding the surface roughness as parameter to the timing measurements

- Photon transport time jitter is factor influencing the timing
- Few photons emitted → majority is reflected at surface
- Investigate timing of BGO and BSO with different surface roughness
- Roughness $R_a$ measured using a profileometer
- $R_a$ is rms along 1 μm

\[ R_a \approx 5 - 20 \text{ nm} \]

\[ R_a \approx 500 - 800 \text{ nm} \]
Energy resolution and photon detection yield of BGO/BSO at

Photon detection yield

Energy resolution

coincidence setup using $^{22}$Na (511keV); cross section 3 mm x 3 mm; +20°C; Teflon wrapping; attached to digital photon counter; BC630 grease
Coincidence timing with BGO and BSO

Timing performance of **BGO** and **BSO** almost similar although \( \text{LY}_{\text{BSO}} : \text{LY}_{\text{BGO}} \approx 1 : 8; \) \( \tau_{\text{decay-BSO}} : \tau_{\text{decay-BGO}} \approx 1 : 3! \)

coincidence setup using \(^{22}\text{Na}\); cross section 3 mm x 3 mm; +20°C; Teflon wrapping; attached to digital photon counter; BC630 grease
Coincidence Resolving Time

Crystal cross section 3 x 3 mm²; surface polished; wrapped in Teflon; opt. coupler BC630; 2 Philips DPCs in coincidence with ²²Na source
Comparison analog - digital SiPM with BGO/BSO

<table>
<thead>
<tr>
<th></th>
<th>size [mm$^3$]</th>
<th>CRT FWHM [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>analog$^1$</td>
<td>2 x 2 x 3</td>
<td>267</td>
</tr>
<tr>
<td>digital$^2$</td>
<td>3 x 3 x 3</td>
<td>250</td>
</tr>
<tr>
<td>analog$^1$</td>
<td>3 x 3 x 20</td>
<td>562</td>
</tr>
<tr>
<td>digital$^2$</td>
<td>3 x 3 x 20</td>
<td>404</td>
</tr>
</tbody>
</table>

1Kwon et al., PMB 61 (2016)  
3Nemallapudi et al., JINST 11 (2016)  
4Brunner et al., JINST 11 (2016)

- UV-sensitive analog SiPM is inferior. Why?  
  - SPRT?  
  - PDE?  
  - First photon time-pickoff?  
- Need better understanding!
MC - Simulation vs measurement

3 mm x 3 mm x 3 mm BGO in coincidence, wrapped in Teflon

- FWHM ≈ 250 ps
- FWTM
- scintillation - scintillation (58 %)
- Cherenkov - scintillation (36 %)
- Cherenkov - Cherenkov (6 %)

scintillation - scintillation (58 %)

Cherenkov - scintillation (36 %)

Cherenkov - Cherenkov (6 %)

TU Delft

S. E. Brunner

SCINT 2017
MC - Simulation studies

20 mm x 3 mm x 3 mm BGO in Teflon in coincidence

- PDE norm. SPRT norm.
  - 456 ps FWHM
  - 1852 ps FWTM
  - C-C 1%
  - S-C 18%
  - S-S 81%

- PDE UV-enhanced SPRT norm.
  - 341 ps FWHM
  - 1487 ps FWTM
  - C-C 2%
  - S-C 23%
  - S-S 75%

- PDE 1 SPRT norm.
  - 250 ps FWHM
  - 700 ps FWTM
  - C-C 15%
  - S-C 47%
  - S-S 37%

- PDE norm. SPRT off
  - 259 ps FWHM
  - 1725 ps FWTM
  - C-C 51%
  - S-C 41%
  - S-S 8%

- PDE UV-enhanced SPRT off
  - 203 ps FWHM
  - 1222 ps FWTM
  - C-C 61%
  - S-C 34%
  - S-S 5%

- PDE 1 SPRT off
  - 154 ps FWHM
  - 476 ps FWTM
  - C-C 77%
  - S-C 21%
  - S-S 2%

- Measured:
  - 404 ps FWHM
  - 2568 ps FWTM

PDE norm. acc. DPC datasheet, 5% SPADs off; UV-enhanced: PDE = 0.4 (270 - 400nm), 5% SPADs off; PDE 1 (270 - 600nm), 5% SPADs off; SPRT norm: $\sigma_{SPRT} = 51$ ps

Major contribution to the CRT coming from the TTS (reflections)!
Summary & Conclusion

- Timing performance of BGO and BSO almost similar although $\text{LY}_{\text{BSO}}:\text{LY}_{\text{BGO}} = 1:8$; $\tau_{\text{decay-BSO}}:\tau_{\text{decay-BGO}} \approx 1:3$

  ➡ Cherenkov (prompt) photons enable timing with BGO/BSO

  ➡ 200 ps FWHM and 750 ps FWTM achieved with BSO

- Energy discrimination from simultaneously detected scintillation photons

  ➡ Timing can be improved by surface optimisation

- BGO/BSO are inferior to L(X)SO:Ce in terms of timing, but provide
  • better stopping power
  • higher photo-fraction
  ➡ higher sensitivity
  • no intrinsic radiation (important for monolithic scintillation det.)
  • are cost-effective
Questions?
Problem of Depth-of-Interaction I
Problem of Depth-of-Interaction II

- Deteriorates time resolution
- Deteriorates spatial resolution

\[ \text{gamma photon speed} = c \]

\[ \text{optical photon speed} = \frac{c}{n} \]

Moses & Derenzo, 1999

Depth of interaction (DOI)
- Deteriorates time resolution
- Deteriorates spatial resolution
MC - simulation details and parameters

- Geant4: version geant4-10-02-patch-01 (26-February-2016), Physics List: stdEM_opt4
- 2 crystals in coincidence with 511 keV photon gun (random direction, 2 photons back-to-back)
- cross section 3 mm x 3 mm (wrapped in Teflon; coupled with grease; Quartz cover glass and opt. glue included)
- $\text{LY}_{\text{BGO}}$: 8200 phot/MeV; $\tau_{\text{rise}} = 50$ ps; $\tau_{\text{decay1}} = 60$ ns; $\tau_{\text{decay1}} = 300$ ns; scint-ratio 1:10
- PDE according to Philips data sheet + 5 % of SPADs deactivated (randomly)
- measured $\sigma_{\text{SPRT}} = 51$ ps [1]
- Measured transmittance and emission spectrum used
- crystal surface using LUTs [2]: SetType(dielectric_LUT); SetModel(LUT); SetFinish(polishedteflonair)

State-of-the-art CRT with Cherenkov emission

- 2010: **250 ps** FWHM, Lecoq, Brunner et al. IEEE TNS 57 (2010), LuAG & PMTs
- 2011: **70 ps** FWHM, Dolenec, Korpar, Krizan et al., NIM A654 (2011); PbF$_2$ & MCP-PMTs
- 2014: **300 ps** FWHM, Brunner, PhD thesis (2014) TU Vienna*; BGO & dSiPM
- 2016: **297 ps** FWHM; Dolenec Korpar Krizan et al., IEEE TNS 61 (2016); PbF$_2$ & aSiPM
- 2016: **270 ps** FWHM; Kwon et al., PMB 61 (2016); BGO & aSiPM
- 2017: **200 ps** FWHM; Brunner et al., PMB 62-11 (2017); BGO & dSiPM

*see [http://katalog.ub.tuwien.ac.at/AC11996520](http://katalog.ub.tuwien.ac.at/AC11996520)
BGO & Digital Photon Counter: Coincidence Resolving Time

Crystal cross section 3 x 3 mm$^2$
Crystal lengths: 3 mm, 5 mm, 8 mm, 12 mm, 20 mm
2 Philips DPCs in coincidence with $^{22}$Na source

**BGO/BSO photoluminescence spectra**

- X-ray excitation 35 kV (current 10 mA)
- Czerny–Turner monochromator (Action Motion Corporation, model vm504)
- PMT: Hamamatsu R943-02
- corrected for PMT sensitivity
Data analysis

\[ \sqrt{n} \]

FWHM

lower error

upper error