Lead Based Halide Crystals for the HHCAL Detector Concept

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Introduction

This is a continuous effort to understand lead based halide (PbFCl, PbF$_2$:Gd) crystals for the homogeneous hadronic calorimeter (HHCAL) detector concept proposed by a Fermilab team, where both Cherenkov and scintillation lights are measured for good hadronic energy resolution.

Requirements for the materials to be used for HHCAL:

- Short nuclear interaction length: ~ 20 cm.
- Good UV transmittance: UV cut-off < 350 nm.
- Some scintillation light, not necessary bright and fast.
- Cost-effective material: < $2/cc for 100 m$^3$!
- Radiation hardness is not crucial at the ILC/CLIC.

R.-Y. Zhu, Talk given in ILCWS-8, Chicago, November 18, 2008
## Candidate Crystals for HHCAL

R.-Y. Zhu., 2011 Linear Colliders Workshop of the Americas, Eugene

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$\text{Bi}_4\text{Ge}<em>3\text{O}</em>{12}$ (BGO)</th>
<th>PbWO$_4$ (PWO)</th>
<th>PbF$_2$</th>
<th>PbClF</th>
<th>$\text{Bi}_4\text{Si}<em>3\text{O}</em>{12}$ (BSO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (g/cm$^3$)</td>
<td>7.13</td>
<td>8.29</td>
<td>7.77</td>
<td>7.11</td>
<td>6.8?</td>
</tr>
<tr>
<td>$\lambda_1$ (cm)</td>
<td>22.8</td>
<td>20.7</td>
<td>21.0</td>
<td>24.3</td>
<td>23.1</td>
</tr>
<tr>
<td>$n$ @ $\lambda_{\text{max}}$</td>
<td>2.15</td>
<td>2.20</td>
<td>1.82</td>
<td>2.15</td>
<td>2.06</td>
</tr>
<tr>
<td>$\tau_{\text{decay}}$ (ns)</td>
<td>300</td>
<td>30/10</td>
<td>?</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>$\lambda_{\text{max}}$ (nm)</td>
<td>480</td>
<td>425/420</td>
<td>?</td>
<td>420</td>
<td>470</td>
</tr>
<tr>
<td>Cut-off $\lambda$ (nm)</td>
<td>310</td>
<td>350</td>
<td>250</td>
<td>280</td>
<td>300</td>
</tr>
<tr>
<td>Light Output (%)</td>
<td>100</td>
<td>1.4/0.37</td>
<td>?</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>Melting point ($^\circ$C)</td>
<td>1050</td>
<td>1123</td>
<td>842</td>
<td>608</td>
<td>1030</td>
</tr>
<tr>
<td>Raw Material Cost (%)</td>
<td>100</td>
<td>49</td>
<td>29</td>
<td>29</td>
<td>47</td>
</tr>
</tbody>
</table>
PbClF Crystals

Guohao Ren of SIC: Talk at the 2nd Workshop for HHCAL

Crystal structure of PbClF

D = 7.11 g/cm³
Melting point = 608°C
Space group = P/4nmm
a = 4.10 Å; c = 7.22 Å

Figure 2.1 Phase relations in PbCl₂-PbF₂ system

Early PbClF crystal samples grown at SICCAS

June 9, 2011
Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
## Recent PbFCl Samples

<table>
<thead>
<tr>
<th>ID</th>
<th>PbFCl-1</th>
<th>PbFCl-2</th>
<th>PbFCl-3</th>
<th>PbFCl-4</th>
<th>PbFCl-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doping</td>
<td>--</td>
<td>Na 0.5at%</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Dimension (mm)</td>
<td>10x10x2</td>
<td>10x10x2</td>
<td>30x10x5</td>
<td>20x10x3</td>
<td>~10x10x9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ID</th>
<th>PWO</th>
<th>PbFCl-1</th>
<th>PbFCl-2</th>
<th>PbFCl-3</th>
<th>PbFCl-4</th>
<th>PbFCl-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-luminescence</td>
<td></td>
<td>Peaked @ 420 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L.O. (% PWO)</td>
<td>100</td>
<td>14</td>
<td>64</td>
<td>33</td>
<td>35</td>
<td>31</td>
</tr>
<tr>
<td>L.O. (% BGO)</td>
<td>1.8</td>
<td>0.25</td>
<td>1.1</td>
<td>0.59</td>
<td>0.63</td>
<td>0.56</td>
</tr>
</tbody>
</table>

June 9, 2011

Talk given in TIPP 2011, Chicago, by Ren-yuan Zhu, Caltech
PbFCl: Transmittance & Emission

Cutoff: <300 nm

Peak: 420 nm

X-ray excited luminescence (20 Kv, 40µA)

- PWO (13x13x13 mm)
- PbFCl-1
- PbFCl-2
- PbFCl-3
- PbFCl-4
PbFCl: PHS & LO

Light Output: 8 p.e./MeV or 1/3 of PWO

PWO

- Constant: 1022.
- Mean: 253.5
- Sigma: 39.37

PMT: R2059, HV = -2100 V, Na-22
Gate: 1000ns, Ped: 150 ch, Cali. = 4.5 ch/p.e.
L.Y. = 23 p.e./MeV

PbFCl-3

- Constant: 513.5
- Mean: 186.2
- Sigma: 29.49

PMT: R2059, HV = -2100 V, Na-22
Gate: 1000ns, Ped: 150 ch.
PbFCl Summary

Decay Time: 24 ns

Summary

Consistent X-luminescence peaked at 420 nm observed in all PbFCl samples.

Transmittance cut-off at <300 nm.

Weak scintillation light with decay time of 24 ns observed in all PbFCl samples.
PbF$_2$:Gd

Consistent photo-luminescence and X-luminescence were observed in Gadolinium doped cubic lead fluoride (PbF:Gd) crystal samples.
No scintillation observed within 1000 ns gate

<table>
<thead>
<tr>
<th>Constant</th>
<th>1104.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>196.8</td>
</tr>
<tr>
<td>Sigma</td>
<td>27.22</td>
</tr>
</tbody>
</table>

PWO (3x3x4 cm)

PMT: R2059, HV = -2100 V, Cs-137
Gate: 1000 ns, Ped: 155 ch, Cali. = 3.0 ch/p.e.
L.Y. = 13.8 p.e./MeV

PbF$_2$

PMT: R2059, HV = -2100 V
Gate: 1000 ns, Cs-137

Undoped
Gd doped
X-Luminescence of PbF$_2$:Gd

Estimated up-limit: $<10\%$ of PWO
Scintillation Decay: PbF$_2$:Gd

An X-ray excited decay time system with 85 ns pulse

\[ I = A_1 \exp\left(-x/\tau_1\right) \]

\[ A_1 = 100.0 \]
\[ \tau_1 = 1.24 \]
\[ \chi^2/DOF = 1.5 \]
X-Luminescence Decay: PbF$_2$:Gd

\[ I = A_1 \exp(-x/\tau_1) + A_2 \exp(-x/\tau_2) \]

- $A_1 = 87.1$, $A_2 = 12.9$
- $\tau_1 = 7.3$, $\tau_2 = 25.6$
- $\chi^2/\text{DOF} = 3.4$

Constant-1: 7 ms
Constant-2: 25 ms
Photoluminescence Decay: PbF:Gd

Constant-1: 6 ms  Constant-2: 22 ms

Photo-luminescence measured with PLS-920 running @ 290K
Ex:272 nm; Em:311nm

Counts

Residuals

Time/ms

Decay Results
τ1 5.80ms
τ2 22.00ms
χ² 1.368
Summary

PbFCl

- Good optical transmittance achieved with cutoff < 300 nm.
- Blue X-luminescence found with a peak @ 420 nm.
- Scintillation decay time constant found to be about 24 ns with LO 15% to 64% of PWO, depending on sample quality.
- It is a good candidate material for the HHCAL detector concept.

PbF$_2$:Gd

- Consistent X- and Photo- luminescence observed
- Two consistent decay time constants found in X-/Photo- luminescence from PbF:Gd: 7 ms/5 ms and 25 ms/22 ms.