Calorimetry with meta-crystals

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Outline

► Introduction - General
► Calorimetry with meta-crystals
► Dual readout and energy correction
► Case studies and simulation results
► Questions - Outlook
Introduction - General

- R&D for future hep calorimetry: mainly 3 lines of approach
  - particle flow approach (CALICE)
  - dual readout calorimetry (DREAM)
  - crystal calorimetry (e.g. see HHCAL workshop)

- particle flow paradigm
  - highly granular EM and HADR calorimeters to allow very efficient pattern recognition for excellent shower separation and PID within jets to provide excellent jet reconstruction efficiency

- dual readout calorimetry
  - measurement of both the ionisation/scintillation and the Cherenkov signals generated by a hadronic shower in order to determine on an event by event basis the electromagnetic fraction of the shower and so to cancel/correct for this source of fluctuation that degrades the energy resolution of the calorimeter

- crystal calorimetry
  - an approach that could combine the excellent energy resolution of crystals (homogeneous detector) with dual readout, if scintillation and Cherenkov signals can be separated and recorded, and with particle flow/imaging capabilities if the detector is segmented with high granularity
Dual readout with metamaterials

- the meta-crystals concept

- consisting of **undoped** and **Ce doped** heavy crystal fibers of identical material. The undoped crystals behave as **Cherenkov radiators** while the doped crystals behave as **scintillators**

- a candidate material is the **Lutetium Aluminium Garnet (LuAG) crystal** 

\[
\text{(Lu}_3\text{Al}_5\text{O}_{12})
\]

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Optical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>6.73 gr/cm³</td>
</tr>
<tr>
<td><strong>Zeff</strong></td>
<td>62.9</td>
</tr>
<tr>
<td>Radiation length (X_0)</td>
<td>1.41 cm</td>
</tr>
<tr>
<td>Interaction length (\lambda_I)</td>
<td>23.3 cm</td>
</tr>
<tr>
<td>Melting point</td>
<td>2260 °C</td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>(8.8 \times 10^{-6}/°C)</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>31 W/m°C</td>
</tr>
<tr>
<td>Light yield (Ce doped)</td>
<td>&gt; 25000 ph/MeV (50% of NaI)</td>
</tr>
<tr>
<td>Emission wavelength</td>
<td>535 nm (Ce doped)</td>
</tr>
<tr>
<td>Decay time (Ce doped)</td>
<td>60 nsec</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.842 at 633 nm</td>
</tr>
<tr>
<td>Cherenkov threshold</td>
<td>97 keV</td>
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<tr>
<td>Max Cherenkov angle</td>
<td>57°</td>
</tr>
<tr>
<td>Total reflection angle</td>
<td>33°</td>
</tr>
</tbody>
</table>

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R&D activities

- material development
  
  comprehensive program of studies within the framework of the Crystal Clear Coll. with focus on hep and medical imaging applications

- testbeam activities
  
  very first testbeam studies with bundles of fibers exposed to electron beam
  
  small scale tests i.e. equivalent to a level of a single calorimetric channel
  
  data collection during Sep08, May09, Nov09

- simulation studies
  
  systematic scanning of the parametric space wrt granularity, sampling fraction, readout fraction, total length etc, for first understanding of performance trends and showstoppers and to proceed from an ideal case to a realistic one
Crystal fiber production

- Fiber diameter between 0.3-3 mm, length up to 2 m
- Pulling rate ranging from 0.1 to 0.5 mm/min
- Capillary die can be non-cylindrical (e.g. square, hexagonal etc)
- Overall cost per unit volume of production expected to be comparable to that of standard crystal growth methods

(courtesy of Fibercryst-Lyon, Cyberstar-Grenoble)

(20 fibers of diameter=2 mm, length=30 cm)
Concept of a readout unit

- A unit consists of a structured distribution of different types of fibers.

- Typical dimensions of a unit:
  \[ d = 1 - 1.5 \, R_M, \quad L = 20 - 25 \, X_0 \]

- Light from different types of fibers is directed to different SiPMTs by using diffractive optics light concentrators (micro-lenses).

- Diffractive optics plate with pattern to match the structure of fibers.
Crystal fiber studies - material development

Transmission

Attenuation

Excitation - Emission

Diffusion

(see also talk by P.Lecoq at HHCAL Workshop)
Fiber bundles exposed to beam

(20 fibers of diameter=2 mm, length=80 mm)  (20 fibers of diameter=2 mm, length=80 mm)

scintillator  
Ce doped LuAG  

Cherenkov radiator  
undoped LuAG
Average pulses

(scintillator)

Ce doped LuAG

(Cherenkov radiator)

undoped LuAG
Testbeam results

Left-Right asymmetry of signal
Dual readout and energy correction

- **correct Eionz for single pions**

  : define CorrectionFactor = 1 - calibr * Echer/Eionz
  : with calibr = Eionz/Echer for electrons at given energy
  : get correction function Fionz() by fitting Eionz vs CorrectionFactor
  : corrected energy = Eionz/Fionz(), applied to pions of various energies

Or equivalently

- **correct Echer for single pions**

  : define CorrectionFactor = 1 - calibr * Echer/Eionz
  : with calibr = Eionz/Echer for electrons at given energy
  : get correction function Fcher() by fitting Echer vs CorrectionFactor
  : corrected energy = Echer/Fcher(), applied to pions of various energies
case of an homogeneous detector

\[ \pi^+ \text{ 1 GeV} \quad \pi^+ \text{ 5 GeV} \quad \pi^+ \text{ 10 GeV} \]

corrected by 1 GeV

corrected by 5 GeV

corrected by 10 GeV
Energy resolution for single pions

corrected by $\pi^- 5$ GeV

corrected by $\pi^- 5$ GeV

homogeneous case  sampling case (e.g. abs:ion:cher 5:18:2)
Case studies

▸ in brief

- systematic scanning of the parametric space wrt granularity, sampling fraction, readout fraction, total length, mixture of conventional and dual readout components, corresponding composition, etc

. "single cases"
  calorimeter with dual readout at full depth

. "mixed cases"
  calorimetric volume composed of conventional and dual readout parts

▸ in the following

- discuss a "single case" calorimeter without leakage \((4.3 \times 4.3 \times 8.6 \lambda_1^3)\)
Correlation plots for various readout fractions

CHER READOUT FRACTION

100%  50%  25%  12.5%  6.25%

IONZ READOUT FRACTION

100%  50%  25%  12.5%  6.25%
Energy resolution vs readout fraction ($\pi^-$ 5 GeV)

corrected by $\pi^-$ 5 GeV

corrected by $\pi^-$ 10 GeV

corrected by $\pi^-$ 20 GeV

similar results with different correction energies
Energy resolution for different correction energies

\( \pi^- 5 \text{ GeV} \)

\( \pi^- 10 \text{ GeV} \)

\( \pi^- 20 \text{ GeV} \)

(different colors denote different ionz readout fractions)

(different symbols denote different energy samples used for correction)
Stochastic term vs readout fraction

(study with single pions)

case of a calorimeter of $\approx 4.3 \times 4.3 \times 8.6 \, \lambda_{\text{I}}^3 (1 \times 1 \times 2 \, \text{m}^3 \, \text{LuAG})$

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Stochastic term and calorimeter length

(Study with single pions)

Stochastic term vs. cher fraction

Calo length:
- 150 cm, 6.44 $\lambda_i$
- 170 cm, 7.30 $\lambda_i$
- 200 cm, 8.58 $\lambda_i$

Ionz fraction:
- 100.00%
- 12.50%

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Open questions

- Design issues and practical questions

  though we are at the very early stage of development of such a concept we always have in mind some design issues that should be studied soon and which need rigorous R&D effort and prototyping

  ▶ material production and cost drivers
  ▶ readout scheme
  ▶ construction
  ▶ scale-up problems
  ▶ + ...

  can only be answered through the usual phase of prototype development, test and study of 1 permille → 1 percent → 10 percent modules of the final detector
Summary - Outlook

- metacrystals for calorimetry
  - R&D effort on 3 fronts
    - material development
    - testbeam activities
    - simulation studies
  - briefly discussed first results with bundles of crystal fibers exposed to beam and mc parametric scan of an ideal calorimeter

- next steps
  - continue simulation studies and material development
  - near-term goal to build a multichannel module (e.g. miniEcal) and expose it to beam