The impact of crystal light yield non-proportionality on a typical calorimetric space experiment.

A paper including the details of this work was recently submitted on JINST.
Space detector for cosmic rays (CR).

- Direct CR detection in the multi-TeV region is relevant for:
  - dark matter models (electron, positron...),
  - CR sources nearby the Earth (electron, positron...),
  - acceleration, propagation models (protons, nuclei...).
  - ...

- Spectrometers (AMS-02, PAMELA, ...):
  - Limited acceptance and M.D.R. → particle energy < ~TeV

- Recent calorimetric experiment:
  - Large acceptance → high energy region
  - Current experiment: DAMPE, CALET, Fermi-LAT...
  - Future experiment: HERD (2027).
Disagreement among experiments.

Electron+positron flux

Oxygen flux

Understand the reason of the discrepancies for a correct interpretation of the data and for designing future experiments.
Main idea of this work.

- Calorimeters are typically made with inorganic scintillating crystals.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Material</th>
<th>Electromagnetic depth ($X_0$)</th>
<th>Hadronic depth ($\lambda_I$)</th>
<th>Launch year</th>
</tr>
</thead>
<tbody>
<tr>
<td>CALET</td>
<td>PWO</td>
<td>27</td>
<td>1.2</td>
<td>2015</td>
</tr>
<tr>
<td>DAMPE</td>
<td>BGO</td>
<td>32</td>
<td>1.6</td>
<td>2015</td>
</tr>
<tr>
<td>FERMI</td>
<td>CsI(Tl)</td>
<td>8.6</td>
<td>0.4</td>
<td>2008</td>
</tr>
<tr>
<td>HERD</td>
<td>LYSO</td>
<td>55</td>
<td>3.0</td>
<td>2027 (expected)</td>
</tr>
</tbody>
</table>

- Possible systematic effect is due to the non proportional light response of the crystals.
- The scintillation light yield depends on dE/dx.
- Minimalist approach: two phenomena are considered.
Minimalist approach: “Birks” (1).

- At high excitation density the quenching (or Birks) effect is dominant.
- Assuming a division of the energy deposition into cylindrical "core" and "halo" regions surrounding the particle trajectory

\[
L'_B = \frac{1 - \eta_H}{1 + B(1 - \eta_H) \times \frac{dE}{dx}} + \eta_H
\]

Birks parameter

Fraction of carries escaped to the halo region
Minimalist approach: “Onsager” (2).

- At low excitation density another phenomenon can be dominant. A fraction of initial electrons and holes that do not form excitons can combine if they are closer than the Onsager radius can combine to form excitons.

\[ L_O = 1 - \eta_{e/h} \exp \left( -\frac{(dE/dx)}{(dE/dx)_O} \right) \]

- Fraction of initial electrons and holes that do not form excitons.
- Strength of the Onsager term.
Minimalist approach and MC simulation.

- Combining the modified Birks and Onsager mechanisms the relative luminosity efficiency is:

\[
L = \left[ 1 - \frac{\eta_e}{h} \exp \left( - \frac{(dE/dx)}{(dE/dx)_O} \right) \right] \times \left[ \frac{1 - \eta_H}{1 + B (1 - \eta_H) \times \frac{dE}{dx}} + \eta_H \right].
\]

- To study the dE/dx in different materials, FLUKA simulation of particle showers is employed.
- Minimum energy threshold: 1 keV for electrons and 100 eV for photons.
- All the physical processes that can contribute to the amount of ionisation are activated.
MIP energy deposit density.

- For every bin of ionisation density, the amount of the energy released is provided by the simulation.

Helium/proton light singal ratio is different from 4.

It will be less or greater than 4 for silicate or alkali scintillator respectively.
Material characterization with nuclei

- The usual ways to study the scintillator non proportionality are Compton electrons, photon response.
- Here the ionization produced by high energy nuclei is used:
  - Technique already exploited by: FERMI, DAMPE, ...

Results of FLUKA simulation for LYSO crystals

Ionization range:
5 MeV/cm – 2 GeV/cm
CaloCube project and prototype.

- CaloCube was a 4 years R&D activity aiming to optimize the design of a wide-acceptance, 3-D imaging calorimeter to be operated in space
- Main application of CaloCube idea → HERD (2027)

2015: prototype made of CsI(Tl) crystals read-out with photo-diodes tested with nuclei at CERN (SPS)

PDs: VTH2090.
Electronics: CASIS chip.
Different crystals tested with nuclei.

- A tray was loaded with cubic crystals made of different scintillator materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Size (cm)</th>
<th>( \rho ) (g/cm(^3))</th>
<th>( \lambda_I ) (cm)</th>
<th>( X_0 ) (cm)</th>
<th>( \lambda_{max} ) (nm)</th>
<th>( \tau_{decay} ) (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGO</td>
<td>2.0</td>
<td>7.1</td>
<td>23</td>
<td>1.1</td>
<td>480</td>
<td>300</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>3.6</td>
<td>4.5</td>
<td>40</td>
<td>1.9</td>
<td>550</td>
<td>1220</td>
</tr>
<tr>
<td>LYSO</td>
<td>2.0</td>
<td>7.4</td>
<td>21</td>
<td>1.1</td>
<td>420</td>
<td>40</td>
</tr>
<tr>
<td>YAP</td>
<td>2.2</td>
<td>5.5</td>
<td>22</td>
<td>2.7</td>
<td>370</td>
<td>27</td>
</tr>
<tr>
<td>YAG</td>
<td>2.5</td>
<td>4.6</td>
<td>25</td>
<td>3.5</td>
<td>550</td>
<td>70</td>
</tr>
<tr>
<td>BaF(_2)</td>
<td>3.1</td>
<td>4.9</td>
<td>31</td>
<td>2.0</td>
<td>300</td>
<td>650</td>
</tr>
</tbody>
</table>

Silicon tracker upstream the prototype: it provides the particle impact position and nuclei charge.

With CSI(Tl) crystals, ions that traversed the test crystal without starting a shower are selected.
Nuclei measurement results

Mean value of the signals divided by $Z^2$

Relative luminosity efficiency

$D_Z = \text{signal (ADC counts)}/Z^2$

Graphs showing relative light yield for CsI(Tl), LYSO, BGO, YAP, and BaF2 as a function of $Z$.
“Minimalist approach” fit.

The output of the simulation and the luminosity data are used to fit the minimalist model.

This is able to reproduce the experimental trends: $\chi^2_{\text{red}}$ from 0.64 to 1.64.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\eta_e/h$</th>
<th>$(dE/dx)_O$</th>
<th>$\eta_H$</th>
<th>$(1/B)$</th>
<th>$\chi^2_{\text{red}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGO</td>
<td>$0.159 \pm 0.033$</td>
<td>$98 \pm 45$</td>
<td>$0.1884 \pm 0.0039$</td>
<td>$364 \pm 42$</td>
<td>$1.64$</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>$0.326 \pm 0.010$</td>
<td>$34.1 \pm 2.8$</td>
<td>$0.121 \pm 0.012$</td>
<td>$1338 \pm 64$</td>
<td>$0.81$</td>
</tr>
<tr>
<td>LYSO</td>
<td>$0.758 \pm 0.045$</td>
<td>$164.7 \pm 8.4$</td>
<td>$0.0274 \pm 0.0048$</td>
<td>$45.1 \pm 9.1$</td>
<td>$0.64$</td>
</tr>
<tr>
<td>YAP</td>
<td>$0.2212 \pm 0.0085$</td>
<td>$90 \pm 11$</td>
<td>$0.174 \pm 0.012$</td>
<td>$873 \pm 70$</td>
<td>$1.24$</td>
</tr>
<tr>
<td>YAG</td>
<td>$0.0912 \pm 0.015$</td>
<td>$73 \pm 29$</td>
<td>$0.1052 \pm 0.0055$</td>
<td>$462 \pm 31$</td>
<td>$1.23$</td>
</tr>
<tr>
<td>BaF$_2$</td>
<td>$0.322 \pm 0.024$</td>
<td>$35.8 \pm 6.2$</td>
<td>$0.3440 \pm 0.0071$</td>
<td>$546 \pm 36$</td>
<td>$1.11$</td>
</tr>
</tbody>
</table>
Typical space calorimeter simulation.

- Possible systematic effects on space calorimeter energy measurements, simulation:
  - homogeneous cube of 1 m$^3$ LYSO, BGO, CsI.
  - high energy electron and proton shower.
- For a real experiment the effect will depend on:
  - crystal manufacturer,
  - specific geometry and calibration,
  - acquisition system (e.g. integration time)
  - ...
- Here we show the possible existence of systematic effects due to non-proportionality and we can not determine quantitatively these effects for running experiments.
MIP vs electron showers.

- Calorimeter calibrated with non-interacting particle on-orbit.
- Different ionization density profile between MIP and shower.

We assume: calibration with MIP.

Systematic shift of the measured total shower energy with LYSO $\sim -2.3\%$.

Constant with electron energy from 10 GeV to 1 TeV
Systematic error on proton showers.

- The ionization density profile is not constant with proton energy, thus the systematic error does depend on energy.
Impact on electron and proton fluxes.

- **Systematic shift of energy measurement**

<table>
<thead>
<tr>
<th>Material</th>
<th>Electrons</th>
<th>Protons 10 GeV</th>
<th>Protons 100 GeV</th>
<th>Protons 1 TeV</th>
<th>Protons 10 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>LYSO</td>
<td>-2.3%</td>
<td>-7.1%</td>
<td>-5.6%</td>
<td>-4.6%</td>
<td>-3.4%</td>
</tr>
<tr>
<td>BGO</td>
<td>-1.1%</td>
<td>-4.3%</td>
<td>-3.0%</td>
<td>-2.3%</td>
<td>-1.8%</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>+0.82%</td>
<td>+2.9%</td>
<td>+2.0%</td>
<td>+1.5%</td>
<td>+1.2%</td>
</tr>
</tbody>
</table>

- **Fluxes affected by the systematic error.**
Conclusion

- CaloCube data and minimalist approach are employed to characterize the non proportionality of scintillators.
- **If the calorimeter response is calibrated with MIP, a effect on the energy measurement of few percents exists.**
- For future experiment, we suggest:
  - to characterize the scintillator material with the flight readout system (e.g. by using high energy nuclei),
  - To estimate the impact of non-proportionality and eventually to implement the effect inside shower simulation.
- About the results published by running experiments, it is not clear if this effect is already included in detector simulation, since it is not mentioned in papers.