Light yield non-proportionality of LYSO(Ce) scintillators to $x/\gamma$ rays and measurement of the Birks-Onsager quenching parameters.

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Scintillating materials

Ideal Scintillator

- High Light output
- Fast decay time
- Very dense
- High Z

Light output should be linear with Energy release

Important to characterise its response

P. Lecoq. [Link to presentation]
LYSO calorimeters in space

LYSO(Ce) Lutetium-Yttrium Oxyorthosilicate is fast (~40ns) dense (7.1g/cm$^3$) high Z ($Z_{\text{eff}}$ ~60) strong and good scintillator (LY~30ph./keV)
For this reason is adopted in medical devices, in current space experiments and in planned space calorimeters.

However LYSO is non-proportional (& slightly radioactive)
Response of LYSO needs an accurate calibration to avoid systematic effects in measured particle fluxes at high-E
Non-proportional light response at high dE/dx (the Birks quenching)

**Excitons**: neutral carriers, higher mobility

$$\frac{dL}{dx} = \frac{dL}{dE} \frac{dE}{dx}$$

- exciton
- exciton (higher energy)
- NR recomb. = phonons

Koba et al. “Scintillation Efficiency of Inorganic Scintillators for Intermediate-Energy Charged Particles”

<table>
<thead>
<tr>
<th></th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
<th>GSO(Ce)</th>
<th>LYSO(Ce)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birks</td>
<td>a</td>
<td>k_B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>0.905</td>
<td>1.08</td>
<td>1.03</td>
<td>0.938</td>
</tr>
<tr>
<td>k_B</td>
<td>9.10x10^{-4}</td>
<td>1.29x10^{-3}</td>
<td>3.22x10^{-3}</td>
<td>7.60x10^{-3} g/(cm²MeV)</td>
</tr>
</tbody>
</table>


- $$k_B = 5.68 \times 10^{-3} \text{ cm/MeV}$$ Helium beam
- $$k_B = 1.03 \times 10^{-3} \text{ cm/MeV}$$ Carbon beam

?? puzzling
Non-proportional light response at high $dE/dx$ (generalised Birks)

$\frac{dL}{dE} = \frac{1}{1 + k_B \frac{dE}{dx}} \rightarrow \frac{1 - \eta_H}{1 + k_B (1 - \eta_H) \frac{dE}{dx}} + \eta_H$

Introducing a percentage of carriers escaping the ionization cylinder

escaping fraction of carriers that radiatively recombines


Excitons: neutral carriers, higher mobility
Non-proportional light response at low dE/dx (the Onsager term)

Low dE/dx

Excitons: neutral carriers, higher mobility

$\eta_e/h$
Fraction of initial electrons and holes that do not form excitons. They can combine to form new excitons if they are closer than the Onsager radius

$L_o = 1 - \eta_e/h e^{-\frac{dE/dx}{(dE/dx)_o}}$


A reference model for non-proportional light response in scintillator is:

$$\frac{dL}{dE} = \left[ \frac{1 - \eta_H}{1 + k_B (1 - \eta_H) \frac{dE}{dx}} + \eta_H \right] \left[ 1 - \eta_e/h \exp \left( -k_o \frac{dE}{dx} \right) \right]$$

Generalised Birks term

Onsager term
Non-proportional light response

\[
\frac{dL}{dE} = \left[ \frac{1 - \eta_H}{1 + k_B(1 - \eta_H) \frac{dE}{dx}} + \eta_H \right] \left[ 1 - \frac{\eta_e}{h} \exp \left( -k_o \frac{dE}{dx} \right) \right]
\]

Generalised Birks term

Onsager term

Adriani et al, 2022 JINST 17 P08014 “Light yield non-proportionality of inorganic crystals and its effect on cosmic-ray measurements”
The measurements of Adriani et al. (2022)

CERN SPS
Argon beam
39*A GeV

4cm
PE target
Z=1 to 18 fragments
Si Tracker

Quenching measured with (Minimum Ionizing) relativistic nuclei with Z ranging from 1 to 18

Results in term of (mod.) Birks-Onsager reference model:

<table>
<thead>
<tr>
<th>Material</th>
<th>$\eta_{e/h}$</th>
<th>$(dE/dx)_0$ (MeV/cm)</th>
<th>$\eta_H$</th>
<th>$1/k_B$ (MeV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGO</td>
<td>0.159 ± 0.033</td>
<td>98 ± 45</td>
<td>0.1884 ± 0.0039</td>
<td>364 ± 42</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>0.326 ± 0.010</td>
<td>34.1 ± 2.8</td>
<td>0.121 ± 0.012</td>
<td>1338 ± 64</td>
</tr>
<tr>
<td>LYSO</td>
<td>0.758 ± 0.045</td>
<td>164.7 ± 8.4</td>
<td>0.0274 ± 0.0048</td>
<td>45.1 ± 9.1</td>
</tr>
</tbody>
</table>

$\eta_{e/h}$ is not compatible with 0 => not “pure” Birks, Onsager term is required

How to compare with other/previous LYSO data?
1) Complementary information from response to x/$\gamma$ ray
2) Koba et al (2011-2007): He-C have $1/k_B = 180$ to 1000 MeV/cm
3) HEPD-02 Proton beam test (analysis still ongoing)
Our measurement of LYSO Light Yield with $\gamma$ rays @ INFN/TIFPA

Hamamatsu R5946 PMT  LYSO (7.9 g)

("by-product" of the search for rare EC decay in $^{176}$Lu )

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Search for electron capture in $^{176}$Lu with a lutetium yttrium oxyorthosilicate scintillator

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we calibrate the detector with gamma rays from $^{241}$Am $^{133}$Ba $^{176}$Lu $^{22}$Na $^{137}$Cs and $^{60}$Co sources

Counts

<table>
<thead>
<tr>
<th>Energy [keV]</th>
<th>Lyso (Counts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20</td>
<td></td>
</tr>
<tr>
<td>20-40</td>
<td></td>
</tr>
<tr>
<td>40-60</td>
<td></td>
</tr>
<tr>
<td>60-80</td>
<td></td>
</tr>
<tr>
<td>80-100</td>
<td></td>
</tr>
</tbody>
</table>

$L_{\alpha\beta\gamma}$ Np

$^{237}$Np* (59.5)
LYSO non-proportionality is non-negligible below 100 keV

- X-ray photon < 100 keV → emitted one or more “slow” electrons
- Lower Light Yield → High dE/dx

- confirmation of the effect observed by many measurements in the past
- the existing measurements have not negligible (not quoted) systematic errors
- is hard to reject the $^{176}$Lu background (40Bq/g)

50% reduction of Light Yield of LYSO for 10 keV $\gamma$ rays

Lu K-edge (63.3 keV)
To characterize and calibrate the LYSO crystal:
- Adopted the Birks+Onsager quenching model
- Geant4 simulation with **very high spatial resolution**
  10nm maxstep and 1nm secondary production cuts
  (FTFP_BERT + G4StandardEM_op4 + G4EmLowEPPPhysics)
- At each step we computed the contribution to the LY based on the dE/dx locally computed.

**fit of experimental data and inference of parameters based on the G4 MC simulations**
Geant4-based MonteCarlo Fit

Set Parameters: $k_B, \eta_H, \eta_{e/h}(dEdx)_O$

gamma ray Energy

Scan in Energy

Geant4 application:
- Mod. Birks
- Onsager
- Small steps

Exploration of the 4D parameter space

- Minimization of the $\chi^2$
- Estimate of the parameter

Heavy load of computation

found (expected) dependence on step size. Systematic related to MC under investigation
Results: forcing $\eta_{e/h} = 0$ ("pure" Birks, no Onsager)

- not good chisquares are obtained
- forcing $\eta_{e/h} = 0$ not full compatibility
- Koba (2007) He beam result "puzzling"

$\chi^2 = 20.7/13$

$k_B = 10.4 \pm 0.9$ mm/GeV

$\eta_H = 0$

$\eta_H$ is compatible with 0 for both

1σ contours

$\chi^2 = 315/100$

$k_B = 0.022$ mm/MeV

$\eta_H = 0.027$
Results: $\eta_{e/h} > 0$ (the “reference” model Birks + Onsager)

$k_B$ are compatible with Adriani (2022)

$\eta_H = 0$ is preferred by Koba & $\gamma$ rays

$\chi^2 = 151/100$

$\chi^2 = 12/13$

$k_B = 1.3$ mm/MeV

$k_o = 0.012$ mm/MeV

$\eta_H = 0$

$\eta_{e/h} = 0.99$

$k_B = 0.186$ mm/MeV

$k_o = 0.29$ mm/MeV

$\eta_H = 0.002$

$\eta_{e/h} = 0.81$

$\chi^2 = 12/13$
Results: $\eta_{e/h} > 0$ (the “reference” model Birks + Onsager)

- observed the (expected) strong correlation of $k_B$ and $\eta_{e/h}$
- indication for a relatively large $\eta_{e/h}$ comes from all the measurements
- a “pure” Birks ($\eta_{e/h} = 0$) rejected with high C.L.
- $x/\gamma$ rays information is “folded” and cannot give precise inference of $k_o$
Conclusion / to-do list

The qualitative picture:
- Birks-Onsager model works from few keV electrons to few GeV nuclei

The quantitative agreement is not perfect:
- would be nice to plot the $1\sigma$ contours from Adriani et al. (2022)
- possible systematics in measurements [e.g. He vs C in Koba et al. (2007)]
- (ongoing study) systematics of the heavy MC computation for x/$\gamma$ rays

A new proton beam test made in 2023:
@ INFN-TIFPA
for LYSO used in HEPD-02 detector
(analysis ongoing)

Thank you!