Li-containing scintillating bolometers for low background physics

Luca Pattavina
INFN-LNGS
luca.pattavina@lns.infn.it

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OUTLINE

- Rare event physics sensitivity
- The bolometric technique
  - pros and cons
- Scintillating bolometers
  - LMO & LEBO
- Conclusions
Detection principle

**General idea:**
to measure the kinetic energy of the decay products/secondary particles/...
(keV-MeV energy scale)

**Calorimetry**
* Excellent energy resolution
* High efficiency
* Wide choice of compounds

**Scint./Track**
* Large mass source
* Particle identification

**Source = Detector**

**Source ≠ Detector**
Sensitivity for DBD0v, rare decays, ...

\( S_{0v} \): half-life corresponding to the minimum number of detectable signals above background at a given C.L.

- high natural i.a. of nuclide candidates or enrichment
- a.i.: isotopic abundance
- Large mass array
- M: detector mass
- t: measuring time
- \( S_{0v} \propto a.i. \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \)
- B: background
- \( \Delta E \): energy resolution

- Deep underground location
- Material selection (radio-pure)
- High granularity

**DBD experiment**

- Q-value: 2995 keV
- Material: ZnSe
- Enriched a.i.: 95%
- Source Mass: \(~10\) kg of Se-82
- Projected Bkg: \(~0.001\) c/keV/kg/y
- Resolution: \(~10\) keV @ ROI
- Sensitivity \( T_{1/2} \): \(~10^{26}\) y in 5 y

**DBD energy spectrum**
The bolometric technique

Almost all the deposited energy is converted into phonons which induce a measurable temperature rise.

The heat capacity of the crystal must be very small
(-\(\rightarrow\) low Temperature \(\sim\)10 mK)

Absorber
- \(M \sim 0.45\) kg
- \(C \sim 10^{-10}\) J/K
- \(\Delta T/\Delta E \sim 500\mu K/MeV\)

Sensor
- \(R = R_0 \exp[(T_0/T)^{1/2}]\)
- \(R \sim 100\) M\(\Omega\)
- \(\Delta R/\Delta E \sim 3\) M\(\Omega/MeV\)

Heat-sink: Copper
Thermal conductance (G): PTFE & gold wires

Thermometer: Ge-NTD
The underground facility

Experimental location:
- Average depth ~ 3650 m w.e.
- Muon flux ~ \( 2.6 \times 10^{-8} \, \mu/s/cm^2 \)
- Neutrons < 10 MeV: \( 4 \times 10^{-6} \, n/s/cm^2 \)
- Gamma < 3 MeV: 0.73 \( \gamma/s/cm^2 \)

Laboratori Nazionali del Gran Sasso
INFN, Italy
Bkg sources in bolometric experiments

Since bolometers are fully-active detectors and are sensitive to all radiation types, various sources can limit the experimental sensitivity.

- Neutrons =>
  - neutron activation: \((n,\gamma)\) reactions
  - appropriate shields are needed

- Muons =>
  - energy deposit in the ROI
  - underground installation & granularity & veto

- \(\beta/\gamma\)s =>
  - natural radioactivity \((^{238}\text{U} \& ^{232}\text{Th})\)
  - material selection

- Degraded \(\alpha\)s =>
  - \(\alpha\)s coming out from detector surfaces
  - surface cleaning and particle discrimination
The simultaneous read-out of light and thermal signals allows to discriminate the α background thanks to the scintillation yield different from β particles.

When a bolometer is an efficient scintillator at low temperature, a small but significant fraction of the deposited energy is converted into scintillation photons while the remaining dominant part is detected through the heat channel.

**QF**: is defined as the ratio of the signal amplitudes induced by an α and an β/γ of the same energy.
Bolometric LD

- HP-Ge disk (3-5 cm diameter, 0.1-1 mm thick)
- SiO$_2$ coating for darkening the surface => reduce light reflections
- Calibration with $^{55}$Fe X-rays @ 5.9 keV and 6.5 keV
  - Energy resolution: ~100 eV
  - Energy threshold: ~100 eV

<table>
<thead>
<tr>
<th>Detector</th>
<th>$\text{FWHM}_{\text{baseline}}$ [keV]</th>
<th>$\text{FWHM}^{^{55}\text{Fe}}$ [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.144±0.002</td>
<td>0.209±0.003</td>
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</tbody>
</table>

Figure 1. Calibrated energy spectrum of the Light Detector, the two prominent lines represent the two characteristics X-rays of $^{55}$Fe at 5.9 keV and 6.5 keV.

Figure 2. Light vs. Heat scatter plots for a calibration measurement with a $^{137}$Cs (left) and $^{40}$K (right) source. In the inset is shown the source peak, where just $\beta/\gamma$ events are selected.

This is the first time that the LY for this type of crystal is computed and it is in agreement with the estimation of $[5]$. The energy resolution of the Li$_2$MoO$_4$ crystal is evaluated applying a cut on the light channel, selecting just $\beta/\gamma$ events, the results vary from 5.19±0.35 keV at 661 keV to 4.35±0.42 keV at 1460 keV (see Fig. 2).
**Li$_2$MoO$_4$**

**Interesting for:**
- DBD-$^{100}$Mo
- n-detection
- solar axions

**Crystal features:**
- growth: Czochralski method
- materials: pure (99.5%) MoO$_3$ and Li$_2$CO$_3$
- weakly hygroscopic

**Cardani et al. arXiv:1307.0134, in pubblication on JINST**

m=33 g
Calibrations $\alpha$ & $n$ & $\gamma$
Background 344 h

Good particle discrimination using **Light vs. Heat**
Li$_2$MoO$_4$ with $\gamma$-source

$^{40}$K source

$^{137}$Cs source

FWHM: 3.7±0.8 keV
@ 661 keV

LY$_{\beta/\gamma}$ = 0.433±0.012 keV/MeV

Small crystal
=> no calibration at 2615 keV

FWHM: 4.7±1.1 keV
@ 1460 keV
Li$_2$MoO$_4$ with AmBe-source

Easy (fast) neutron tagging:

\[ ^6\text{Li} + ^1\text{n} \rightarrow ^3\text{H} + ^4\text{He} + 4.78 \text{ MeV} \]

$^6\text{Li}$:
- Large absorption cross section
  - 940 b @ 25 meV

$^6\text{Li}$:
- Natural i.a.
  - 7.6%

- Elastic neutrons scattering on Li, Mo and O
- Thermal neutron absorptions
- Fast neutron absorptions
3.3 Calibration with AmBe-source

During the testing of our Li\textsubscript{2}MoO\textsubscript{4} crystals, while the cluster of events at 5 MeV is produced by the resonance neutron capture, the first one, at 2.23 MeV, is produced by the reaction \( {}^3\text{H} + {}^4\text{He} \) because of its larger density energy deposit. In Fig. 4, we can see the energy dependence of the stopping power. As previously shown, \( \text{LY}({}^3\text{H} + {}^4\text{He}) = 0.122 \pm 0.022 \text{ keV/MeV} \).

The measured light yield of \( {}^6\text{Li} \) is shown in Fig. 5. The achieved FWHM energy resolution is 13.53\(^\pm\)0.02 keV. In Fig. 6, we are just able to give a cumulative \( \text{LY} \). This detector proved to be able to tag neutrons with kinetic energy varying from few meV to some MeV, assuming that the energy transfer from the neutron to the reaction products is linear.

In Fig. 7, we see the energy spectrum of low light yield events (lower band of the Light vs. Heat scatter plot for the calibration measurement with an AmBe-source). The larger counts at 4.78 MeV, this is estimated considering the amount of light produced by thermal neutron absorption peak at 4.78 MeV; the absorption cross section shows a resonance at about 240 keV. In the specific, the crystal was faced to a smeared Sm source, while in the lower one there are direct neutron interactions in the absorber. The energy dependence of \( \text{LY}(e^{-}) \) can induce saturation effects in the scintillator. The choice of such a low energy represents a consequence of the energy dependence of the stopping power. As previously shown, \( \text{LY}(e^{-}) \) is estimated at 5.3 MeV.

\( \text{LY}(\text{He}) = 0.122 \pm 0.022 \text{ keV/MeV} \)

FWHM @ 4.78 MeV: 14\(^\pm\)2 keV

\( {}^6\text{Li} \) neutron absorption cross section

JAEA Nuclear Data Center
\[ \text{Li}_2\text{MoO}_4 \text{ with } \alpha\text{-source} \]

Assuming linearity of LY\(_{\beta/\gamma}\):

\[ QF_\alpha(E) = \frac{LY_\alpha(E)}{LY_{\beta/\gamma}(E)} \]

\[ QF_\alpha(^{147}\text{Sm}) = 0.29 \pm 0.01 \]

\[ QF_\alpha(^{210}\text{Po}) = 0.42 \pm 0.03 \]

QF\(_\alpha\) is larger compared to other MO compounds like: ZnMoO\(_4\) and PbMoO\(_4\) (x2.5)

**Discrimination Power:**

\[ DP(E) = \frac{|\mu_\alpha(E) - \mu_\beta\gamma(E)|}{\sqrt{\sigma^2_\alpha(E) + \sigma^2_\beta\gamma(E)}} \]

\[ DP(1 \text{ MeV}-2.3 \text{ MeV}) \sim 3 \]

No evidence of particle discrimination with PSA

=> larger crystals are needed!

PSD works very well MO xtals
Li$_2$MoO$_4$ background

First measurement:
HP-Ge (1240 h)

<table>
<thead>
<tr>
<th>Chain</th>
<th>Nuclide</th>
<th>Activity (mBq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}$Th</td>
<td>$^{228}$Ac</td>
<td>$\leq 32$</td>
</tr>
<tr>
<td></td>
<td>$^{212}$Pb</td>
<td>$\leq 24$</td>
</tr>
<tr>
<td></td>
<td>$^{208}$Tl</td>
<td>$\leq 12$</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$^{214}$Pb</td>
<td>$\leq 20$</td>
</tr>
<tr>
<td></td>
<td>$^{214}$Bi</td>
<td>$\leq 21$</td>
</tr>
<tr>
<td></td>
<td>$^{40}$K</td>
<td>$= 170(80)$</td>
</tr>
<tr>
<td></td>
<td>$^{60}$Co</td>
<td>$\leq 8$</td>
</tr>
<tr>
<td></td>
<td>$^{137}$Cs</td>
<td>$\leq 4$</td>
</tr>
</tbody>
</table>

O.P. Barinova et al., NIM A 607 (2009) 573

Scintillating bolometer:
344 h bkg

New limits:

<table>
<thead>
<tr>
<th>Chain</th>
<th>Nuclide</th>
<th>Activity [$\mu$Bq/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}$Th</td>
<td>$^{232}$Th</td>
<td>$&lt; 94$</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$^{238}$U</td>
<td>$&lt; 107$</td>
</tr>
<tr>
<td></td>
<td>$^{210}$Pb</td>
<td>$729 \pm 160$</td>
</tr>
</tbody>
</table>

the crystal is hygroscopic: contaminated in $^{210}$Pb ($^{210}$Po)

Solar axions search

Detection of $^7$Li solar axions by means of resonant absorption on analogue targets in the labs.

In the Sun: $pp \rightarrow \ldots \rightarrow ^7$Be + e$^-$ → $^7$Li* → $^7$Li + axion

in the lab: $^7$Li + axion → $^7$Li* → $^7$Li + γ

We look for a γ emission at about 478 keV

Doppler effects ~0.5 keV
nuclear recoil ~$10^{-2}$ keV
... small crystal

Total number of absorptions:

$N_{abs} = N_{^7Li} \times T \times C^{te} \times \left( \frac{m_a}{1 \text{ eV}} \right)^4$

A.V. Derbin et al., JETP Lett. 81 (2005) 365

If we reverse the equation (considering BR and detection $\varepsilon$ (~5%)):

$m_a < 39 \text{ keV} \quad @ \quad 90 \text{ C.L.}$

on a 33 g crystal & 344 h bkg measurement

Current best limit:

$m_a < 8.6 \text{ keV} \quad @ \quad 90 \text{ C.L.}$

Li$_6$Eu(BO$_3$)$_3$

Interesting for:
- Eu-151 $\alpha$ decay
- n-detection
- solar axions

Crystal features:
- growth: Czochralski method in air atmosphere
- materials: high purity (99.99%) Li$_2$CO$_3$, Eu$_2$O$_3$ and B$_2$O$_3$

First bolometric test with 5x5x5 mm$^3$ crystal in: 2012 J. Phys.: Conf. Ser. 375 012025

Excellent particle discrimination using Light vs. Heat
Li$_6$Eu(BO$_3$)$_3$ Light Yield

\[ \text{LY}_\beta/\gamma = 7.38 \pm 0.02 \text{ keV/MeV} \]

Assuming linearity of \( \text{LY}_\beta/\gamma \):

\[ QF_\alpha(E) = \frac{\text{LY}_\alpha(E)}{\text{LY}_\beta/\gamma(E)} \]

- \( QF_\alpha^{(147}\text{Sm}) = 0.54 \pm 0.01 \)
- \( QF_\alpha^{(210}\text{Po}) = 0.84 \pm 0.05 \)
Li$_6$Eu(BO$_3$)$_3$ background

Live Time: >300 h bkg

Internal contaminations:

<table>
<thead>
<tr>
<th>Chain</th>
<th>Nuclide</th>
<th>Activity (mBq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}$Th</td>
<td>$^{232}$Th</td>
<td>3.5</td>
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<tr>
<td>$^{232}$Th</td>
<td>$^{232}$Th</td>
<td>3.5</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>$^{232}$Th</td>
<td>3.5</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$^{238}$U</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$^{238}$U</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>$^{226}$Ra</td>
<td>$^{226}$Ra</td>
<td>2.9</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>$^{210}$Po</td>
<td>6.2</td>
</tr>
<tr>
<td>$^{147}$Sm</td>
<td>$^{147}$Sm</td>
<td>4.5</td>
</tr>
</tbody>
</table>

First evaluation of intrinsic radiopurity level in 2.7 g LEBO crystal: 
*NIM A 572 (2007) 734-738*

Radioactive contaminations in Li$_6$Eu(BO$_3$)$_3$ crystal

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<th>Nuclide</th>
<th>Activity (Bq/kg)</th>
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<tbody>
<tr>
<td>$^{232}$Th</td>
<td>$^{238}$Ac</td>
<td>&lt;0.20</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>$^{232}$Pb</td>
<td>&lt;0.25</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>$^{228}$Th</td>
<td>&lt;0.13</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$^{214}$Pb</td>
<td>&lt;0.17</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$^{214}$Bi</td>
<td>&lt;0.07</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>$^{40}$K</td>
<td>&lt;1.5</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>$^{60}$Co</td>
<td>&lt;0.026</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>$^{137}$Cs</td>
<td>&lt;0.081</td>
</tr>
<tr>
<td>$^{208}$Bi</td>
<td>$^{208}$Bi</td>
<td>&lt;0.009</td>
</tr>
<tr>
<td>$^{152}$Eu</td>
<td>$^{152}$Eu</td>
<td>0.949(48)</td>
</tr>
<tr>
<td>$^{154}$Eu</td>
<td>$^{154}$Eu</td>
<td>0.212(35)</td>
</tr>
</tbody>
</table>

Limits are given at 90% C.L.
$^{151}\text{Eu}$ in $\text{Li}_6\text{Eu(BO}_3\text{)}_3$

About 40% of the crystal mass is made of Eu:
-\(\rightarrow\) given $^{151}\text{Eu}$ isotopic abundance
-\(\rightarrow\) about 1.5 g of the crystal is made of $^{151}\text{Eu}$

\(\alpha\)-decay of $^{151}\text{Eu}$ never observed, just an indication in:


**Abstract**

The indication for the \(\alpha\) decay of $^{151}\text{Eu}$ (\(Q_{\alpha} = 1.964\text{ MeV}\)) with the half-life \(T_{1/2}^{\alpha} = 5.3^{+11}_{-3} \times 10^{18}\text{ yr}\) has been observed for the first time with the help of a low background CaF$_2$(Eu) crystal scintillator (mass of 370 g) in measurement at the Gran Sasso National Laboratories of the INFN during 7426 h. In a conservative approach the lower limit on the half-life of $^{151}\text{Eu}$ has been established as \(T^{\alpha} \geq 1.7 \times 10^{18}\text{ yr}\) at 68% C.L.

The discovery of this decay is not far away...

... $\text{Li}_6\text{Eu(BO}_3\text{)}_3$ scintillating bolometer seems to be the perfect tool

- Large mass of Eu
- Particle discrimination
- High detection efficiency
- Good energy resolution
Conclusions

- Li-scintillating bolometers are a suitable tool for low background physics from DBD to solar axions

- the double read-out brings an abrupt reduction of the background in the ROI

<table>
<thead>
<tr>
<th>Li₂MoO₄</th>
<th>Li₆Eu(BO₃)₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>QFα(^147Sm) = 0.29±0.01</td>
<td>QFα(^147Sm) = 0.54±0.01</td>
</tr>
<tr>
<td>QFα(^210Po) = 0.42±0.03</td>
<td>QFα(^210Po) = 0.84±0.05</td>
</tr>
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</table>

* high radiopurity level
* good energy resolution

* low radiopurity level
* poor energy resolution

... bright future is ahead but still some work is needed ...