A $^{100}$Mo pilot experiment with scintillating bolometers and related CUPID activities

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Outline

- CUPID: a next-generation $0\nu2\beta$ bolometric experiment
- The $^{100}\text{Mo}$ way: LUMINEU $\rightarrow$ CUPID-Mo
- Surface sensitivity: the CROSS project
Outline

➢ CUPID: a next-generation $0\nu 2\beta$ bolometric experiment

➢ The $^{100}\text{Mo}$ way: LUMINEU $\rightarrow$ CUPID-Mo

➢ Surface sensitivity: the CROSS project
CUPID

Follow-up to CUORE with background improved by a factor 100

- Keep high energy resolution of CUORE (< 10 keV FWHM)
- Reduce / control background from materials and from muon / neutrons
- Optimize the enrichment-purification-crystallization chain
- Improve detector technology to get rid of α / surface background

About CUORE

see B. Fujikawa’s talk
CUPID goal

IH ($\Delta m_{23}^2 < 0$)

NH ($\Delta m_{23}^2 > 0$)

$g_A = 1.269$ (no quenching)
CUPID goal

Request:
\[b < 10^{-4} \text{ counts/(keV kg y)}\]

\[g_A = 1.269 \text{ (no quenching)}\]
CUPID

Follow-up to CUORE with background improved by a factor 100

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See C. Nones’ talk

About CUORE

see B. Fujikawa’s talk

See L. Cardani’s talk

See N. Casali’s talk
CUPID – pilot experiments

Follow-up to CUORE with background improved by a factor 100
- Keep high energy resolution of CUORE (< 10 keV FWHM)
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CROSS - ERC

See C. Nones’ talk
See L. Cardani’s talk
See N. Casali’s talk

About CUORE
see B. Fujikawa’s talk
**CUPID – pilot experiments**

Follow-up to CUORE with background improved by a factor $100$

- Keep high energy resolution of CUORE ($< 10$ keV FWHM)
- Reduce / control background from materials and from muon / neutrons
- Optimize the enrichment-purification-crystallization chain
- **Improve detector technology to get rid of $\alpha$ / surface background**

About CUORE

*see B. Fujikawa’s talk*

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**CROSS - ERC**

- **Surface effects**
- **Scintillating foil**

**Al Film**

- Sensitivity to surface alphas / betas

**Luke effect**

**TES**

**MKID**

**MMC**

**Sensitivity to bulk / surface alphas**

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**LUMINEU – CUPID-0/Mo**

See C. Nones’ talk

See N. Casali’s talk

See L. Cardani’s talk

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**ROI**

- $< 2615$ keV
- $> 2615$ keV

**CUPID**

**TeO$_2$**

**ZnSe**

**ZnMoO$_4$ / Li$_2$MoO$_4$**

**CdWO$_4$**

**Scintillation**

**Enrichment**
Outline

- CUPID: a next-generation 0ν2β bolometric experiment
- The $^{100}$Mo way: LUMINEU $\rightarrow$ CUPID-Mo
- Surface sensitivity: the CROSS project
Interest of $^{100}\text{Mo}$ as a $0\nu2\beta$ emitter

- $^{100}\text{Mo} \rightarrow ^{100}\text{Ru} + 2e^-$
- $Q_{\beta\beta} = 3034$ keV
- $I.A.(100) = 9.7\%$
- Enrichable by gas centrifugation

Caveats (but not showstoppers)

- $T_{1/2}(2\nu) = 7.1 \times 10^{18}$ y – the fastest one in all $0\nu2\beta$ candidates
- $^{214}\text{Bi}$ line at 3054 keV – B.R. 0.021 % - Compton edge 2818 keV
Viable Mo-based crystals

Crystals successfully tested so far as scintillating bolometers:

- CdMoO$_4$
- PbMoO$_4$
- SrMoO$_4$
- CaMoO$_4$
- ZnMoO$_4$
- Li$_2$MoO$_4$

**AMoRE**

- **Drawbacks:**
  - Necessity of $^{48}$Ca depletion
  - Radiopurity (difficult to purify Ca from U, Th, Ra)

**LUMINEU**

- Initial choice (2012): ZnMoO$_4$
- First tests on large Li$_2$MoO$_4$ crystals: spring 2014

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**Selection of Li$_2$MoO$_4$ for a pilot experiment** (March 2016)

- Better bolometric performance
- Easy crystallization / excellent quality
- Outstanding radiopurity

**Caveats**

- Hygroscopic material
- $^{40}$K is natural contaminant
- Lower light yield ($\sim$0.8 keV/MeV)

See C. Nones’ talk

*Astropart. Phys. 72, 38 (2016)*
Preparing a $^{100}$Mo experiment

Funding / resources from

- ANR (France) – main fund provider (LUMINEU: 2012-2017)
- CEA-Saclay – substantial funds / PhD
- CSNSM direction – funds for crystals (« AP interne »)
- EDELWEISS – underground facility, electronics & DAQ
- IN2P3 – dedicated personnel (Post-Doc, technician)
- KINR Kiev – radiopure scintillator know-how, simulation, – enriched $^{100}$Mo
- ITEP Moscow – enriched $^{100}$Mo
- NIIC Novosibirsk - crystals
- INFN / LUCIFER (LNGS / Rome) – underground facility and manpower for R&D
Extension of the Mo collaboration: CUPID-Mo

New participants

LAL – Orsay, France

MIT
UCB and LBL
UCLA

Fudan Shanghai
USTC Hefei

USA

China

MoU in preparation
Li$_2$MoO$_4$: purification and crystallization

From 2013 to 2016, a series of important milestones were achieved:

- Mo purification / crystallization protocol (NIIC, Novosibirsk, Russia) (Mo irrecoverable losses < 4%)
- Selection of the appropriate Li$_2$CO$_3$ powder for compound formation
- Successful program to control internal content of $^{40}$K (from ~60 mBq/kg to < 5 mBq/kg)
  - Random coincidences: $2\nu 2\beta + ^{40}$K << $2\nu 2\beta + 2\nu 2\beta$
- Efficient use of existing ~10 kg of $^{100}$Mo (A.I. 96-99%) (~9 kg to ITEP-Moscow and ~1 kg to KINR-Kiev)
  - MoU among IN2P3 / INFN / ITEP – February 2015
  - Natural isotopic abundance: 9.7%

NIM A 729, 856 (2013)
JINST 9, P06004 (2014)
EPJC 74, 3133 (2014)
JINST 10, P05007 (2015)
http://arxiv.org/abs/1704.01758 (submitted to EPJC)
Li$_2^{100}$MoO$_4$ scintillating bolometers: a mature technology

Multiple tests with natural and enriched crystals (2014-2017) in LSM and LNGS with outstanding results in terms of:

- Reproducibility → excellent performance uniformity
- Energy resolution → ~ 4-6 keV FWHM in RoI
- $\alpha/\beta$ separation power → > 99.9 %
- Internal radiopurity → < 5 – 10 $\mu$Bq/kg in $^{232}$Th, $^{238}$U; < 5 mBq/kg in $^{40}$K

Compatible with $b \leq 10^{-4}$ [counts/(keV kg y)]

Temperature readout

- NTD Ge thermistors
- Room temperature electronics (CUORE style) or
- Cooled JFET (EDELWEISS)

EDELWEISS

http://arxiv.org/abs/1704.01758
Energy resolution

Array of **four** enriched detectors, \( M \sim 210 \text{ g} \ (\varnothing=44\text{mm}-h=45 \text{ mm}) \), **LSM** (EDELWEISS setup)

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Non-optimal calibration condition: **high pile-up effect**

For the detector farther from the source (low pile-up effect) better energy resolution (**\(~4\text{keV FWHM}\)**)
Light detector performance

Light detectors coupled to Li$_2^{100}$MoO$_4$ bolometers

- Electronic-grade pure Ge wafer (UMICORE)
- Diameter: 44 mm – Thickness: 0.17 mm
- Equipped with NTD Ge thermistor (~ 5 – 9 mg)
- Exposed side coated with SiO layer (70 nm) to increase light absorption

<table>
<thead>
<tr>
<th>Light detector</th>
<th>Conditions</th>
<th>Signal $\mu$V/keV</th>
<th>FWHM$_{Bsl}$ keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b-LD</td>
<td>optimal over bias</td>
<td>1.3 0.7</td>
<td>0.08 0.11</td>
</tr>
<tr>
<td>1t-LD</td>
<td>optimal over bias</td>
<td>2.4 1.2</td>
<td>0.07</td>
</tr>
<tr>
<td>2b-LD</td>
<td>optimal over bias</td>
<td>1.5 1.1</td>
<td>0.11 0.12</td>
</tr>
<tr>
<td>2t-LD</td>
<td>optimal over bias</td>
<td>1.1 0.85</td>
<td>0.09 0.11</td>
</tr>
</tbody>
</table>

Satisfactory performance (~100 eV FWHM baseline) – Good reproducibility
99.9% $\alpha$ rejection with > 99 % $\beta$ acceptance ($LY \sim 0.4$-$0.7$ keV/MeV)
**Investigation of $^{100}$Mo $2\nu 2\beta$ decay**

### Preliminary

$^{2\nu\beta}\text{Mo}$, $T_{1/2} = 6.96(6) \times 10^{18}$ yr

$^{40}\text{K}$ (internal) $= 0.8(3)$ mBq/kg

Signal/Bkg $\sim 8$ above 1.5 MeV

### Results

- **Exposure**: $28$ kg$\times$d
- **Enrichment**: $96.9\%$ of $^{100}$Mo
- **eff$_{PSD}$**: $97\%$
- **Fit**: $160$-$2650$ keV $\Rightarrow$ Effect $= 24320 \pm 229$ decays

$T_{1/2} = [6.96 \pm 0.06] \times 10^{18}$ yr

### Table: One of the most precise $^{100}$Mo half-life values

<table>
<thead>
<tr>
<th>$T_{1/2}$ [10$^{18}$ yr]</th>
<th>Exposure</th>
<th>Experiment</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$7.11 \pm 0.02$ (stat) $\pm 0.54$ (syst)</td>
<td>7.37 kg$\times$yr</td>
<td>NEMO-3</td>
<td>PRL 95 (2005) 182302</td>
</tr>
<tr>
<td>$7.15 \pm 0.37$ (stat) $\pm 0.66$ (syst)</td>
<td>0.08 kg$\times$yr</td>
<td>LUCIFER</td>
<td>JPG 41 (2014) 075204</td>
</tr>
<tr>
<td>$6.90 \pm 0.15$ (stat) $\pm 0.42$ (syst)</td>
<td>0.03 kg$\times$yr</td>
<td>LUMINEU</td>
<td>arXiv:1704.01758</td>
</tr>
<tr>
<td>$6.96 \pm 0.06$ (stat) $\pm 0.35$ (syst)</td>
<td>0.08 kg$\times$yr</td>
<td>LUMINEU</td>
<td>Presented here</td>
</tr>
</tbody>
</table>
Investigation of $^{100}$Mo $0\nu 2\beta$ decay

We performed $0\nu 2\beta$ search joining the two runs involving enriched crystals at LSM.

Possible origin of the background:
- 2615+583 keV from close Th contamination [$^{208}$Tl peak 40x wrt Cuoricino]
- Multiple high energy $\gamma$’s induced by muons [no coincidence study in our analysis]
Measures to mitigate the background

Remove known Th sources in the vicinity of the detectors
➢ Connectors and cables belonging to the EDELWEISS setup

Substantial simplification of the cabling system

Activate coincidences among detectors and with the muon veto
➢ EDELWEISS data on γ’s above 2.6 MeV show a substantial contribution to background coming from events in coincidence

Goal: background reduction by one order of magnitude in the β band above 2.6 MeV → \( b \sim 10^{-3} \text{ counts/(keV kg y)} \)
Next pilot experiments

CUPID-Mo Phase I (20 crystals):
- 20 $^{100}\text{Mo}$-enriched (97%) $\text{Li}_2\text{MoO}_4$ presently in France
  ($\varnothing 44 \times 45$ mm, 0.21 kg each; 4.18 kg total)
  $\Rightarrow$ 2.34 kg of $^{100}\text{Mo}$ ($1.37 \times 10^{25}$ $^{100}\text{Mo}$ nuclei)
- 20 Ge light detectors ($\varnothing 44 \times 0.175$ mm)+SiO
- EDELWEISS set-up @ LSM (France)

START DATA TAKING: December 2017

CUPID-Mo Phase II (20+20 - or more - crystals):
- At least additional 20 $\text{Li}_2^{100}\text{MoO}_4$
- CUPID-0 set-up in hall A @ LNGS (Italy)
  (under discussion)

<table>
<thead>
<tr>
<th>Year</th>
<th>S1</th>
<th>S2</th>
<th>S1</th>
<th>S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>4-crystal array assembly</td>
<td>4-crystal array operation (LSM)</td>
<td>20-crystal production (first batch)</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>1 tower test (LSM)</td>
<td>20-crystal array operation (LSM)</td>
<td>20-crystal production (second batch)</td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>20-crystal array assembly (second batch)</td>
<td>20-crystal array operation (LNGS)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Tower structure in CUPID-Mo
Sensitivity of CUPID-Mo

The primary aim of CUPID-0/Mo is to demonstrate the maturity of the Li$_2^{100}$MoO$_4$ technology in terms of crystal purity, bolometric performance, active methods for background rejection and reproducibility of all the relevant parameters. However, the physics reach of CUPID-Mo is quite interesting.

In calculating the sensitivity (90% C.L.), we will assume:

- $b = 1 \times 10^{-3}$ counts/(keV kg y)
- 8 keV energy window
- 78% efficiency

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Half life limit [90% c.l.]</th>
<th>$M_{\beta\beta}$ [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 20 crystal [20×0.5 cr.x]y</td>
<td>$1.4 \times 10^{24}$</td>
<td>240 – 670</td>
</tr>
<tr>
<td>(2) 20 crystal [20×1.5 cr.x]y</td>
<td>$4.2 \times 10^{24}$</td>
<td>140 – 390</td>
</tr>
<tr>
<td>(3) 40 crystal [40×3 cr.x]y</td>
<td>$1.7 \times 10^{25}$</td>
<td>70 – 200</td>
</tr>
</tbody>
</table>

First two options sensitivities substantially unchanged by $b = 1 \times 10^{-2}$ counts/(keV kg y)
$g_A = 1.269$ (no quenching)
This can be achieved in **2018 in only 6 months**!
We performed a specific study on a natural 150 g Li$_2$MoO$_4$ detector operated in LNGS. A calibration with an AmBe source provided enough statistics in the $\beta$ and $\alpha$-like bands.
### Possible configurations in CUPID

<table>
<thead>
<tr>
<th>Single element</th>
<th>Number of elements</th>
<th>Isotope mass [kg]</th>
<th>Number of $^{100}$Mo nuclei</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø50×50 mm – 300 g</td>
<td>1260</td>
<td>1.2×10^{27}</td>
<td></td>
</tr>
<tr>
<td>Ø60×40 mm – 350 g</td>
<td>1092</td>
<td>213</td>
<td></td>
</tr>
<tr>
<td>45×45×55 mm – 340 g</td>
<td>1110</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If PSD works for $\alpha$ particle rejection (as preliminary results seem to demonstrate), a very simple configuration **without light detectors** can be envisaged.

If light detectors are kept, the available volume for the source will be reduced by ~10%.

<table>
<thead>
<tr>
<th>Background [counts/(keV kg y)]</th>
<th>Number of BKG counts [8 keV, 10 y]</th>
<th>Count limit [90% c.l.]</th>
<th>Half life limit [90% c.l.]</th>
<th>$M_{\beta\beta}$ [meV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \times 10^{-4}$</td>
<td>3</td>
<td>4.4</td>
<td>$1.4 \times 10^{27}$</td>
<td>7.3 – 21</td>
</tr>
<tr>
<td>$2 \times 10^{-5}$</td>
<td>0.6</td>
<td>2.9</td>
<td>$2.2 \times 10^{27}$</td>
<td>5.9 – 17</td>
</tr>
</tbody>
</table>
CUPID: a next-generation $0\nu 2\beta$ bolometric experiment

The $^{100}\text{Mo}$ way: LUMINEU $\rightarrow$ CUPID-Mo

Surface sensitivity: the CROSS project
Current role of surface radioactivity

CUORE background model

- \( TeO_2 \): natural radioactivity
- \( CuNOSV \): natural radioactivity
- \( CuNOSV \): cosmogenic activation
- \( TeO_2 \): cosmogenic activation
- \( CuOFE \): natural radioactivity
- \( RomanPb \): natural radioactivity
- \( ModernPb \): natural radioactivity
- \( SI \): natural radioactivity
- \( Rods \) and \( 300KFlan \): natural radioactivity
- Environmental \( \mu \)
- Environmental \( n \)
- Environmental \( \gamma \)

\( 90\% \text{ CL limit} \)

Value

CUORE goal

arXiv:1704.08970 [physics.ins-det]
Eliminating surface α’s is enough?

The residual background after alpha rejection comes mainly from high Q-value beta emitters from surface contamination

$^{226}\text{Ra}$ – generates $^{214}\text{Bi}$ – 3.27 MeV endpoint

$^{228}\text{Th}$ – generates $^{208}\text{TI}$ – 5.00 MeV endpoint
Getting rid of the surface beta component looks mandatory to achieve \( b < 10^{-4} \) counts/(keV kg y) necessary for zero background at the tonne x year scale.

The residual background after alpha rejection comes mainly from high Q-value beta emitters from surface contamination:
- \(^{226}\text{Ra}\) – generates \(^{214}\text{Bi}\) – 3.27 MeV endpoint
- \(^{228}\text{Th}\) – generates \(^{208}\text{TI}\) – 5.00 MeV endpoint
CROSS: new advancement opportunity

ERC advanced grant CROSS
Cryogenic Rare-event Observatory with Surface Sensitivity

CROSS is a bolometric experiment to search for 0ν-DBD

- **Core of the project** (high risk / high gain)
  - Background rejection through **pulse shape discrimination**
    - Surface sensitivity through superconductive Al film coating
    - Fast NbSi high-impedance TES to replace / complement NTDs
      - get rid of light detectors

- Complete crystallization of available $^{100}$Mo (10 kg) in Li$_2$MoO$_4$ elements

- Purchase / crystallize $^{130}$Te (up to 17 kg) in TeO$_2$ elements

- Run demonstrator in a dedicated cryostat (LSC – Spain)
The evolution of the bolometric technique

- \( b = 10^{-2} \text{ counts/(keV kg y)} \)
- \( b = 10^{-3} \text{ counts/(keV kg y)} \)
- \( b = 10^{-4} \text{ counts/(keV kg y)} \)

**Pure bolometers**
- CUORE-0, CUORE

**Luminescent bolometers**
- High Q value
- \( \alpha/\beta \) separation
- LUCIFER, LUMINEU (CUPID-0/Se, CUPID-Mo)
- Cherenkov TeO\(_2\)

**Surface sensitivity**
- CROSS

CUPID
BACK UP
Light yield

Light-yield plots with $^{232}$Th calibration

Without reflecting foil

Significant LY reduction without reflecting foil

However, $\alpha/\beta$ separation is sufficient even without reflecting foil
2νββ decay random coincidences

Contribution to the background index in the ROI: $\phi 50 \text{ mm} \times 50 \text{ mm} (300 \text{ g})$

$$\text{BKG}(rc) \left[ \text{counts/}(\text{keV} \ \text{kg} \ \text{y}) \right] = 3 \times 10^{-4} \left[ T_R / 1 \text{ ms} \right] \left[ M / 300 \text{ g} \right]$$

Our approach (partial simulation + PSD)
- Take a large value for $T_R$ (typically $T_R \sim 3 \times \text{rise time}$)
- Use real-shape pulses
- Use real noise baselines
- Generate pulses with correct 2ν pulse amplitude distribution
- Calculated rejection efficiency by PSD of pulse-pair separated by less than $T_R$
- Multiply the above formula by rejection efficiency

In a real case (heat channel):
$T_R = 45 \text{ ms}$
Rejection efficiency by PSD = 99.3 % (using the so-called mean-time method) (95% acceptance)

$$\text{BKG}(rc) \left[ \text{counts/}(\text{keV} \ \text{kg} \ \text{y}) \right] \sim 1 \times 10^{-4}$$

It can be improved:
- Full simulation
- Advanced pulse shape parameters (after optimum filtering)
Neutrons

\[ ^6\text{Li}(n,t)^\alpha \quad \sigma = 940 \text{ barn} \quad Q = 4.78 \text{ MeV} \]

(thermal neutrons)

Harmless
No associated \(\beta\) radiation
Huge internal energy deposition

\[ ^7\text{Li}(n,\gamma)^8\text{Li} \quad \sigma = 45.4 \text{ mbarn} \]

(thermal neutrons)

\[ ^8\text{Be}^* + e^- + \nu \rightarrow \alpha + \alpha \]

Prompt (\(\Gamma \sim 1.5 \text{ MeV}\))

Harmless
Very low cross section
Mixed events with \(\alpha\) component
Choice of CROSS material ($^{100}$Mo – $^{130}$Te)

\[
\begin{align*}
Q &= 2527 \text{ keV} \\
Q &= 3034 \text{ keV}
\end{align*}
\]
Choice of CROSS material ($^{130}\text{Te}$)

- Crystallization / purification chain for TeO$_2$ extensively studied in CUORE and precursors in natural crystals (SICCAS, Shanghai, China)
- Excellent results in terms of performance and radiopurity
  \[ \Rightarrow \text{Internal contamination in } ^{226}\text{Ra and } ^{228}\text{Th are less than 1 } \mu\text{Bq/kg} \]
- Recently, the study was extended to enriched crystals (USC et al., SICCAS)
  - **Irrecoverable losses** $\sim$ 28% (less good than $^{100}\text{Mo}$ but lower isotope price)
  - Detector performance of natural crystals si confirmed

<table>
<thead>
<tr>
<th>Chain</th>
<th>Nuclide</th>
<th>$^{130}\text{TeO}_2$-1 [(\mu\text{Bq/kg})]</th>
<th>$^{130}\text{TeO}_2$-2 [(\mu\text{Bq/kg})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$^{232}\text{Th}$</td>
<td>$&lt;4.3$</td>
<td>$&lt;4.8$</td>
</tr>
<tr>
<td></td>
<td>$^{228}\text{Th}$</td>
<td>$&lt;2.3$</td>
<td>$&lt;3.1$</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$^{238}\text{U}$</td>
<td>$7.7 \pm 2.7$</td>
<td>$15.1 \pm 4.4$</td>
</tr>
<tr>
<td></td>
<td>$^{234}\text{U}$</td>
<td>$&lt;6.3$</td>
<td>$&lt;5$</td>
</tr>
<tr>
<td></td>
<td>$^{230}\text{Th}$</td>
<td>$&lt;5.7$</td>
<td>$&lt;3.8$</td>
</tr>
<tr>
<td></td>
<td>$^{226}\text{Ra}$</td>
<td>$&lt;2.3$</td>
<td>$&lt;3.1$</td>
</tr>
<tr>
<td></td>
<td>$^{210}\text{Po}$</td>
<td>$3795 \pm 60$</td>
<td>$6076 \pm 88$</td>
</tr>
</tbody>
</table>

Radiopurity is less good than in natural crystals but compatible with $b < 10^{-4}$ counts/(keV kg y)

$^{130}\text{Te}$: 15-20 $/g$

$^{100}\text{Mo}$: 90 $/g$

PLB 767, 321 (2017)
Detector performance

Two enriched TeO$_2$ modules (LNGS)
$M = 430$ g
$\Delta E_{\text{FWHM}} \sim 5$ keV at 2.6 MeV

Two enriched Li$_2$MoO$_4$ modules (LNGS+LSM)
$M = 210$ g
$\Delta E_{\text{FWHM}} \sim 5$ keV at 2.6 MeV

Th calibration
Al films as pulse shape modifiers

Coating of all crystal surfaces with SC Al films

Discriminate surface events by pulse shape (PSD)

Proof of concepts achieved in 2010 in CSNSM

Al films as pulse shape modifiers

\[ \chi^2 = \sum (\text{Pulse}_i - \text{Template}_i)^2 \]

- Bulk events
- $^{241}$Am source alphas impinging on the Al film
Fast NbSi sensors

Replace standard NTD Ge with high impedance transition edge NbSi sensor

Higher sensitivity (x 10) – Faster response \(\Rightarrow\) it may be necessary for PSD

Proof of concept achieved with a NbSi meander on a 32 g Ge absorber

Rise time: 2.5 ms vs. 20 ms for NTDs

The meander has 6 mm diameter, a spiral shape, a line width of 45 \(\mu\)m and a pitch of 60 \(\mu\)m.

The length/width aspect ratio is 9700.
If the NbSi signal contains an important component of **athermal phonons**, signal-amplitude position dependence is possible with consequent **loss of energy resolution**

CROSS foresees in its baseline solution to keep NTD Ge readout (slow response, thermal signal)

**Double readout**

**Energy readout**

**Time readout**
CROSS demonstrator (CROSS-DEM)

- Complete crystallization of available $^{100}$Mo (10 kg)
- Purchase / crystallize $^{130}$Te (up to 17 kg)
- Fabricate demonstrator with 90 crystals in dedicated refrigerator

<table>
<thead>
<tr>
<th>Section of CROSS-DEM</th>
<th>Number of crystals</th>
<th>Total detector mass [kg]</th>
<th>Isotopic abundance</th>
<th>Total isotope mass [kg]</th>
<th>Number of candidate nuclides</th>
</tr>
</thead>
<tbody>
<tr>
<td>CROSS-DEM-Te</td>
<td>30</td>
<td>22.8</td>
<td>93% ($^{130}$Te)</td>
<td>17.0</td>
<td>$7.9 \times 10^{25}$ ($^{130}$Te)</td>
</tr>
<tr>
<td>CROSS-DEM-Mo</td>
<td>60</td>
<td>16.2</td>
<td>99% ($^{100}$Mo)</td>
<td>9.14</td>
<td>$5.4 \times 10^{25}$ ($^{100}$Mo)</td>
</tr>
</tbody>
</table>

Low radioactivity refrigerator, based on a pulse tube, with experimental space $\varnothing30 \times 60$ cm – muon veto

To be installed in LSC (former ROSEBUD hut)
CROSS sensitivity

\[ \Delta E_{\text{FWHM}} = 8 \text{ keV} \]

Matrix element span

CUPID/CROSS Te \( \Rightarrow \) 543 kg of \(^{130}\text{Te}\)
CUPID/CROSS Mo \( \Rightarrow \) 212 kg of \(^{100}\text{Mo}\)