CUPID-Mo: Paving the way to next generation bolometric $2\beta_0\nu$ experiments

Pia Loaiza on behalf of the Cupid-Mo collaboration

XIX Int. Workshop on Neutrino Telescopes, 24 February 2021
A demonstrator for next generation experiment CUPID (Cuore Upgrade with Particle IDentification)

A competitive $2\beta 0\nu$ experiment by itself:
World’s best limit $T_{1/2}$ in $^{100}Mo$
CUPID-Mo concept

CUORE $^{130}\text{Te}$
Bolometers
Heat

CUORE $^{130}\text{Te}$
Scintillating bolometers
Heat and Light

No $\gamma/\beta - \alpha$ identification

CUPID-Mo $^{100}\text{Mo}$
Scintillating bolometers
Heat and Light

$\gamma/\beta - \alpha$ identification
The main background comes from $\alpha$ particles (from surface contaminations close to the crystals) → flat continuum

![Graph showing CUORE Preliminary data for TeO$_2$]
Heat and light detection allows $\alpha$ rejection

$Q_{\beta\beta}^{^{100}\text{Mo}} = 3034$ keV, above $\gamma$ background from natural radioactivity
CUPID-Mo detectors

- $\text{Li}_2^{100}\text{MoO}_4$ scintillating crystals $+$ Neutron Transmutation Doped (NTD) Ge sensors $\rightarrow$ heat
- Ge wafers $+$ NTD $\rightarrow$ light detectors
- Crystals in copper holders, surrounded by a reflecting foil
CUPID-Mo towers and set-up

- Installed in the EDELWEISS-III cryogenic set-up at the Laboratoire Souterrain de Modane, France (4800 m.w.e)
- 20 Li$_2^{100}$MoO$_4$ crystals of 210 g, 97% enriched in $^{100}$Mo $\rightarrow$ 2.26 kg of $^{100}$Mo
The data

- Data taking
  March 2019 - July 2020 (427 days)
- Exposure for physics data:
  2.16 kg·y
- Significant amount of time dedicated to calibration
Data production

- Blinded data analysis in 3034 keV ± 50 keV
- Data analysis: Base cuts + Multiplicity cut M1-single crystal + Pulse shape analysis + Light yield cut + muon veto anticoincidence
- Total efficiency after cuts (exposure weighted average)
  \[ \epsilon = (90.5 \pm 0.4 \text{ (stat)} \pm 0.9 \text{ (syst)}) \% \]
Cupid-Mo performances

Energy resolution

- $\Delta E$ (FWHM) = 7 keV at 2615 keV (CUPID goal: $\sim$ 5 keV at $Q_{\beta\beta} = 3034$ keV)
- Can be improved at lower temperature and no stabilization issue.

LUMINEU@LSM:
$\Delta E$(FWHM)=5-6 keV at 3034 keV


Alpha discrimination

- $>99.9\%$ alpha separation for all detectors

CUPID-Mo performances and prospects, EPJ-C 80:44 (2020)
Radiopurity of LMO crystals

- The $\alpha$ region is populated by $\alpha$ decays occurring in the crystals and/or in components directly facing them. Radiopurity in the bulk of the crystals obtained from the counting rate in $\alpha$ peaks.

<table>
<thead>
<tr>
<th>Chain</th>
<th>Nuclide</th>
<th>Bulk activity ($\mu$Bq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}$Th</td>
<td>$^{232}$Th</td>
<td>0.22(9)</td>
</tr>
<tr>
<td></td>
<td>$^{228}$Th</td>
<td>0.38(9)</td>
</tr>
<tr>
<td></td>
<td>$^{224}$Ra</td>
<td>0.34(9)</td>
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<tr>
<td></td>
<td>$^{212}$Bi</td>
<td>0.22(7)</td>
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<tr>
<td>$^{238}$U</td>
<td>$^{238}$U</td>
<td>0.35(10)</td>
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<tr>
<td></td>
<td>$^{234}$U + $^{226}$Ra</td>
<td>1.22(17)</td>
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<tr>
<td></td>
<td>$^{230}$Th</td>
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<td></td>
<td>$^{222}$Rn</td>
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<tr>
<td></td>
<td>$^{218}$Po</td>
<td>0.35(9)</td>
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<tr>
<td></td>
<td>$^{210}$Po</td>
<td>95(6)</td>
</tr>
<tr>
<td></td>
<td>$^{190}$Pt</td>
<td>0.19(8)</td>
</tr>
</tbody>
</table>

- $^{238}$U/$^{232}$Th and daughters $\sim (0.2 - 1) \mu$Bq/kg →
- Background contribution for CUPID: $2 \cdot 10^{-6}$ cts/(keV·kg·y) (CUPID Background goal: $10^{-4}$ cts/(keV·kg·y)}
Background model

- Data for background model: 1.66 kg·y exposure
- RooFit and JAGS-based fits

Geant4 rendering of CUPID-Mo

BI [2985 - 3085] keV:
(4 ± 2) \times 10^{-3} \text{ counts/(keV kg y)}

Preliminary

P. Loaiza (IJCLab)

CUPID-Mo

24 Feb. 2021

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Background model

- Dominant $2\beta2\nu$ spectrum
  $E < 3$ MeV

- Background in ROI: $^{208}$Tl, $^{214}$Bi in external sources, $2\beta2\nu$ pile-up
Background model: Surface contaminations

Surface contaminations from fit of data in $\alpha$ region

- U/Th crystal surface contamination $< 3$ nBq/cm$^2$
New limit on $2\beta0\nu$ of $^{100}$Mo

New world leading limit on $2\beta0\nu$ of $^{100}$Mo:

\[ T_{1/2} > 1.5 \cdot 10^{24} \text{ y (90\% CI)} \]

\[ m_{\beta\beta} < (310 - 540) \text{ meV} \]

($T_{1/2} > 1.1 \cdot 10^{24} \text{ y, NEMO-3, 2015}$

$T_{1/2} > 0.95 \cdot 10^{23} \text{ y, AMoRE, 2020}$

Considering $g_A = 1.27$ and Nuclear Matrix Elements:

Conclusions

- CUPID-Mo: 20 Li$_2^{100}$MoO$_4$ detectors operated with simultaneous readout of heat and light $\rightarrow$ $\alpha$ rejection
- Data taking March 2019 - July 2020
- Has successfully demonstrated the maturity of the technology for the next generation experiment CUPID
- World leading limit on $2\beta^0\nu$ of $^{100}$Mo, with 1.21 kg·y of $^{100}$Mo: $T_{1/2} > 1.5 \cdot 10^{24}$ y (90% CI)
- 4th most stringent limit $m_{\beta\beta} < (310 - 540)$ meV
- Data taking is over (total exposure for physics data=2.8 kg·y). On-going studies on $2\beta^2\nu$ of $^{100}$Mo, $2\beta^2\nu$ excited states, potential for dark matter search
• G. Fantini, ‘Latest result from the CUORE experiment’ (23/02)
• E. Celi, ’Double beta decay results from the CUPID-0 experiment’ (23/02)
• A. Campani, ’The search for $\nu$EC$\beta^+$ of $^{120}$Te with CUORE’ (23/02)
• A. Ressa, ’Scintillating Li$_2^{100}$MoO$_4$ bolometers for 2$\beta$0$\nu$ search’ (23/02)
• S. Dell’Oro, ’A novel technique for the study of pile-up events in cryogenic bolometers’ (23/02)
• A. Giuliani, ’CUPID: a next generation bolometric neutrinoless double beta decay experiment’ (24/02)
The CUPID-Mo collaboration

Data unblinding

P. Loaiza (IJCLab)

CUPID-Mo

24 Feb. 2021


CUPID-Mo general meeting, March 2018, CSNSM
Back up slides
CUPID-Mo - Energy scale

- Energy scale is set with pol2 in calibration data
- Check consistency in time in calibration data

- Estimate possible energy bias based on physics data, $E_B = (-0.2 \pm 0.4) \text{ keV}$
CUPID-Mo ROI resolution scaling

- Obtain a global scaling factor Calibration @2615 keV <-> Physics @3034 keV
- Test several hypothesis:
  - linear, sqrt, pol2 fit -> linear is ruled out by calibration data -> take remaining more conservative estimate (pol2)
Definition of the ROI

Before unblinding, we have defined the ROI for each data set and for each channel.

Optimization of the signal ROI based on Poisson counting analysis in Signal, Background likelihood space, assuming:

- An expected final CUPID-Mo exposure of $2.8 \, \text{kg} \times \gamma$
- A background index $b = 5 \times 10^{-3} \, \text{counts/(keV kg yr)}$

Large central ROI $\sim 18 \, \text{keV average width}$