Search for neutrinoless double beta decay of $^{100}$Mo with the CUPID-Mo detector

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(on behalf of the CUPID-Mo Collaboration)

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100Mo is one of the best candidates to search for neutrinoless double beta decay

\[ Q_{\beta\beta} = 3.034 \text{ MeV} \]
Natural abundance is 9.7%
Enrichment by centrifugation
What one can extract from 2β-decay experiments?

- Lepton number non-conservation ($\Delta L=2$)
- Nature of neutrino mass (Dirac or Majorana?)
- Absolute mass scale
- Type of mass ordering (normal or inverted)
- CP violation in the lepton sector
## Best present limits on $<m_\nu>$

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$T_{1/2}$, yr; 90% CL</th>
<th>$&lt;m_\nu&gt;$, eV</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{136}$Xe</td>
<td>$&gt; 5.6 \times 10^{25}$</td>
<td>$&lt; 0.08-0.23$</td>
<td>KamLAND-Zen</td>
</tr>
<tr>
<td></td>
<td>$&gt; 1.07 \times 10^{26}$</td>
<td>$&lt; 0.06-0.16$</td>
<td></td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>$&gt; 1.8 \times 10^{26}$</td>
<td>$&lt; 0.08-0.18$</td>
<td>GERDA</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>$&gt; 1.7 \times 10^{25}$</td>
<td>$&lt; 0.10-0.49$</td>
<td>CUORE</td>
</tr>
<tr>
<td></td>
<td>$&gt; 3.2 \times 10^{25}$</td>
<td>$&lt; 0.08-0.36$</td>
<td></td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>$&gt; 1.1 \times 10^{24}$</td>
<td>$&lt; 0.33-0.62$</td>
<td>NEMO-3</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>$&gt; 3.5 \times 10^{24}$</td>
<td>$&lt; 0.33-0.75$</td>
<td>CUPID-0</td>
</tr>
</tbody>
</table>
DBD and neutrino mass ordering

Inverted ordering (IO):
\[ <m_{\nu}> = 14-50 \text{ meV} \]
(Can be tested by next generation of 2\(\beta\)-decay experiment)

Normal ordering (NO):
\[ <m_{\nu}> = 0-30 \text{ meV} \]
Limiting case \(\rightarrow\) \[ <m_{\nu}> = 1-4 \text{ meV} \]
\(\beta\): \[ <m_{\nu}> < 1.1 \text{ eV} \]
\(2\beta\): \[ <m_{\nu}> < 0.18 \text{ eV} \]
\[ \Sigma m_{\nu} < 0.12 \text{ eV (PLANCK’2018)} \]

Global analysis prefer NO (3-3.5\(\sigma\));
NO - \[ \Sigma m_{\nu} > 0.06 \text{ eV} \], IO - \[ \Sigma m_{\nu} > 0.1 \text{ eV} \]
NEXT GENERATION EXPERIMENTS

• LEGEND, nEXO, CUPID, AMoRE,...

• CUPID (CUORE Upgrade with Particle IDentification):
  - Main idea is to use existing CUORE infrastructure and scintillating bolometers Li$_2$MoO$_4$ (~ 1500 crystals, ~ 250 kg of $^{100}$Mo)
  - Sensitivity $\sim 1.5 \cdot 10^{27}$ yr, $<m_\nu> \sim 10^{-17}$ meV

• CUPID-Mo – is a demonstrator for CUPID
CUPID-Mo at Modane

4800 m w.e. depth

shared EDELWEISS cryogenic Infrastructure operated at @ 20 - 22 mK

20 Li$_2^{100}$MoO$_4$ detectors of ~210 g, 96.6% enriched (2.26 kg $^{100}$Mo)

Ge-NTD based sensor readout

physics data taking March 2019 - June 2020
CUPID-Mo design

Crystal growth and $^{100}$Mo Enrichment

NIIC, Novosibirsk, Russia

- purification of enriched Mo (from the NEMO-3 experiment) to MoO$_3$
- low radioactivity Li$_2$CO$_3$
- double crystallization (low thermal gradient Czochralski technique)
- surface polish with radio-pure SiO$_2$ oil based slurry
- storage in dry N$_2$ atmosphere (Li$_2$MoO$_4$ is slightly hygroscopic)

Isotope concentration: 96.6±0.2 %
4.158 kg Li$_2^{100}$MoO$_4$
2.258 kg $^{100}$Mo
The CUPID-Mo installation at LSM
CUPID-Mo single module

Source $^{100}\text{Mo} = \text{Detector Li}_2\text{MoO}_4$

(High detection efficiency)
CUPID-Mo performance

Energy resolution

a rejection power:
> 99.9% for all detectors

Average energy resolution is 7.7 keV (FWHM) at $Q_{\beta\beta}$ (3040 keV)

Crystals bulk $\alpha$ activity
(19/20 Li$_2$^{100}MoO$_4$, 2.17 kg$\times$yr)

<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>0.22(9)</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>$^{228}$Th</td>
<td>0.38(9)</td>
</tr>
<tr>
<td>$^{224}$Ra</td>
<td>$^{224}$Ra</td>
<td>0.34(9)</td>
</tr>
<tr>
<td>$^{212}$Bi</td>
<td>$^{212}$Bi</td>
<td>0.22(7)</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$^{238}$U</td>
<td>0.35(10)</td>
</tr>
<tr>
<td>$^{230}$Th</td>
<td>$^{230}$Th</td>
<td>0.48(12)</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>$^{222}$Rn</td>
<td>0.47(10)</td>
</tr>
<tr>
<td>$^{218}$Po</td>
<td>$^{218}$Po</td>
<td>0.35(9)</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>$^{210}$Po</td>
<td>95(6)</td>
</tr>
<tr>
<td>$^{190}$Pt</td>
<td>$^{190}$Pt</td>
<td>0.19(8)</td>
</tr>
</tbody>
</table>

$U/Th$: < 1 \(\mu\)Bq/kg
CUPID-Mo results

New world leading limit on $0\nu2\beta$ of $^{100}\text{Mo}$:

$$T_{1/2}^{(0\nu)} > 1.4 \times 10^{24} \text{ yr}$$

$$<m_\nu> < 310-540 \text{ meV} \quad (90\% \text{ C.L.})$$

$$[ T_{1/2} > 1.1 \times 10^{24} \text{ yr} \quad (\text{NEMO-3; 2015})$$

$$T_{1/2} > 0.95 \times 10^{23} \text{ yr} \quad (\text{AMoRE; 2019})$$

$$B = (4 \pm 2) \times 10^{-3} \text{ counts/keV} \cdot \text{kg} \cdot \text{yr}$$
Future prospects

I. Full statistics is 2.8 kg·yr. So, we hope to improve the limit in \( \sim 30\% \) (up to \( \sim 1.8 \cdot 10^{24} \) yr)

II. Next possible step with CUPID-Mo (+ CROSS):
- \( \sim 50 \) Li\( _2^{100}\)MoO\( _4 \) crystals
- 3 years of measurements
\( T_{1/2} > 1.5 \cdot 10^{25} \) yr; \( <m_\nu> <100-170 \text{ meV} \)

III. CUPID:
\( T_{1/2} > 1.1 \cdot 10^{27} \) yr (3\( \sigma \)); \( <m_\nu> < 12-20 \text{ meV} \)
CUPID in a nutshell
- ∼1500 Li$_2$MoO$_4$ scintillating crystals (∼250 kg of $^{100}$Mo)
- FWHM: 5 keV at $Q_{\beta\beta}$
- $\alpha$ rejection via light vs heat cut: > 99.9%
- Background index: $10^{-4}$ counts/(keV · kg · yr)
- $T_{1/2}(0\nu) > 1.1 \times 10^{27}$ yr (3σ)
- $<m_\nu> < 12$-$20$ meV (IH)

CUORE cryostat, mature design, data-driven background model

Can be built now!
■ TDR and construction readiness for end 2021
■ Schedule and budget will be driven by $^{100}$Mo enrichment $\rightarrow$ ∼ 4 years
I. **CUPID-Mo** detector has been successfully tested and has shown excellent performance.

II. The world leading limit on $0\nu\beta\beta$ decay of $^{100}$Mo was obtained:

\[ T_{1/2} > 1.4 \times 10^{24} \text{ yr}; \quad <m_\nu> < 310-540 \text{ meV} \]

III. Good prospects of **CUPID** have been demonstrated.
CUPID-Mo Collaboration
Back up slides
Calibration spectrum

- 19/20 detectors with good performance
- Analysis efficiency 90.5 %
- 200 days of physics data,
  ~7 keV FWHM @ 2615 keV (calibration)

CUPID-Mo, Neutrino 2020
2.17 kg x yr, Preliminary