CUPID-Mo: a double beta decay experiment with Li$_2^{100}$MoO$_4$ scintillating bolometers

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Neutrino masses

- Neutrino oscillation discovery proved that neutrinos do have mass
- But their absolute mass scale and hierarchy are still open questions:

![Graph showing the mass hierarchy of neutrinos](image-url)
Double Beta Decay

Allowed by SM:

\[ T_{1/2} (2\nu\beta\beta): \sim 10^{18} - 10^{21} \text{ years} \]

Forbidden by SM, possible only if neutrinos are Majorana particles:

\[ T_{1/2} (0\nu\beta\beta): > 10^{24} - 10^{26} \text{ years} \]

- Challenge is to reduce background as much as possible

**Background index:** \( \text{counts/(keV} \times kg \times y) \):

- \( b \sim 10^{-1} \) in « classical » source=detector experiments
- \( b \sim 10^{-2} - 10^{-3} \) in current source=detector and in classical external-source experiments
- \( b \sim 10^{-4} \) in future experiments (minimum request to cover inverted hierarchy)
Observation challenge for $0\nu\beta\beta$:

- New physics beyond the Standard model
- Majorana nature of neutrino
- Answer about origin of matter/antimatter asymmetry in the Universe
- Definition of absolute scale of neutrinos mass:

**Current generation**

**GEN1** $\Rightarrow \sim 10-100$ kg

**Next generation**

**GEN2** $\Rightarrow \sim 0.2-1$ ton

**Long term generation**

**GEN3** $\Rightarrow >10$ ton
Isotope selection: why $^{100}$Mo?

- There is no “perfect” isotope, but...
  - High energy of decay: $Q_{2\beta} = 3034 \text{ keV} > 2615 \text{ keV}$
  - Isotopic abundance = 9.7%
  - Possibility of enrichment in a large amount (enrichable by gas centrifugation)
  - Favorable theoretical predictions
  - High detection efficiency using molybdate crystal
  - Very high energy resolution and powerful particle discrimination (cryogenic scintillating bolometers)
Molibdenum-based crystals

- Crystals successfully tested as scintillating bolometers:

  - CaMoO$_4$
  - CdMoO$_4$
  - PbMoO$_4$
  - SrMoO$_4$
  - 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

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

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

Cons:
- Hygroscopic material
- $^{40}$K is natural contaminant
- Lower light yield (~0.8 keV/MeV)
Scintillating bolometers

- The nuclear energy is measured as a temperature increase in a crystal
- Thermometer provides phonon signal
- Typical signal sizes: 0.1 mK / MeV, converted to about 0.1-0.5 mV / MeV
- High energy resolution: 5-7 keV (0.2%)
- High registration efficiency: (70% - 90%)
- Flash of light is produced by the absorption of a particle
- Different particles produce different amount of light
- Powerful particle discrimination - potential to reject background

\[
\Delta T = \frac{E}{c} \approx 0.1 mK
\]
CUPID (CUORE Upgrade with Particle IDentification)

- Follow-up to CUORE with background improved by a factor 100
- Reduce/control background from materials and from muon / neutrons
- Improve detector technology to get rid of α/surface background
Tests of ZnMoO$_4$, natural and enriched. (from 2008)

Tests of Li$_2$MoO$_4$
First crystals - 2010

Li$_2^{100}$MoO$_4$: production of first enriched crystal in 2015

20 enriched crystals: autumn 2017. Prove of 0-background experiment concept

Two suspended towers, 4 enriched Li$_2^{100}$MoO$_4$ crystals winter 2016 – spring 2015
Test of technology and background evaluation for the future Demonstrator

Suspended tower in LSM to compare ZnMoO$_4$ and Li$_2^{100}$MoO$_4$ to choose best (2015-2016)
LSM underground laboratory

- Laboratoire Souterrain de Modane (LSM):
  - Frejus tunnel
  - 1.7 km rock overburden (~4.8 km w.e.)
  - cosmic $\mu$ reduction = $10^{-8}$ (1/m$^2$h)
  - Deradonized air flow (~30 mBq/m$^3$)

- EDELWEISS set-up:
  - Clean room
  - Copper cryostat
  - Low radioactivity lead (min. 20 cm)
  - Polyethylene (min. 50 cm)
  - Monitoring of $\mu$ / n / Ra
  -Muon veto
Two suspended towers

Test of technology for demonstrator with 20 crystals and R&D detectors with another compounds for 2β-decay research.
Performance of 4 enriched crystals

Enriched Li$_2^{100}$MoO$_4$ crystals demonstrate high performance:

- ~50 nV/keV sensitivity
- 1-2 keV FWHM noise
- ~6 keV FWHM at 2615 keV ⇒ FWHM = 6 keV at Q$_{\beta\beta}$ at not optimal conditions

<table>
<thead>
<tr>
<th>Crystal ID</th>
<th>Signal, nV/keV</th>
<th>FWHM, keV at energy, keV</th>
<th>Energy, keV</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>1461</td>
</tr>
<tr>
<td>1t</td>
<td>40</td>
<td>~1.0</td>
<td>4.0(2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2615</td>
<td>5.8(6)</td>
</tr>
<tr>
<td>1b</td>
<td>47</td>
<td>~1.2</td>
<td>4.7(2)</td>
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<td></td>
<td></td>
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<td>5.7(6)</td>
</tr>
<tr>
<td>2t</td>
<td>50</td>
<td>~2.4</td>
<td>4.1(5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.5(5)</td>
</tr>
<tr>
<td>2b</td>
<td>48</td>
<td>~2.0</td>
<td>5.1(4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.7(6)</td>
</tr>
<tr>
<td>Total</td>
<td>~46</td>
<td>~1.6</td>
<td>4.8(1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.0(3)</td>
</tr>
</tbody>
</table>
Neutron calibration: alpha discrimination

$\gamma(\beta) [2.5-2.7 \text{ MeV}] / \alpha+t [5.0-5.5 \text{ MeV}]$ Discrimination Power = 9.5(5)
Background: ~600h

For all LMO’s: $\alpha$’s in 2.7-3.9 MeV~0.2 cnts/yr/kg/keV

High bulk and surface purity

LMO 1t

LMO 2t

LMO 1b

LMO 2b
Double beta decay of $^{100}$Mo

Investigation of $^{100}$Mo $2\nu 2\beta$:
- Exposure: 28 kg×d
- Enrichment: 96.9% of $^{100}$Mo
- $\text{eff}_{\text{PSD}}$: 97%
- Fit: 160-2650 keV ⇒ Effect = 24320±229 decays
- $T_{1/2} = [6.96±0.06] \times 10^{18}$ yr

Sensitivity to $^{100}$Mo $0\nu 2\beta$:
- $Q_{\beta\beta}(^{100}\text{Mo})$: 3034 keV
- ROI: 10 keV window @ $Q_{\beta\beta}$
- $\text{eff}_{0\nu 2\beta}$: 70% in ROI
- BI: 0.05 cnts/yr/kg/keV ⇒ Bkg: 0.04 counts
- Effect: 0 counts ⇒ $\text{limS}$: 2.4 counts at 90% CL
- $\text{limT}_{1/2} = 5 \times 10^{22}$ yr @ 90% CL
CUPID-Mo experiment

- Detectors of the 1st batch of 20 crystals will be assembled and operated in LSM coexisting with EDELWEISS low-mass WIMP search.

20-detector demonstrator schedule:

- **June-July 2017** – underground test of a single 4-detector tower

- **November 2017 – half 2018** – long underground run, first results of background model and sensitivity will come out.

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

<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>20 crystal [20x0.5 cr.xy]</td>
<td>$1.4 \times 10^{24}$</td>
<td>240 – 670</td>
</tr>
<tr>
<td>20 crystal [20x1.5 cr.xy]</td>
<td>$4.2 \times 10^{24}$</td>
<td>140 – 390</td>
</tr>
<tr>
<td>40 crystal [40x3 cr.xy]</td>
<td>$1.7 \times 10^{25}$</td>
<td>70 – 200</td>
</tr>
</tbody>
</table>

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

▪ Properties of neutrino: mass scale, Dirac or Majorana – answer to this question is important for development of new theories

▪ Cryogenic scintillating bolometers are promising detectors for high-sensitivity searches for $0\nu\beta\beta$ decay

▪ Detectors, developed in the framework of the LUMINEU project, show excellent performance: a few keV energy resolution, 20 sigma $\alpha/\beta$ particle discrimination power at the $Q_{2\beta}$ value of $^{100}\text{Mo}$

▪ $\text{Li}_2^{100}\text{MoO}_4$ crystals are perspective material for $0\nu\beta\beta$ decay research, also can be used as neutron detectors with high energy resolution

▪ Operation of four $\text{Li}_2^{100}\text{MoO}_4$ scintillating bolometers array was highly successful

▪ Goal of Cupid-Mo demonstrator: long run with 20 $\text{Li}_2^{100}\text{MoO}_4$ crystals to prove “zero-background” concept for future ton-scale experiment
Thanks for your attention!

In physics, you don't have to go around making trouble for yourself - nature does it for you.

Frank Wilczek
Backups
Dilution refrigerators

- Complicated system
- It has to be wholly isolated from the environment: vacuum chamber
- To cool down below the LHe temperature ($\approx 4K$) the cryostat uses a mixture of two isotopes of helium: $^3$He and $^4$He.
- Two ways to pre-cool:
  - Wet: LHe bath which provides the first cooling stage at 4.2 K.
  - Dry: pulse tube cooler using heat-exchange gas
Uncertainty in predictions: Nuclear Matrix Elements

- Complicated nuclear many-body problem
- Cannot be measured independently
- Different methods have been used for the calculation of neutrinoless double-β decay NMEs:
Going underground
CUORE (Cryogenic Underground Observatory for Rare Events)

- Operation already started.

Array of 988 $\text{TeO}_2$ 5\(\times\)5\(\times\)5 cm\(^3\) detectors (750 g each)

\[M = 741 \text{ kg of TeO}_2 = 206 \text{ kg of } ^{130}\text{Te}\]
CUPID-0/Se experiment: CUORE Upgrade with Particle IDentification

- Search for 0nbb decay of 82Se with Zn82Se scintillating bolometers
- Data taking with 26 enriched detectors is ongoing
- Expected 1 yr sensitivity is T1/2 ~ 1025 yr
Neutrinos properties: a door to new physics

- Nature of neutrino:
  - Dirac (particle and anti-particle are different, like electron and positron)
  - Majorana (particle and anti-particle cannot be distinguished)

- Neutrino oscillations: neutrinos do have masses (in SM they are considered to be massless), but scale is not defined
This can be achieved in **2018**!
Pulse-shape parameter

Li$_2$MoO$_4$ bolometer, AmBe data, 20 h, LNGS

Li$_{130}$MoO$_4$ bolometer, ZM503A, March 2016, LSM