CUPID

Marco Vignati
INFN Roma
on behalf of the CUPID group of interest

DBD16, 8-10 November 2016, Osaka
Cuore Upgrade with Particle ID

- \( \Delta E < 10 \) keV (Bolometers)
- CUORE infrastructure

- \( \sim 1 \) ton isotope (\(^{130}\)Te, \(^{82}\)Se, \(^{100}\)Mo)
- Background 0.1 count / ton y

Other isotopes:
- Mo
- Ge
- Xe

m_{\beta\beta} [eV]

Inverted hierarchy

CUORE sensitivity (Te)

CUORE-0 + Cuoricino limit (Te)

CUPID sensitivity

Normal hierarchy

m_{\text{lightest}} [eV]
Bolometric technique

- Dielectric crystals (low heat capacitance) source embedded in the detector
- NTD-Ge thermistor: \( R(T) \approx 1 \Omega \cdot \exp \left( \frac{3K}{T} \right)^{\frac{1}{2}} \)
- Resolution @0νββ energy (2528 keV): \( \Delta E \approx 5 \text{ keV FWHM} \)
- No particle identification
CUORE at Gran Sasso lab in Italy

CUORE
988 $^{nat}$TeO$_2$ bolometers

206 kg $^{130}$Te
(34% abundance in Te)

Start data taking at the end of 2016
• More than 15 tons of lead and copper at low temperature.
• Detector calibration system: $^{232}$Th calibration sources deployed from 300 K to 10 mK
• Base temperature: 6.3 mK
• Cooling power: 3μW @ 10 mK
CUORE sensitivity

CUORE-0 + Cuoricino limit (Te)

CUORE sensitivity (Te)

Inverted hierarchy

Normal hierarchy

Other isotopes

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CUPID sensitivity

- CUORE-0 + Cuoricino limit (Te)
- CUORE sensitivity (Te)
- Inverted hierarchy
- CUPID sensitivity
- Normal hierarchy

Other isotopes

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• Use enriched isotope to increase DBD nuclei by a factor ~3.

• Enable particle ID to suppress background.

• Select ultra-low background materials.

• Switch from Tellurium to another isotope?

Can make a bolometer
Background expected in CUORE

CUORE Preliminary

CUORE-0 bkg. model

Surface of TeO$_2$
- Bulk of TeO$_2$
- Bulk of near elements
- Cosmogenic Activation of CuNOSV elements
- Cosmogenic Activation of TeO$_2$

HPGe and NAA
- Far Bulk: CuOF$_E$ elements
- Far Bulk: Roman Pb
- Far Bulk: Modern Pb
- Far Bulk: Superinsulation
- Far Bulk: Stainless steel parts

$\gamma, \mu, n$ fluxes at LNGS
- Environmental muons
- Environmental neutrons
- Environmental gammas

CUPID

CUORE GOAL

90%CL limit

Value
CUORE-0, the test of a single CUORE tower, showed that most of the background in CUORE will be dominated by degraded $\alpha$ particles from natural radioactivity.

### Source Contributions

<table>
<thead>
<tr>
<th>Component</th>
<th>Fraction [%]</th>
<th>Counts / (keV kg y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystals</td>
<td>21.4</td>
<td>0.012</td>
</tr>
<tr>
<td>Holder</td>
<td>74.4</td>
<td>0.005</td>
</tr>
<tr>
<td>Shields</td>
<td>4.2</td>
<td>0.001</td>
</tr>
</tbody>
</table>

**Table 9: Sources contributing to the 0\(^{\text{th}}\) counting rate in this region (i.e. excluding the $\alpha$ component, $\beta$ component and $\gamma$ component).**
β/γ particles emit different amount of light than αs.

Light can be produced by scintillation or by Cherenkov effect.
Option: scintillating crystals
### Zn$^{82}$Se

<table>
<thead>
<tr>
<th></th>
<th>Zn$^{82}$Se</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Q-Value [keV]</strong></td>
<td>2998</td>
</tr>
<tr>
<td><strong>Isotopic abundance [%]</strong></td>
<td>9.2</td>
</tr>
<tr>
<td><strong>$T^{2v}$ [years]</strong></td>
<td>$9 \times 10^{19}$</td>
</tr>
<tr>
<td><strong>$\Delta E$ [keV FWHM]</strong></td>
<td>10-30</td>
</tr>
<tr>
<td></td>
<td>(430 g bolometer)</td>
</tr>
</tbody>
</table>

**Pros**
- Q-value
- R&D concluded

**Cons**
- $\Delta E$
- $^{214}$Bi at 3000 keV

**Light detector:** Germanium disk operated as bolometer

**Heat detector:** ZnSe bolometer
Zn$^{82}$Se crystal test

- Preliminary test with 3 Zn$^{82}$Se
- Smeared α source for discrimination power (DP)
- Operation in Hall C LNGS cryostat: working temperature not optimal ~20 mK
  - energy resolution spoiled ~30 keV
  - but excellent α background rejection

Discrimination power:

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

<table>
<thead>
<tr>
<th>Crystal</th>
<th>$DP(Q_{\beta\beta})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnSe-1</td>
<td>12</td>
</tr>
<tr>
<td>ZnSe-2</td>
<td>11</td>
</tr>
<tr>
<td>ZnSe-3</td>
<td>10</td>
</tr>
</tbody>
</table>
CUPID-0: Zn$^{82}$Se pilot experiment

- 24 Zn$^{82}$Se ($\sim$95% enr.) + 2 naturals ZnSe
  - $^{82}$Se mass: $\sim$5.2 kg ($3.9 \times 10^{25}$ atoms)
- OFHC Cu frame + TECM cleaning
- PTFE stands + standard CUORE cleaning
- 3M ESR reflective foil

- Installed last month at Gran Sasso lab
- Data taking by the end 2016.
- Expected bkg. $< 1.5 \times 10^{-3}$ counts/keV/kg/y
- Sensitivity in 1 year: $9 \times 10^{24}$ y
## Li$_2^{100}$MoO$_4$

<table>
<thead>
<tr>
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<th>Zn$^{82}$Se</th>
<th>Li$_2^{100}$MoO$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Q-Value [keV]</strong></td>
<td>2998</td>
<td>3034</td>
</tr>
<tr>
<td><strong>Isotopic abundance [%]</strong></td>
<td>9.2</td>
<td>9.7</td>
</tr>
<tr>
<td><strong>T$_{2\nu}$ [years]</strong></td>
<td>9 x 10$^{19}$</td>
<td>7 x 10$^{18}$</td>
</tr>
<tr>
<td><strong>$\Delta E$ [keV FWHM]</strong></td>
<td>10-30 (430 g bolometer)</td>
<td>5-8 (210 g)</td>
</tr>
<tr>
<td><strong>Pros</strong></td>
<td>Q-value R&amp;D concluded</td>
<td>Q-value PID w/o light detector</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>$\Delta E$ $^{214}$Bi at 3000 keV</td>
<td>2$\nu$ pileup bkg.</td>
</tr>
</tbody>
</table>

Pros

- Q-value R&D concluded
- PID w/o light detector

Cons

- $\Delta E$ $^{214}$Bi at 3000 keV
- 2$\nu$ pileup bkg.
Li$_2^{100}$MoO$_4$ crystal test

- Control of crystal internal content of $^{40}$K $<$ 5 mBq/kg (Random coincidences: $2\nu2\beta$ + $^{40}$K $\ll$ $2\nu2\beta$ + $2\nu2\beta$)
- Mo purification / crystallization protocol with irrecoverable losses $<$ 4%.
- Excellent crystal radiopurity and ease of production.
- Particle ID on heat channel via pulse shape

\[ \text{Decay time (ms)} \]
\[ \text{Energy (keV}_{ee}) \]

150 g crystal

\[ \gamma(\beta) \]
\[ \text{nuclear recoils} \]
\[ ^{6}\text{Li(n,t)}\alpha \]
\( \textbf{Li}_{2}^{100}\text{MoO}_{4}: \text{Pilot experiment} \)

- Background due to 2ν pileup: \(10^{-4}\) counts/keV/kg/y to be improved via advanced pulse shape analysis.

- 20 crystals (209g each) have been ordered and will be operated at Modane and/or Gran Sasso\(\text{(under discussion)}\).
  
  - 2.46 kg of \(^{100}\text{Mo}\) - \(1.35 \times 10^{25}\) nuclei.
  
  - Another 20 crystals to be ordered.

- Radiopurity of \(\text{Li}_{2}^{100}\text{MoO}_{4}\) crystals
  
  \[7.1 \mu \text{Bq/kg} \] for 30 years

\[\text{FWHM} \approx 5 \text{ keV}\]

<table>
<thead>
<tr>
<th></th>
<th>(\mu \text{Bq/kg})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{top})</td>
<td>(\text{bottom})</td>
</tr>
<tr>
<td>(^{232}\text{Th})</td>
<td>(\leq 3) (\leq 11)</td>
</tr>
<tr>
<td>(^{228}\text{Th})</td>
<td>(\leq 8) (\leq 6)</td>
</tr>
<tr>
<td>(^{238}\text{U})</td>
<td>(\leq 5) (\leq 11)</td>
</tr>
<tr>
<td>(^{226}\text{Ra})</td>
<td>(\leq 7) (\leq 11)</td>
</tr>
<tr>
<td>(^{210}\text{Po})</td>
<td>(230(20)) (60(10))</td>
</tr>
<tr>
<td>(^{40}\text{K})</td>
<td>(\leq 4.6 \times 10^{3}) (\leq 6.6 \times 10^{3})</td>
</tr>
</tbody>
</table>
Option: TeO$_2$, again
<table>
<thead>
<tr>
<th></th>
<th>Zn\textsuperscript{82}Se</th>
<th>Li\textsubscript{2}\textsuperscript{100}MoO\textsubscript{4}</th>
<th>\textsuperscript{130}TeO\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q-Value [keV]</td>
<td>2998</td>
<td>3034</td>
<td>2528</td>
</tr>
<tr>
<td>Isotopic abundance [%]</td>
<td>9.2</td>
<td>9.7</td>
<td>34</td>
</tr>
<tr>
<td>(T^{2\nu}) [years]</td>
<td>9 \times 10^{19}</td>
<td>7 \times 10^{18}</td>
<td>8 \times 10^{20}</td>
</tr>
<tr>
<td>(\Delta E) [keV FWHM]</td>
<td>10-30 (430 g bolometer)</td>
<td>5-8 (210 g)</td>
<td>5 (750 g)</td>
</tr>
<tr>
<td>Pros</td>
<td>Q-value R&amp;D concluded</td>
<td>Q-value (PID) w/o light detector</td>
<td>(\Delta E)</td>
</tr>
<tr>
<td>Cons</td>
<td>(\Delta E)\textsuperscript{214}Bi at 3000 keV</td>
<td>2\nu pileup bkg.</td>
<td>(\gamma) bkg. Challenging PID</td>
</tr>
</tbody>
</table>
Noise of NTD-Ge light detectors is too high (30 - 100 eV) compared to the signal (100 eV) → need noise lower than 20 eV RMS, with a technology scalable to 1000 detectors.
Light detectors: Neganov Luke

- Apply DC voltage to the wafer of the light detector.
- e-h pairs produced by photons are accelerated by the electric field → energy transfer to the wafer lattice → heat.
- Use NTD-Germanium thermistor as sensor.

Germanium wafer + NTD on 750g TeO₂

Silicon wafer + NTD on 6g TeO₂
Light detectors: TES sensor

Superconducting Film

Sapphire wafer + W-TES on 285 g TeO₂

Ir/Au/Ir rilayer TES


Need to develop a 1000 channel readout of SQUIDs
Light detectors: MKID sensor

Microwave Kinetic Inductance Detector (MKID).
high scalability and multiplexing, no microphonic noise.

- **Phase I** - completed: single pixel, high-Q (1.5x10⁵) Aluminum resonator.


- **Phase III** - 2017-18: test at LNGS with TeO₂ bolometers.
130TeO2: Pilot experiment

- Select light detector technology: scalability, reproducibility and compatibility with CUORE infrastructure.
- Plan for an array of enriched 130TeO2 bolometers in 2018.
- Preliminary results from two 435 g enriched crystals produced at SICCAS (CUORE crystals producer):


Table 4: Activity of trace contaminations belonging to 232Th and 238U chains for the two crystals. The total collected statistic is 663.8 hours for 130TeO2-1 and 505.8 hours for 130TeO2-2. Limits at 90 % C.L. See text for more details.

<table>
<thead>
<tr>
<th>Chain</th>
<th>Nuclide</th>
<th>130TeO2-1 [µBq/kg]</th>
<th>130TeO2-2 [µBq/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>232Th</td>
<td>232Th</td>
<td>&lt;4.3</td>
<td>&lt;4.8</td>
</tr>
<tr>
<td>228Th</td>
<td>228Th</td>
<td>&lt;2.3</td>
<td>&lt;3.1</td>
</tr>
<tr>
<td>238U</td>
<td>238U</td>
<td>7.7 ± 2.7</td>
<td>15.1 ± 4.4</td>
</tr>
<tr>
<td>234U</td>
<td>234U</td>
<td>&lt;6.3</td>
<td>&lt;5</td>
</tr>
<tr>
<td>230Th</td>
<td>230Th</td>
<td>&lt;5.7</td>
<td>&lt;3.8</td>
</tr>
<tr>
<td>226Ra</td>
<td>226Ra</td>
<td>&lt;2.3</td>
<td>&lt;3.1</td>
</tr>
<tr>
<td>210Po</td>
<td>210Po</td>
<td>3795 ± 60</td>
<td>6076 ± 88</td>
</tr>
</tbody>
</table>

M. Vignati
Backgrounds other than $\alpha$s

- Need CUPID-0 ($\text{Zn}^{82}\text{Se}$) and CUORE data to confirm simulations.
- Anyhow, non-$\alpha$ background must be reduced by more than 10x
  - Need the development of technologies to measure contaminations of candidate materials for detector and cryostat (Copper, teflon…).
  - Need a muon veto
Conclusions

• CUPID aims at completely covering the inverted hierarchy of $\nu$ mass.

• 3 Pilot experiments:
  ▸ 2016 - Zn$^{82}$Se, start of data taking end of the year.
  ▸ 2017 - Li$_2^{100}$MoO$_4$
  ▸ 2018 - $^{130}$TeO$_2$

• Selection of the best technology for CUPID.

• CUPID will start after CUORE, so after 2022-2023.

We are open to collaborations, contact us!