CUPID-0: a double-readout cryogenic detector for DBD

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Experimental search for $0\nu\beta\beta$

**WHAT WE ARE LOOKING FOR**

$2\nu\beta\beta$: $(A, Z) \to (A, Z + 2) + 2e^- + 2\bar{\nu}_e$
- allowed in the SM and already observed with $T_{1/2} > 10^{18}$ y

$0\nu\beta\beta$: $(A, Z) \to (A, Z + 2) + 2e^-$
- not allowed in the SM
- expected with $T_{1/2} > 10^{25}$ y

**If observed:**
- lepton number violation
- neutrinos are Majorana particles
- measures effective electron neutrino mass

$$m_{\beta\beta} \equiv |e^{i\alpha_1}|U_{e1}^2|m_1 + e^{i\alpha_2}|U_{e2}^2|m_2 + |U_{e3}^2|m_3|$$

**EXPERIMENTAL SIGNATURE**

**EXPERIMENTAL SENSITIVITY**

Lifetime corresponding to the minimum detectable number of events over background at a given C.L.:

$$S^{0\nu} \propto e \cdot i.a. \cdot \frac{MT}{\sqrt{b\Delta E}} \quad b \neq 0$$

$$S^{0\nu} \propto e \cdot i.a. \cdot MT \quad b = 0$$

- $M$: Total active mass in kg
- $\epsilon$: Detector efficiency
- $i.a.$: Isotopic abundance
- $b$: Background in c/keV/kg/y
- $\Delta E$: Detector resolution @ ROI in keV
- $T$: Exposure time in y
Scintillating Thermal Detectors (STDs)

A bolometer is a highly sensitive calorimeter operated @ cryogenic temperature (~10 mK).

Energy depositions are measured as temperature variations of the absorber.

- STDs features:
  - high energy resolution O(1/1000)
  - wide choice of compound TeO₂, ZnMoO₄, ZnSe
  - high detection efficiency (source = detector)
  - scalable to large masses
  - particle ID

If the absorber is also an efficient scintillator the energy is converted into heat + light

A background-free experiment is possible:
- α-background: identification and rejection
- β-background: ββ isotope with large Q-value
CUPID-0 (CUORE Upgrade with Particle ID prototype)

Since bolometers are fully active detectors, they show a large background component due to energy degraded $\alpha$ particles.

In CUORE-0 the degraded $\alpha$ background was a minor contribution at $^{130}$Te $Q_{\beta\beta}$ (2527.5 keV).

CUPID-0 use a higher $Q_{\beta\beta}$ isotope and rejects $\alpha$ signals using the scintillation LIGHT.

In CUORE it dominates over the 2615 keV ($^{208}$Tl) multi-Compton: it’s the major component in the ROI.

Excellent discrimination can be obtained based on the shape of the light pulse.
CUPID-0 Detector

CUPID-0 is the first array of scintillating bolometers for the investigation of $^{82}\text{Se} \, 0\nu\beta\beta$

- $^{82}\text{Se}$ Q-value 2998 keV (above $^{208}\text{Tl}$ line)
- 95% enriched Zn$^{82}\text{Se}$ bolometers
- 26 bolometers (24 enr + 2 nat) arranged in 5 towers
  - 10.5 kg of ZnSe
  - 5.17 kg of $^{82}\text{Se} \rightarrow 3.8 \times 10^{25} \beta\beta$ nuclei
- LD: Ge slab operated as bolometer. One face coated with 60 nm SiO$_2$ $\rightarrow$ Light collection enhancement $\sim$50%
- Simplest modular detector $\rightarrow$ scale up
  - Copper structure (ElectroToughPitch)
  - PTFE clamps
  - Reflecting foil (VIKUITI 3M)

Main goal:
Minimize mass of passive materials next to the detector
Zn\textsuperscript{82}Se crystals production cycle

1. Raw (elemental) Se certification
2. SeF\textsubscript{6} synthesis
3. SeF\textsubscript{6} enrichment
4. Se conversion
5. Se beads production certification
6. Zn elemental purification
7. Enriched Se elemental purification
8. Zn\textsuperscript{82}Se synthesis
9. Zn\textsuperscript{82}Se crystal growth certification
10. Recovery and recycling
11. Mechanical processing
12. Package and shipment
13. Grown crystals
14. Metal Zn
15. Enriched Se powder

similar for any crystal candidate
**Zn$^{82}$Se crystals production**

**enrichment:** $^{82}$Se from 8.82% to 96.30% (URENCO, Almelo, Holland)

**Zn$^{82}$Se synthesis and crystal growth:**
(ISMA Kharkiv Ukraine with strong INFN contribution)

**final processing (cutting and polishing):**
@ LNGS, INFN Italy

**production yields:**
synthesis: 98.35%  
(99.55% at S-1, 99.40% at VTT and 99.40% at HTT)  
crystal growth*: 95%  
cutting*: 96.72%  
shaping and polishing*: 99%

*including recovered material for recycling

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Radio-purity measured during crystal production

<table>
<thead>
<tr>
<th>Nuclides</th>
<th>Metal $^{82}$Se [$\mu$Bq/kg]</th>
<th>Metal Zn [$\mu$Bq/kg]</th>
<th>Crystal [$\mu$Bq/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}$Th</td>
<td>&lt;110</td>
<td>&lt;95</td>
<td>7±2</td>
</tr>
<tr>
<td>$^{228}$Th</td>
<td>&lt;61</td>
<td>&lt;36</td>
<td>26±2</td>
</tr>
<tr>
<td>$^{224}$Ra</td>
<td>&lt;110</td>
<td>&lt;61</td>
<td>27±3</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>&lt;110</td>
<td>&lt;66</td>
<td>10±2</td>
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<tr>
<td>$^{226}$Ra</td>
<td>&lt;110</td>
<td>&lt;66</td>
<td>33±4</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td></td>
<td></td>
<td>150±8</td>
</tr>
</tbody>
</table>

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confirmed by CUPID-0 data

CUPID-0 Copper Cleaning

Copper cleaning procedure for mitigating surface contaminations

- **Pre-cleaning**: lubricant removal from machining
- **Tumbling**: abrasion + smoothening
  - removal 1.2 um (0.06 um/h)
- **Electropolishing**: smoothening + contaminants dissolution
  - removal 100 um (12 um/h)
- **Chemical etching**: SUBU+passivation
  - removal 10 um (120 um/h)
- **Plasma etching**: desorption
  - 0.2 um (1 um/h)
CUPID-0 assembly

Detector assembly performed in ~2 weeks inside a low-Rn underground clean room at LNGS

#1 LD installation

#2 ZnSe and light reflector installation

#3 Fixing of ZnSe

#4 LD installation

#5 Tower completed
Detector installed in the former CUORE-0 cryostat after some improvements:

- Refurbishment of the Rn-abatement system next to the cryostat (to reduce in particular $^{214}\text{Bi}$)
- A second stage pendulum to reduce vibrational noise (fundamental for the LD performance)
- New Cryostat wiring: can host up to 120 det.

In June 2017 the commissioning was finished and the data taking started
CUPID-0 exposure

- Exposure for $0\nu\beta\beta$: 9.95 kg x yr ($3.88 \times 10^{25}$ emitters x yr)

- Official data-taking, from 01/06/2017 to 14/12/2018: about 560 d.
CUPID-0 full spectrum - 5.46 (Zn$^{82}$Se) kg y exposure

Cosmogenic activation

- Rejection of “non-particle-like” events through pulse shape on thermal pulses.
- Anti-coincidence between ZnSe crystals
- $\alpha$ rejection by light shape
- Delayed coincidences veto

$T_{1/2} = (9.2\pm0.7) \cdot 10^{19}$ yr

A. S. Barabash, https://doi.org/10.1016/j.nuclphysa.2015.01.001
**β/γ** background: $^{232}$Th internal and surface contaminations

We apply a 3 half-life time veto after all $^{212}$Bi α events

Rejection of the $^{208}$Tl induced background (internal crystal contamination)

**Surface** crystal contamination -> we veto after all α interactions with energy between 2 and 6.5 MeV
CUPID-0 limit - 5.46 (Zn$^{82}$Se) kg y exposure

Exposure

5.46 (Zn$^{82}$Se) kg y

Background

3.2 $^{+1.3}_{-1.1}$ counts/keV/ton/y (Zn$^{82}$Se)

Lower limit, half-life:

$T_{1/2}(0\nu) \geq 4.0 \times 10^{24}$ yr (90% C.L.)

Eff. (trigger + data sel. + $\beta\beta$ containment) 75 ± 2 %
January 2019: stop data taking for a major detector upgrade:

- Remove the reflective foils
- Install a new clean copper shield
- Introduce a (partial) muon veto
What can we learn with detector upgrades:

- Check the bulk/surface ratio of the external radio-contaminations
- Improve the detector stability and understand the origin of $^{208}$Tl contamination
- Study the muon contribution via MC/data comparison or muon tagging
- …
Conclusions

CUPID-0: first large array of enriched scintillating bolometers for the study of $^{82}$Se $0\nu\beta\beta$

- Proved the potential of PID for background rejection
- Will continue with the Phase-II program

Despite the small exposure, best 90% C.I. limit on the $0\nu\beta\beta$ of $^{82}$Se

$$\tau_{1/2} > 4.0 \cdot 10^{24} \text{ yr in } 2.90 \text{ kg yr of } ^{82}\text{Se}$$

(Nemo results: $\tau_{1/2} > 3.6 \cdot 10^{23} \text{ yr in } 3.5 \text{ kg yr of } ^{82}\text{Se}$)

New data release soon, together with other studies ($2\nu\beta\beta$, CPTV, Bkg model….)