New Results on Double Beta Decay with CUPID-O

Stefano Pirro - INFN-LNGS
CUPID-0 Collaboration
The Bolometric technique

\[ \frac{dR}{dE} \approx 5-20 \text{k}\Omega/\text{keV} \]

**Diagram:**
- Incident particle
- Crystal absorber Ø 45 mm h35 ÷55 mm
- Thermometer (NTD Ge, R ~ 10 MΩ)
- Weak thermal link (PTFE)
- Thermal bath 10-30 mK
- \( R(T) \)
- \( R_{\text{load}} \)
- \( R_{\text{load}} \gg R(T) \)

**Graph:**
- Amplitude [mV]
- Time [s]

- \( \sim 1.6 \text{ MeV} \)
Bolometer are total active detectors: they are *surface* sensitive

Most of the natural alpha decays has $Q_\alpha = 4$-$6$ MeV

$E_\alpha \approx Q_{\beta\beta}$

$\Delta E \sim 2$-$4$ MeV
Scintillating Bolometers: rudiments of operation

Operating Temperature for **massive** detectors: 10÷30 mK
A Bolometric Light Detector (BLD) is a fully active a particle detector.

The time response of a BLD is the same of a standard bolometer $O (~1 \text{ few ms})$.

The QE of a BLD is “simply” given by the absorption coefficient.

Operating Temperature for **massive** detectors: 10÷30 mK

*In the MeV region…*
The Lucifer ERC Grant (2010-2015) was dedicated to R&D to be finalized in one enriched Demonstrator made of enriched scintillating crystals in the order of few kg of enriched material. During the R&D several crystals containing $^{82}\text{Se}$, $^{100}\text{Mo}$, $^{116}\text{Cd}$ were tested and also the tiny Cherenkov light from a (non scintillating) TeO$_2$ was measured.
LUCIFER Low-background Underground Cryogenics Installation For Elusive Rates

Choice induced by non availability on the market (2012) of $^{100}$Mo and $^{116}$Cd

isotope: $^{82}$Se, $^{100}$Mo, $^{116}$Cd
material: ZnSe, ZnMoO$_4$, CdWO$_4$
technique: scintillating bolometer

From 2016 this activity is funded by INFN under the INFN-CUPID Project. For this reason, LUCIFER is called now CUPID-0, the first demonstrator in view of CUPID.

JW Beeman et al, Ad. in High Energy Phys. 2013, Article ID 237973

Stefano Pirro NDM 2018 Daejeon July 3 2018
Lucifer - The forerunner of CUPID

CUORE Upgrade with Particle IDentification

R&D towards CUPID: arXiv:1504.03612

CUPID: arXiv:1504.03599

Stefano Pirro NDM 2018 Daejeon July 3 2018
CUPID-0 represents the first enriched bolometer $\beta\beta$-experiment that is demonstrating the background rejection achievable for hybrid $\beta\beta$ scintillating bolometers.
The enriched Selenium (96.5%) was provided by URENCO stable Isotopes

Crystal growth at ISMA Kharkiv

Crystal polishing made in Clean Room @ LNGS

<table>
<thead>
<tr>
<th>Chain</th>
<th>Nuclide</th>
<th>Activity (µBq/kg)</th>
<th>Concentration (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Th</td>
<td>$^{232}_{\text{Th}}$</td>
<td>&lt; 61</td>
<td>&lt; 0.015</td>
</tr>
<tr>
<td></td>
<td>$^{228}_{\text{Ra}}$</td>
<td>&lt; 110</td>
<td>&lt; 0.026</td>
</tr>
<tr>
<td>Th</td>
<td>$^{228}_{\text{Th}}$</td>
<td>&lt; 110</td>
<td>&lt; 0.009</td>
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<tr>
<td>U</td>
<td>$^{238}_{\text{U}}$</td>
<td>&lt; 110</td>
<td>&lt; 0.009</td>
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<tr>
<td></td>
<td>$^{226}_{\text{Ra}}$</td>
<td>&lt; 110</td>
<td>&lt; 0.009</td>
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<tr>
<td>Th</td>
<td>$^{234}_{\text{Th}}$</td>
<td>&lt; 6200</td>
<td>&lt; 0.500</td>
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<tr>
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<td>$^{234m}_{\text{Pa}}$</td>
<td>&lt; 3400</td>
<td>&lt; 0.280</td>
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<tr>
<td>U</td>
<td>$^{235}_{\text{U}}$</td>
<td>&lt; 74</td>
<td>&lt; 0.13</td>
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<tr>
<td>K</td>
<td>$^{40}_{\text{K}}$</td>
<td>&lt; 990</td>
<td>&lt; 32</td>
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<tr>
<td>Co</td>
<td>$^{60}_{\text{Co}}$</td>
<td>&lt; 65</td>
<td>&lt; 1.6 × 10^{-12}</td>
</tr>
<tr>
<td>Se</td>
<td>$^{75}_{\text{Se}}$</td>
<td>110 ± 40</td>
<td>(2.0 ± 0.7) × 10^{-13}</td>
</tr>
</tbody>
</table>
The CUPID-0 tower

26 ZnSe Crystal 24 enriched 2 natural: Driving Idea: minimize frame mass, type of pieces, use only certified (large bar) copper.

ZnSe 78% Cu 22% PTFE 0.1% 0.14% VIKUTI™ reflector
Light detectors are the fundamental part of the experiment since they permit the alpha background discrimination.

- **44.5 mm dia, 170 μm thick pure Ge wafer**
- **SiO₂ coating to increase light absorption**

Performance evaluated with $^{55}$Fe source:

- $\tau_{\text{rise}(10-90)} \approx 1.8 \text{ ms}$
- $\tau_{\text{decay}(90-30)} \approx 6 \text{ ms}$
- $\sigma \approx 50 \text{ eV}$
The overall detector

CUPID-0: the first array of enriched scintillating bolometers for 0νββ decay investigations
CUPID @ LNGS

1400 m of rock

3650 m.w.e.

3 main halls 100x20x18 m³

µ-Flux ~1 m²h⁻¹

100 km east from Rome

Easy access from Highway tunnel
Low radioactive custom wet Oxford 200 (9 mK) (1988)

Completely customized Leiden dry 400 (6.8 mK) 2012
The CUPD-0 experimental hall and Faraday cage

- Cooldown: February 2017
- Detector commissioning: March-May 2017
- Background data since: June 2017
- Q-Value \(2997.9 \pm 0.3\) keV
- 95% enriched \(\text{Zn}^{82}\text{Se}\) crystal
- 26 crystals (2 natural)
- 10.5 kg of ZnSe, 5.17 kg of \(\text{Se}^{82}\)
- 2 enriched crystal excluded from analysis (bad quality)
- Total \(\beta\beta\) nuclei for analysis \(3.41 \times 10^{25}\)
First Result on the Neutrinoless Double-$\beta$ Decay of $^{82}$Se with CUPID-0

O. Azzolini et al.
Phys. Rev. Lett. 120, 232502 (2018) – Published 5 June 2018

The CUPID-0 experiment improves the half-life limit of the $^{82}$Se neutrinoless double beta decay by almost an order of magnitude.

https://arxiv.org/abs/1802.07791
The achieved live time is extraordinary high for a bolometric experiment. It is mainly due to the work devoted to:

- Double stage damping system
- refurbished/improved mixture injection line
- Improved He refill procedure
- Tower+MC temperature stabilization system

A not negligible fraction of dead time (within the Tests/Refills) was/is induced by earthquakes.

Total Exposure = 3.44 kg y ZnSe
Presently we cannot give the actual performance since, for obvious reasons, no $^{55}$Fe sources were mounted on CUPID-0.

Nevertheless the performances can be inferred by roughly looking at the S/N ratio at the scintillation signal @2615 keV: it is very good for all the detectors.

The discrimination factor evaluated on internal $\alpha$-lines is completely satisfying.
Energy calibration

The mean baseline energy resolution of the detector is 3.8 keV. This indicates that the actual energy resolution is dominated by the low crystalline structure of the crystals (position effects).
Total background - 3.44 kg y

- $^{65}$Zn - EC
- $^{40}$K
- $^{208}$Tl
We have chosen a symmetric window (± 200 keV) across $Q_{\beta\beta}$.
The alpha are recognized thanks to the Light shape.
A not negligible background is induced by internal contamination belonging to the $^{232}$Th chain, through the decay of $^{208}$Tl with Q-Value of 5 MeV. The decay is preceded ($T_{1/2} \approx 3$ min) by the $\alpha$-decay of $^{212}$Bi, Q-value 6.2 MeV.
Background in the RoI (3)

Efficiencies

- Trigger: 99.44 %
- Heat Shape + alpha DC: 93±2 %
- Light Shape: 100 %
- $\beta\beta$-containment: 81 %
- TOTAL efficiency: 75 ± 2 %
ββ-0ν Results

Background Level: 3.6x10^{-3} \text{ counts/(keV kg y)}

\[ T^{0\nu}_{1/2}(^{82}\text{Se} \rightarrow ^{82}\text{Kr}) > 2.4 \times 10^{24} \text{ y} \ (90\% \text{C.I.}) \]

This result overcomes by 1 order of magnitude the results of Nemo recently republished (https://arxiv.org/abs/1806.05553)

CUPID-0 Analysis paper: https://arxiv.org/abs/1806.02826 submitted to EPJ-C
CUPID-0 Timeline

Start cool-down

Commissioning

Reached base temperature

physics (PRL 2018) 3.44 kg y

2017
June 2017

2018
Dec 2017

physics 2.02 kg y

April 2018

56Co calibration
Energy resolution in ROI = (22.5 ± 1.2) keV FWHM, consistent with (23.0 ± 0.6) keV extracted from $^{232}$Th calibration, used or PRL analysis. Residuals @ $Q_{\beta\beta}$ < 3 keV

$T_{1/2}(^{56}\text{Co}) = 77$ days

$\chi^2/\text{NDF} = 13.24 / 7$

$E_0 = 5.82\pm0.44$ [keV]

$a = (5.6\pm0.2)e^{-03}$
Exposure: $3.44 + 2.02 = 5.46$ kg x y of $^{82}$Se

BL: $3.2^{+1.3}_{-1.1} \times 10^{-3}$ counts/(keV kg y)

$T_{1/2}^{0\nu} > 4.0 \times 10^{24}$ y (90% C.I.)

$m_{\beta\beta} < (292 - 596)$ meV
From J. Engel, J Menéndez, Rep. on Prog. in Physics 80, 046301 (2017) arXiv:1610.06548 updated accordingly to

$^{76}\text{Ge}$: Phys. Rev. Lett. 120 (2018) 132503

$^{130}\text{Te}$: Phys. Rev. Lett. 120 (2018) 132501

$^{82}\text{Se}$: previous slide

KamLAND-Zen ($^{136}\text{Xe}$)

IH

NH
Yesterday we submitted the paper on *Search of the neutrino-less double beta decay of $^{82}\text{Se}$ into the excited states of $^{82}\text{Kr}$ with CUPID-0* [https://arxiv.org/abs/1807.00665](https://arxiv.org/abs/1807.00665)

The number of $2\nu$ collected so far is $\approx 2 \cdot 10^5$

We are still fixing the background model

The main difficulty is the “absence” of peaks ($^{232}\text{Th}$ and $^{238}\text{U}$ to perform a very precise background model)
CUPID-0 is not equipped with a µ-veto: most of its induced background can be discriminated through anticoincidence. Nevertheless the residual (single) interaction represents the largest background of CUPID-0 in the RoI. This contribution can be evaluated through MC simulation normalized on the high energy – high multiplicity background data.

Half of the background in the RoI could be due to µ.
Conclusions

- CUPID-0 demonstrator is working extremely good and with an unprecedented LT
- The BI is extremely small and is only limited by the “old” facility
- in 10 months of operation we increased the previous $0\nu$ limit of $^{82}\text{Se}$ by a factor $15$
- We are evaluating the possibility to mount an additional internal Cu-shield and a $\mu$-veto to further decrease the background
- The goal is to approach $10^{25}$ y by the end of the next year.
- We are evaluating the possibility to add a enriched Li$_2$MoO$_4$ tower just below CUPID-0 by the middle of next year

But, more important, CUPID-0 & CUORE represent the definitive proof of principle of CUPID