Backgrounds and sensitivity of the CUPID experiment

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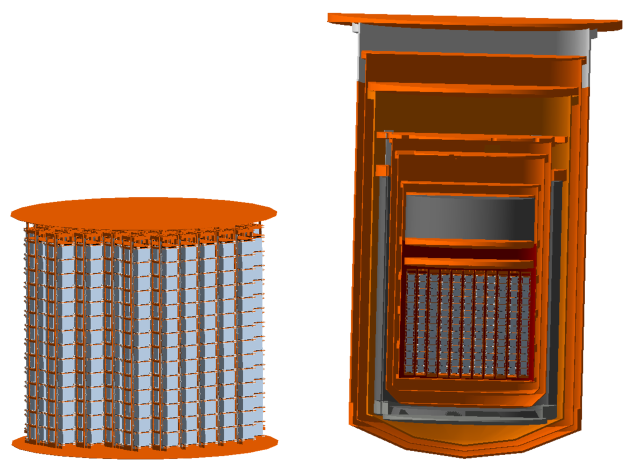
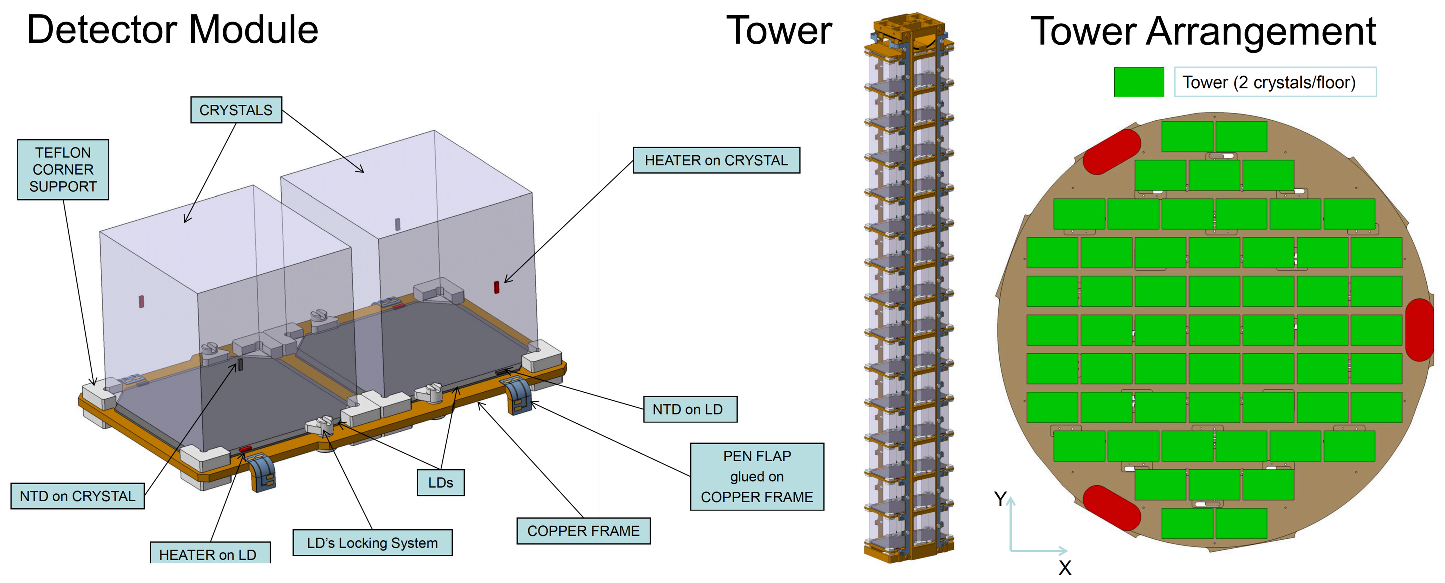
CUPID, the next generation bolometric $0\nu\beta\beta$ experiment

CUore Upgrade with Particle IDentification

- Exploit CUORE infrastructure
- Detection of heat and scintillation light signals allowing α discrimination
- $Li_2{}^{100}MoO_4$ scintillating crystals
- ^{100}Mo, $Q_{\beta\beta}$=3034 keV
- Total mass= 450 kg, ^{100}Mo mass=240 kg



GEANT4 rendering of CUPID.



- 1596 $Li_2{}^{100}MoO_4$ crystals of 45 x 45 x 45 mm^3
- Light detectors with Neganov-Trofimov-Luke, NTL, amplification

Physics goals

- Sensitivity $T^{0\nu}_{1/2} \sim 10^{27}$ y, sufficient to exclude the Inverted Ordering, IO, parameter space or make a discovery in $m_{\beta\beta} \sim$ [10 – 20] meV.

Requires:

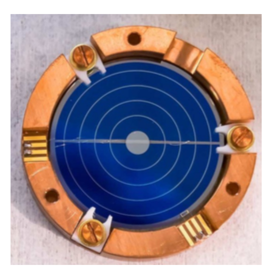
- Background index, BI = 10^{-4} counts/(keV·kg·yr)
- Energy resolution, FWHM, $\sim$ 5 keV at $Q_{\beta\beta}$
- Livetime: 10 years

Background sources

- Radioactivity from:
  - Crystals
  - Close components: Copper frames, Teflon supports, CuPEN readout
  - 10 mK components: vessel, Cu plates, flange
  - Cryostat and shields
- $2\nu\beta\beta$ pileup: The random coincidence of two or more $2\nu\beta\beta$ events in the same crystal happening so close in time that the signal is equivalent to that of the sum of the two events.
- Muons
- Neutrons

$2\nu\beta\beta$ Pile-up

- Light detectors with NTL amplification mechanism used for pile-up rejection
- Current performances of NTL light detectors in terms of signal/noise and risetime are capable to achieve a background level in ROI from pile-up $\sim 5 \times 10^{-5}$ counts/(keV·kg·yr).



Background simulations

- GEANT4 based program. Selection cuts: single crystal, γ/β induced events
- ROI: (3034 ± 15) keV to avoid 3000 keV and 3053 keV γ's from ^{214}Bi.

Method:

BASED ON PAST ACHIEVEMENTS IN RADIOACTIVITY LEVELS OF MATERIALS.
We use the probability density functions of the activities from CUORE/CUORE-0/CUPID-Mo background models, w_j, and sample the full posterior distribution for each step i in the Markov Chain:

$$b_i = \sum_{j=1}^{\text{Nsources}} \text{Pois}(N_j) \frac{w_{i,j}}{\Delta E \times N_{gen}} \quad (1)$$

- Translate the activity pdf to BI using the number of events in ΔE, N_j, from CUPID simulations.
- We estimate the marginalised posterior distribution as the mode ± smallest 68% interval

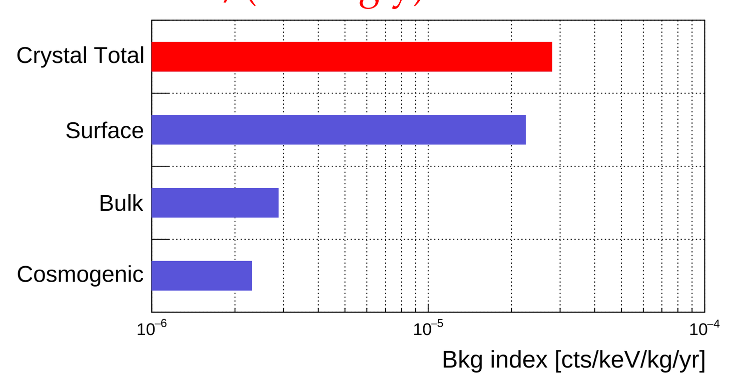
Estimated backgrounds from detector components

Crystals

We use the activities and the probability density functions from the CUPID-Mo background model [1].

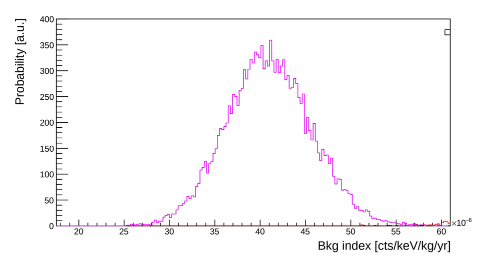
- ^{226}Ra/^{228}Th bulk < 0.2 μBq/kg / 0.4 ± 0.2 μBq/kg → (2.9 ± 1.1) × 10^{-6} cts/(keV·kg·y)
- ^{226}Ra/^{228}Th surface 2.0 ± 0.5 nBq/cm^2/ < 2.5 nBq/cm^2 → (2.2 ± 0.7) × 10^{-5} cts/(keV·kg·y)

Cosmogenics: Activities assume 90 days at sea level and 1 year cooling-down → 2.3 × 10^{-6} cts/(keV·kg·y)



The dominant background in the ROI is the surface contamination at the level of 2 × 10^{-5} cts/(keV·kg·y). Can be further decrease improving polishing and handling.

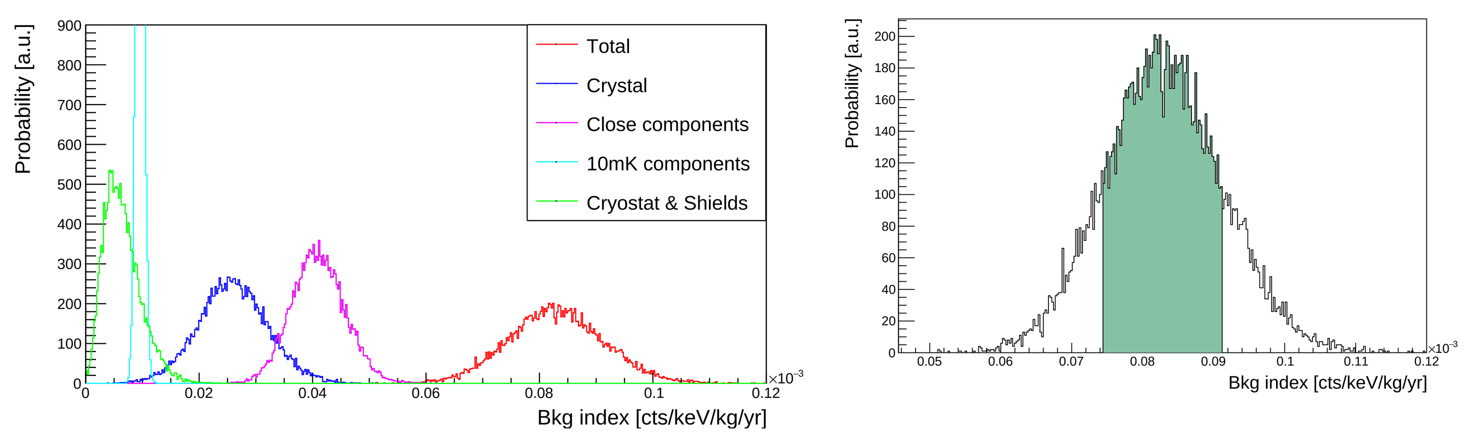
Close components



- We use the activities and the probability density functions from the CUORE-0 background model [2].
- The leading contribution is the surface copper frames at the level of 4 × 10^{-5} cts/(keV·kg·y).
- Total $4.1^{+0.5}_{-0.4} \times 10^{-5}$ cts/(keV·kg·y)

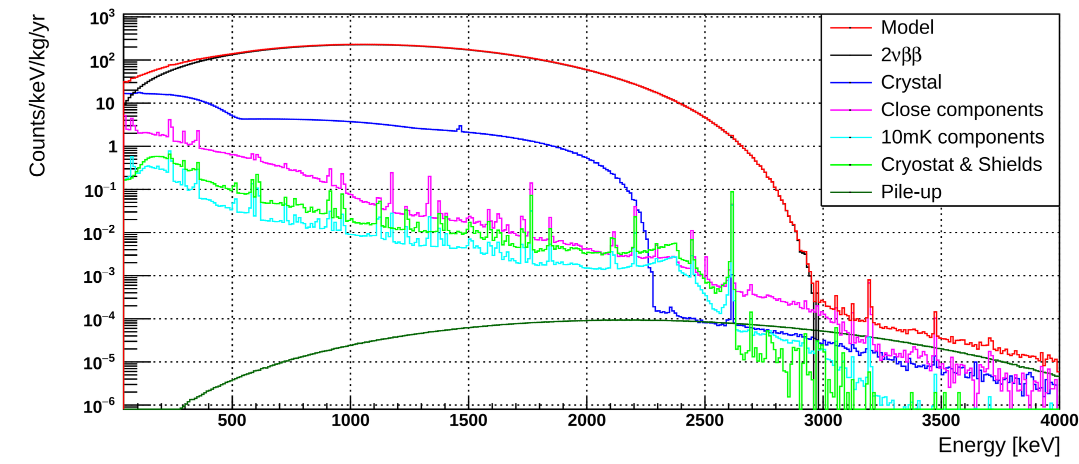
10 mK components and Cryostat and shields Subdominant contributions

Total estimated backgrounds from detector components

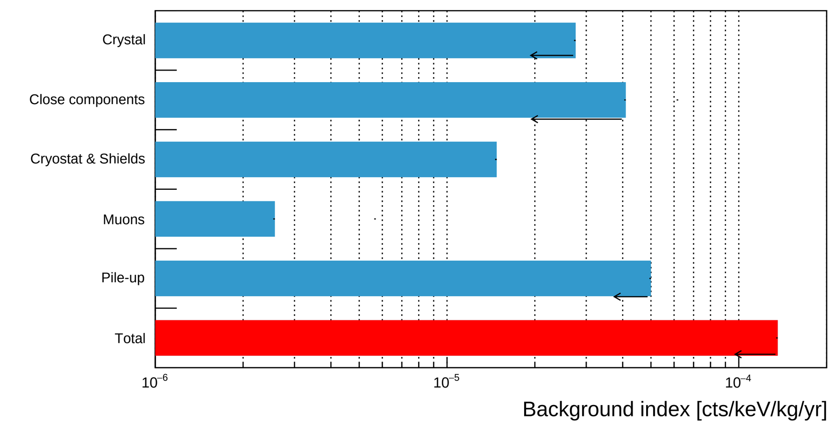


- Total in ROI from radioactivity in materials: 8.3 ± 0.9 × 10^{-5} cts/(keV·kg·y)
- The driving contributions are contaminations on the surface mainly from close components, Cu frames, PTFE, CuPEN

Reconstructed background spectrum



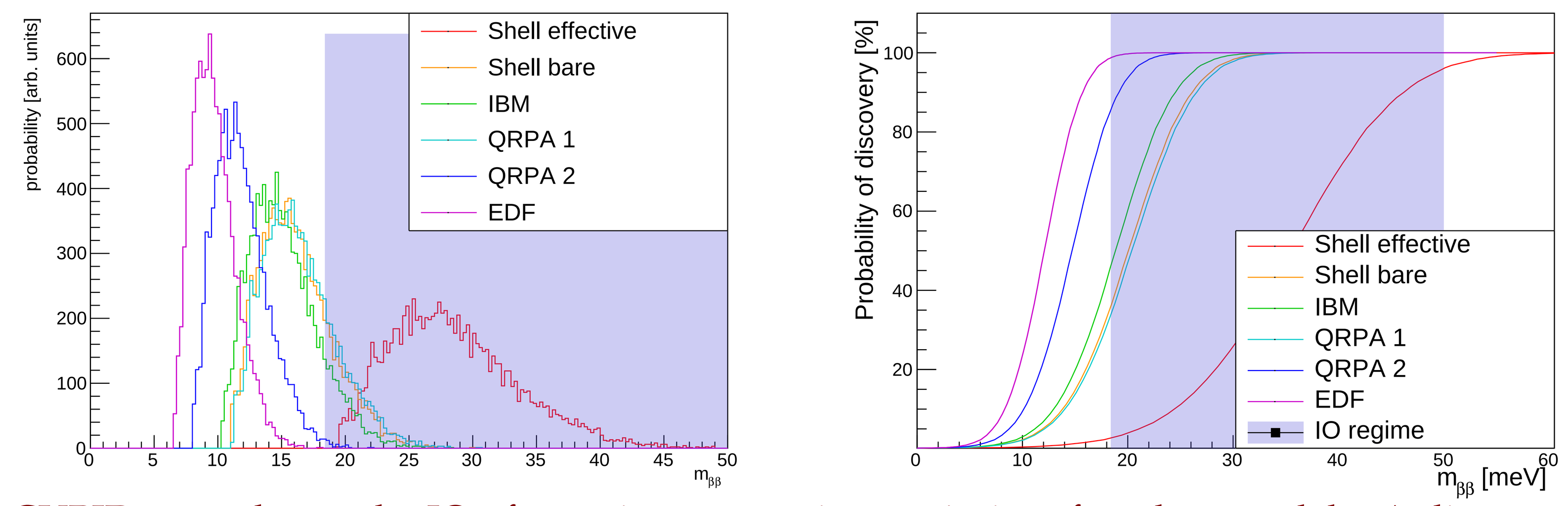
Total estimated backgrounds



- Using past experiments achievements, the total estimated background in ROI 1.36 × 10^{-4} cts/(keV·kg·y)
- We plan to reach BI baseline = 10^{-4} counts/(keV·kg·yr) by improvements in progress: further reduction of surface contaminations from extreme controlled storage conditions, cleaner machining practices and more effective cleaning. Pile-up can be further reduced by new analysis algorithms.

Sensitivity

- We developed Bayesian and Frequentist frameworks.
- We generate pseudo experiments with the CUPID baseline BI= 10^{-4} counts/(keV·kg·yr) .
- $T^{0\nu}_{1/2}$ limit, Bayesian at 90% c.i = 1.6 × 10^{27} y. Flat prior on the decay rate or equivalently $m^2_{\beta\beta}$
- $T^{0\nu}_{1/2}$ discovery, Frequentist at 3 σ = 1.0 × 10^{27} y
- Convert $T^{0\nu}_{1/2}$ limit to the limit on $m_{\beta\beta}$ using NMEs from different nuclear models



CUPID can rule out the IO of neutrino masses in a majority of nuclear models. A discovery is very likely for the most favorable nuclear models for the smallest $m_{\beta\beta}$ values in the IO.

References

1. Augier et al (CUPID-Mo coll.). The background model of the CUPID-Mo $0\nu\beta\beta$ experiment. *Eur. Phys. J. C*, 83, 675 (2023).
2. Alduino et al (CUORE-0 coll.). Measurement of the two-neutrino double-beta decay half-life of ^{130}Te with the CUORE-0 experiment. *Eur. Phys. J. C*, 77, 13 (2017).