Optimization of a single module of CUPID

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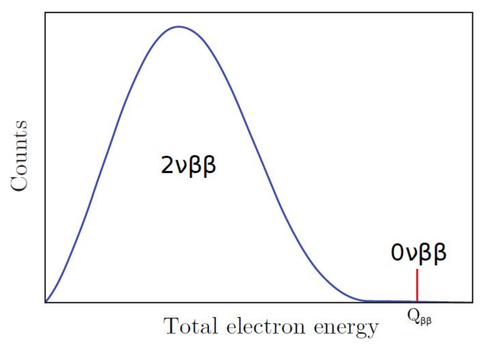
Neutrinoless Double β Decay



$(A,Z) \rightarrow (A,Z+2) + 2e^-$

Nuclear process not allowed in the Standard Model (ΔL = 2)

➔ Neutrino Nature: $0\nu\beta\beta$ possible only if neutrino is a Majorana particle (neutrino and anti-neutrino are the same particle)

➔ Most sensitive process to total lepton number violation

Half-Life $0\nu\beta\beta$ sensitivity:

$$S_{0\nu} \propto \epsilon \sqrt{\frac{MT}{B\Delta}}$$

Energy Resolution and Efficiency (**Δ,ε**): Bolometric technique

Low Background (**B**): Underground experiments, Radiopure Materials

Large Exposure (**MT**): Ton-scale experiments

Present: $10^{25\text{-}26}$ y

Future experiments: $10^{27\text{-}28}$ y

If "zero-background":

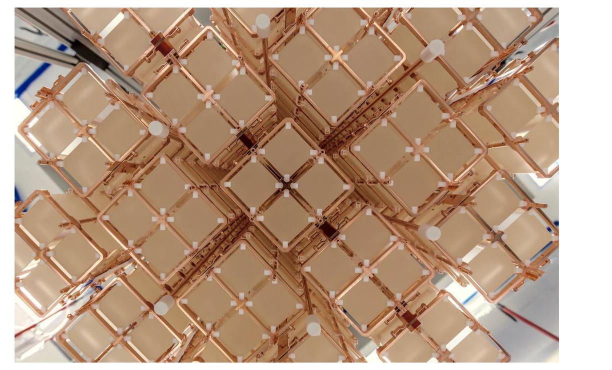
$$S_{0\nu} \propto \epsilon MT$$

Scintillating Bolometers and Light Detectors for Particle Identification

CUORE & CUPID

CUORE experiment demonstrated the possibility of building a bolometric experiment on a 1 ton scale, using TeO_2 crystals.

It showed the potential of such detector in terms of cryogenic stability and detector performances.



➔ 0.3% FWHM energy resolution at $Q_{\beta\beta}$ (2527 keV)

➔ > 1 ton × year exposure

(High sensitivity neutrinoless double-beta decay search with one tonne-year of CUORE data (Apr 14, 2021))

CUORE background level in the ROI is limited by the presence of α particles from surfaces contamination of detector material.

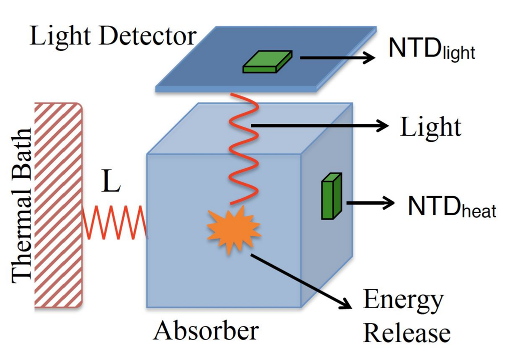
CUPID will use the same cryogenic infrastructure of CUORE, using scintillating Li_2MoO_4 crystals to search for $0\nu\beta\beta$ of ^{100}Mo in a "zero-background" environment (<10^{-4} counts/ kg/ keV/ y)

➔ Reject α particles induced background

➔ ^{100}Mo higher Q-value also mitigate γ background

Scintillating Bolometers

- Particles interacting in the crystal release energy producing phonons and thus increasing the temperature
- A very sensitive cryogenic thermometer, NTD-Ge thermistor, converts the temperature increase into an electric signal
- Operated at about 10mK to convert energy release in a detectable temperature increase (100 μK/MeV)

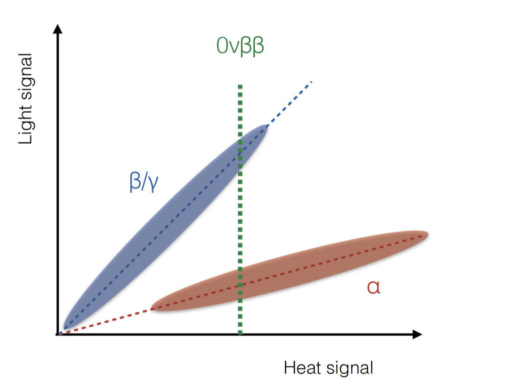


Excellent energy resolution due to thermal phonon detection (~ 0.3% FWHM at 0νββ Q-value)

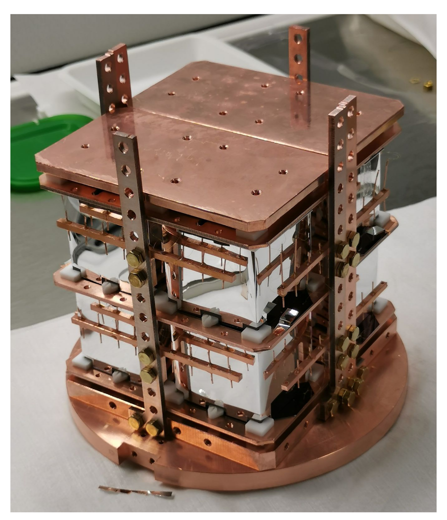
Intrinsic energy resolution only due to fluctuation in phonons collection (~ 10 eV). Electric and thermal noise are the dominant component.

Scintillating crystals allow to detect simultaneously heat and light produced by the same particle. The production of scintillating photons is quenched for α particles.

This technique allows to reject the background induced by α particles



Single Module of CUPID



Detector composed by 8 ^{100}Mo enriched Li_2MoO_4 cubic crystals (LMO) arranged in 2 floors

- First Run: covered with reflecting foil
- Second Run: reflecting foil removed

Each crystal equipped with 2 light detectors on top and bottom faces: overall 12 light detectors arranged in 3 floors

Detectors held by a PTFE and Copper structure which works as a thermal sink.

Light detectors (LD) are made of a Ge wafer coated with SiO. These have a quasi-square shape to cover the crystal faces and allow the gluing of a thermistor.

Indeed they work also as bolometers, detecting scintillation photons produced in the crystal.

Main purposes of the R&D Test:

- Performance of the new assembly. The cooling to 10 mK resulted to be uniform among crystals and light detectors floors.
- Light detectors and Particle Identification: Quasi-square LD tested for the first time to improve the light collection
- Energy resolution of LMO

Light Yield Analysis

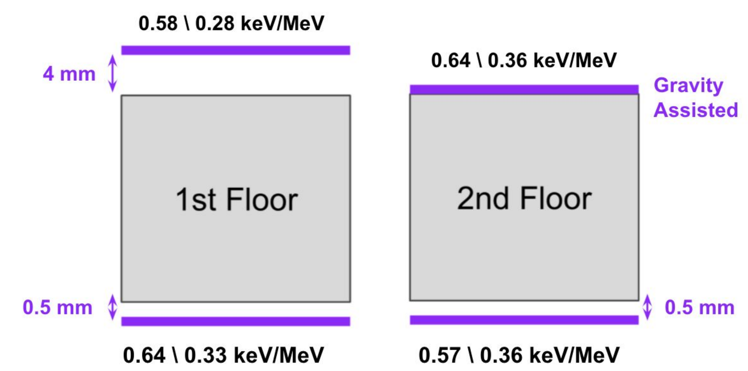
The aim of this CUPID R&D test is to improve the light collection and subsequently the discrimination of α particles. From the last test, in which circle LD has been used, it resulted that to have a powerful α background rejection a reflecting foil (RF) covering the crystals is needed (Characterization of cubic Li2100MoO4 crystals for the CUPID experiment. *Eur. Phys. J. C* 81, 104 (2021))

In this test we used **quasi-square LD**, to better match the cubic crystals faces, both with and without RF.

The assembly allowed to study the effect of different spacing between crystals and LD on the light yield:

- 1^{st} Floor: 0.5 (bottom LD) and 4 mm (top LD)
- 2^{nd} Floor: 0.5 (bottom LD) and Gravity Assisted (top LD)

Scheme of the 2 different configuration of LD. Above and below each LD is reported the LY measured by the single LD with\without RF.



Signal-to-Noise ratio of LD improved by using a matched filter (Optimum Filter) and synchronizing the heat and light pulses. The latter technique allows to compute the light pulses amplitude at a fixed time with respect to the heat one, improving the estimate at lower energies. Light signals calibrated with a ^{55}Fe X-ray source.

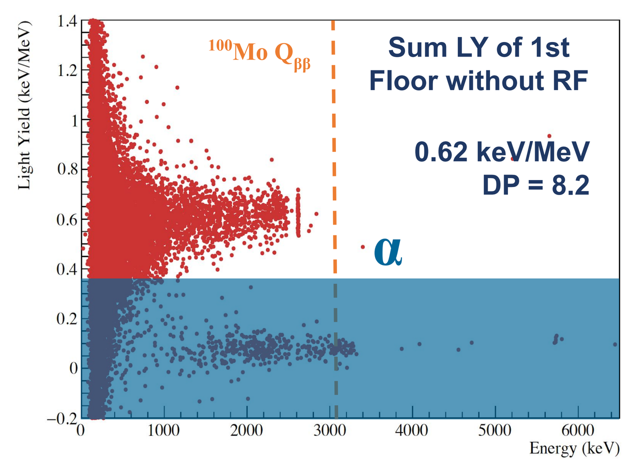
Noise RMS is between 30-70 eV in all LD, no differences among different floors.

Light Yield (LY) estimated from the distribution of light - heat energy signal ratio.

Results with RF: LY from the sum of 2 LDs signals

- 1^{st} Floor LY: 1.22±0.06 keV/MeV
- 2^{nd} Floor LY: 1.21±0.06 keV/MeV

Total LY are compatible in the 2 configurations, and the LY from single LD (in the figure above) compensate each other. Thus the light collection is saturated, and a closer LD collect more scintillation photons. However the differences are not significant for our purposes.



Results without RF: LY from the sum of 2 LDs signals

- 1^{st} Floor: 0.62±0.04 keV/MeV
- 2^{nd} Floor: 0.70±0.05 keV/MeV

Removing RF light collection is not saturated, so it is different in the 2 configuration, even if differences are not very significant. LY is about ½ with respect to the case with RF

In both cases LY improved of 15-20% with respect to the case of circle LD already tested during 2020 Hall C R&D runs (see here)

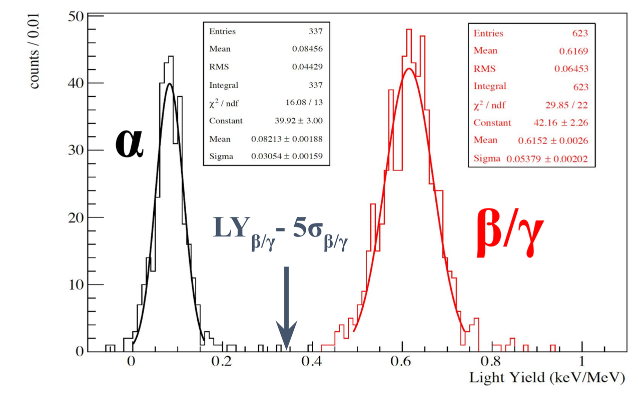
Discrimination Power

$$DP = \frac{LY_{\beta/\gamma} - LY_\alpha}{\sqrt{\sigma^2_{\beta/\gamma} + \sigma^2_\alpha}}$$

Complete rejection if DP > 4-5.

Achieved in case of RF and without RF by summing signals from the 2 LDs.

In few cases DP too low if NO RF and a single LD.



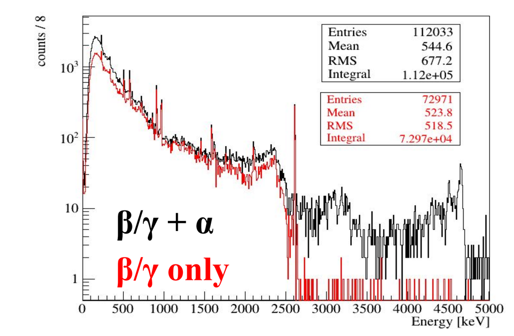
LY from sum of 2 LDs of LMO-2 without RF (DP = 8.2)

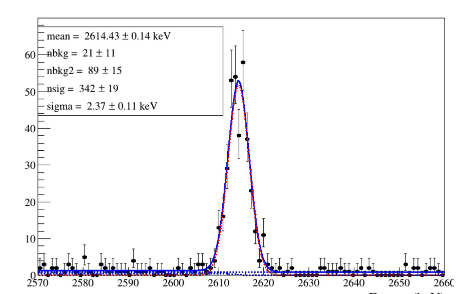
Rejection higher than 99.9 % in case of 2 LD and no RF even assuming 5σ of signal acceptance

Energy Resolution Analysis

Detector response improved by removing temperature instabilities dependence. The drift of amplitude with temperature is studied on a monoenergetic γ-ray peak (^{208}Tl at 2615 keV). Then the heat signals have been stabilized by correcting their temperature dependence.

Calibration performed thanks to a ^{232}Th source which provides many γ peaks in the energy range of 239 - 2615 keV. α from ^{238}U source covered with Mylar film. Only a fraction of energy is released in the crystals to emulate surfaces contamination





Resolution estimated from the FWHM resulting from the fit of the most intense γ peaks (namely 239, 583, 911 and 2615 keV).

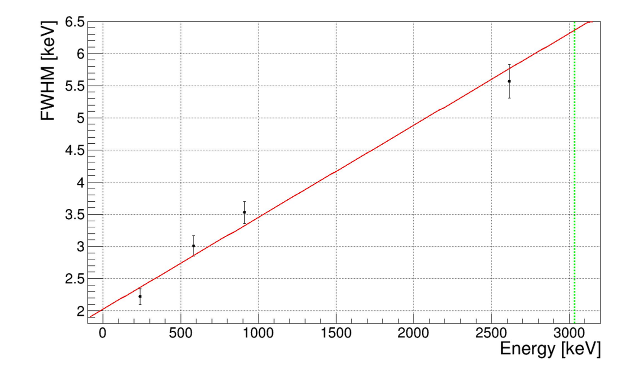
Than extrapolated at ^{100}Mo ββ Q-value by a linear fit.

Resolution from weighted average of 8 LMO:

➔ **6.0 ± 0.3 keV**

Resolution from the overall spectrum of 8 LMO:

➔ **6.4 ± 0.3 keV**



LMO resolution is improved with respect to the 2020 R&D test (see here), probably due to improved cryogenics conditions. Resolution approaches the CUPID final goal of 5 keV.