

The CUPID neutrinoless double beta decay experiment

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September 6, 2023

$0\nu\beta\beta$ interplays

Theoretical inputs:

g_A
 $\mathcal{M}$
 $G_{0\nu}$

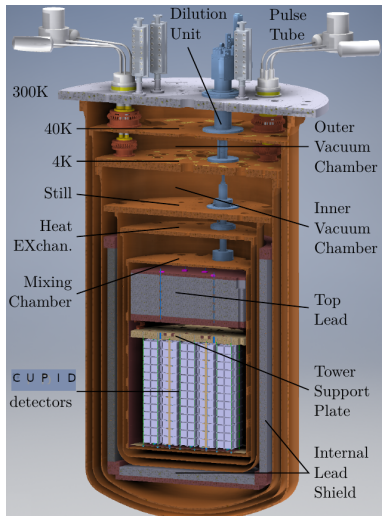
$0\nu\beta\beta$
experiments
 $2\nu\beta\beta$ decays

β decays

Majorana ν

Lepton number violation
 $m_{\beta\beta}$

CUORE Upgrade with Particle Identification



Next generation bolometric ton-scale experiment in CUORE infrastructure

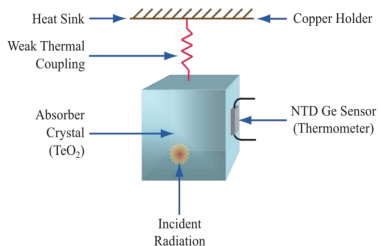
Discovery sensitivity:
 $T_{1/2}(^{100}\text{Mo}) > 10^{27} \text{ y}$
 $m_{\beta\beta} < 20 \text{ meV}$

The detection concept

CUORE ^{130}Te

Bolometers

Heat

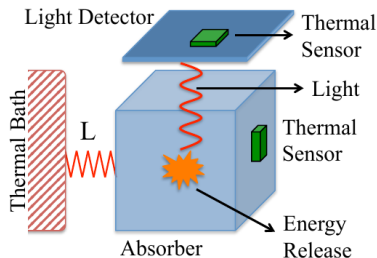


No $\gamma/\beta - \alpha$ identification

CUPID ^{100}Mo

Scintillating bolometers

Heat and Light

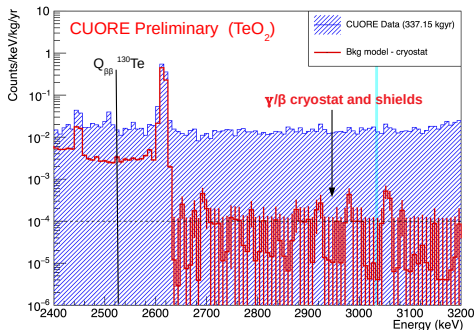


$\gamma/\beta - \alpha$ identification

CUORE Background

The main background comes from α particles (from surface contaminations close to the crystals) $\rightarrow$ flat continuum

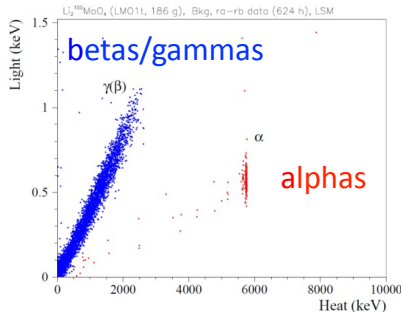
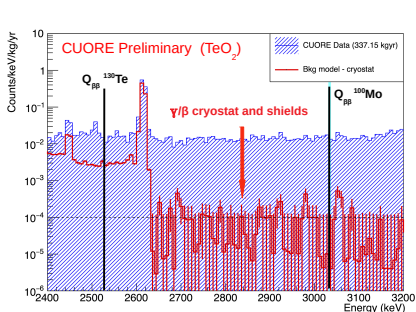
See also K. Vetter talk



Subdominant contributions :

- cosmogenic muons
- γ 's from cryostat and shields
- γ 's from holders

From CUORE to CUPID

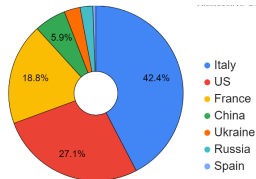


- $Q_{\beta\beta} (^{100}\text{Mo}) = 3034 \text{ keV}$, above γ background from natural radioactivity
- Heat and light detection allows α rejection

CUPID collaboration

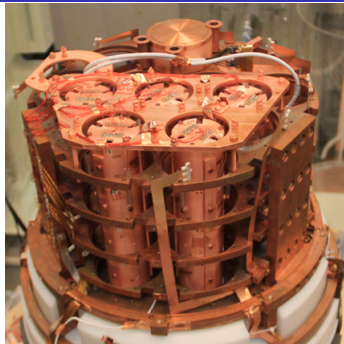


7 countries
~ 180 members



CUPID demonstrators: CUPID-Mo

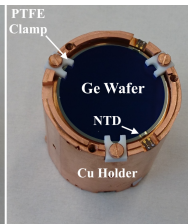
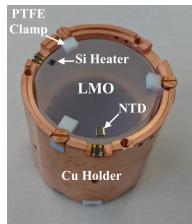
L. Imbert talk



- First demonstrator using $\text{Li}_2^{100}\text{MoO}_4$ enriched in ^{100}Mo
- 20 $\text{Li}_2^{100}\text{MoO}_4$ crystals
- At Laboratoire Souterrain de Modane in Edelweiss cryostat

Performances close to CUPID goals reached

- α rejection at 99.9%
- Excellent radiopurity of crystals
- Energy resolution ~ 7 keV FWHM at 3034 keV



CUPID-Mo limit on $0\nu\beta\beta$ half-life

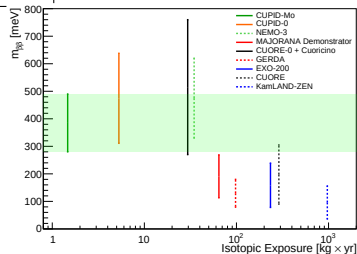
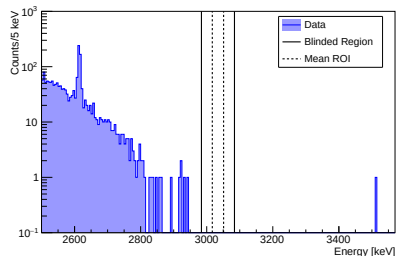
- After unblinding 0 events observed in ROI
- Leads to a limit:

$$T_{1/2}^{0\nu}(^{100}\text{Mo}) > 1.8 \times 10^{24} \text{ yrs } 90\% \text{ c.i.}$$

- Under light Majorana neutrino exchange model:

$$\langle m_{\beta\beta} \rangle < 280 - 490 \text{ meV}$$

EPJC 82, 1033 (2022)



CUPID-Mo Decays to excited states

Phys.Rev.C 107 (2023) 2, 025503

$$T_{1/2}(2\nu \rightarrow 0_1^+) = 7.5 \pm 0.8 \text{ (stat.)}_{-0.3}^{+0.4} \text{ (syst.)} \times 10^{20} \text{ yrs}$$

$$T_{1/2}(2\nu \rightarrow 2_1^+) > 4.4 \times 10^{21} \text{ yrs (90\% c.i.)}$$

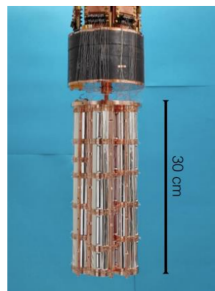
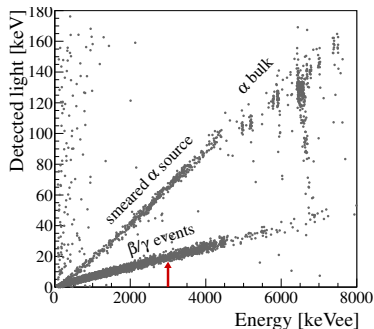
$$T_{1/2}(0\nu \rightarrow 0_1^+) > 1.2 \times 10^{23} \text{ yrs (90\% c.i.)}$$

$$T_{1/2}(0\nu \rightarrow 2_1^+) > 2.1 \times 10^{23} \text{ yrs (90\% c.i.)}$$

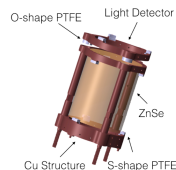
New measurement and most stringent limits on other processes

CUPID demonstrators: CUPID-0

- Zn^{82}Se crystals
- 5.5 kg ^{82}Se
- At LNGS



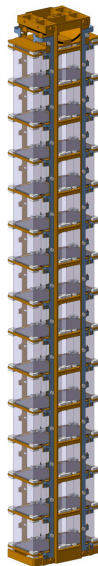
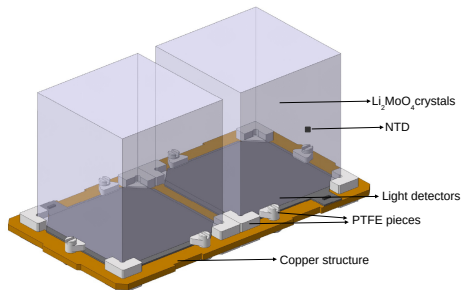
L. Pagnanini talk



- Demonstrator of dual read-out technique
- Direct proof that α s dominate backg above 2.6 MeV

The CUPID detectors

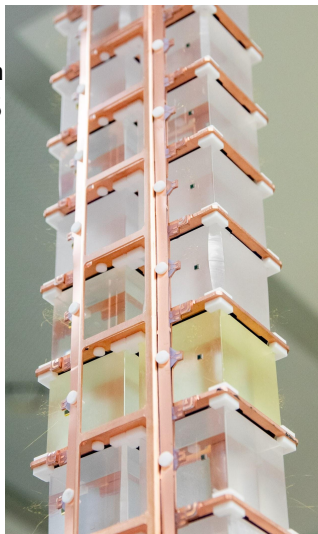
- Cubic crystals $45 \times 45 \times 45 \text{ mm}^3$
- Enrichment $> 95\%$
- 1596 crystals $\rightarrow 240 \text{ kg } ^{100}\text{Mo}$
- 1710 Ge light detectors



Baseline design prototype tower

- First single tower cooled down in July and October 2022 at LNGS
 - 14 floors
 - 28 LMOs
 - 30 Ge light detectors
- Validation of assembly procedures
- Validation of thermal scheme. All channels cool down with reasonable temperature distribution and no dependence on position in the tower.

New tests in the coming months



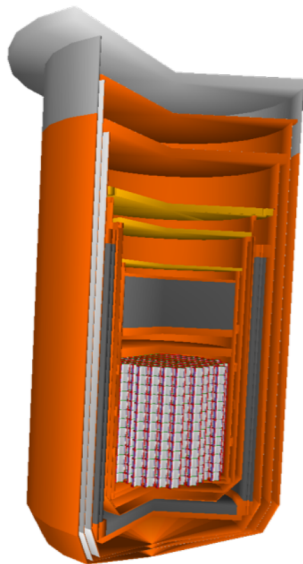
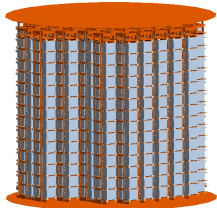
- Sensitivity $T_{1/2}^{0\nu} \sim 10^{27}$ y, sufficient to exclude the Inverted Ordering regime or make a discovery in $m_{\beta\beta} \sim [10 - 20]$ meV.

Requires:

- Background index, $BI = 10^{-4}$ counts/(keV·kg·yr)
- Energy resolution, FWHM, ~ 5 keV at $Q_{\beta\beta}$ (3034 keV)
- Livetime: 10 years

Background estimations

- Dedicated MC simulations with CUPID detectors design
- Data driven background budget, inputs from CUPID-Mo, CUORE-0 and CUORE background models
- Measurements, limits already existing for all materials



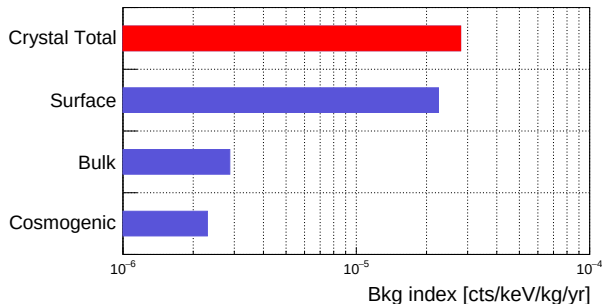
Background estimation

Crystals

Probability density functions of activities from CUPID-Mo bckg model

- $^{226}\text{Ra}/^{228}\text{Th}$ bulk $(2.9 \pm 1.1) \times 10^{-6} \text{ cts}/(\text{keV}\cdot\text{kg}\cdot\text{y})$
- $^{226}\text{Ra}/^{228}\text{Th}$ surface $(2.2 \pm 0.7) \times 10^{-5} \text{ cts}/(\text{keV}\cdot\text{kg}\cdot\text{y})$

Cosmogenics: assume 90 days at sea level and 1 yr cooling-down $\rightarrow$
 $2.3 \times 10^{-6} \text{ cts}/(\text{keV}\cdot\text{kg}\cdot\text{y})$



Background estimation

Close components (copper, PTFE, cables)

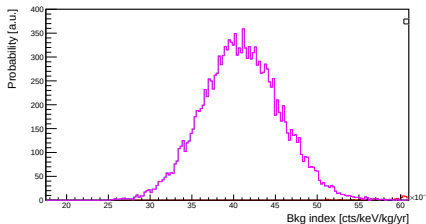
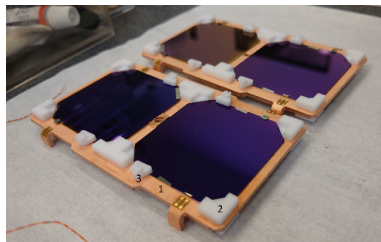
Probability density functions of activities from CUORE-0 bkg model

Leading contribution: surface copper frames

Total: $4.1^{+0.5}_{-0.4} \times 10^{-5}$ cts/(keV·kg·y)

can be reduced by improvements on surface contaminations by

- more effective cleaning
- extreme controlled storage conditions
- cleaner machining practices



Cryostat and shields

- Prob. density functions of activities from CUORE bkg model
- Contaminations in cryogenic infrastructure and shields well understood

Total 1.4×10^{-5} cts/(keV·kg·y)

- Muons are expected to give a non-negligible bckg in CUPID → muon veto will be added → bckg from muons $\sim 10^{-6}$ cts/(keV·kg·y)



$2\nu\beta\beta$ pile-up

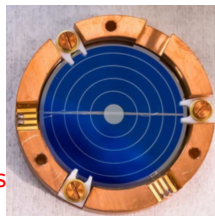
- Due to the relatively fast rate of ^{100}Mo $2\nu\beta\beta$, $T_{1/2} \sim 7 \times 10^{18}$ yr, the random coincidence in time of two $2\nu\beta\beta$ decays may cause an important background
- Mitigate by pulse shape discrimination
- Exploit faster **light channels**
- Standard light detectors, LD: Ge wafers with NTD readout
- CUPID LD baseline: standard with signal enhanced $\times 10$ by **Neganov-Trofimov-Luke effect**.

Required performance demonstrated on 8 LDs

Baseline energy resolution ~ 6 eV RMS

Risetime ~ 0.5 ms

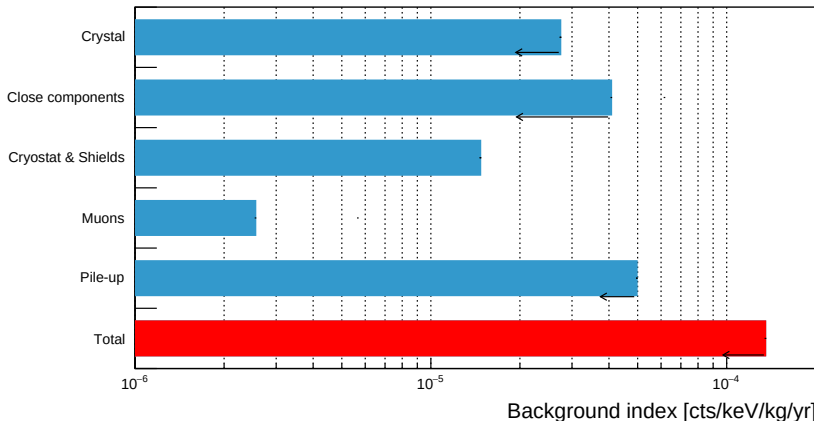
Corresponds to pileup resolution ~ 0.17 ms



Capable to achieve bckg from pile-up $\sim 5 \times 10^{-5}$ counts/(keV·kg·yr)

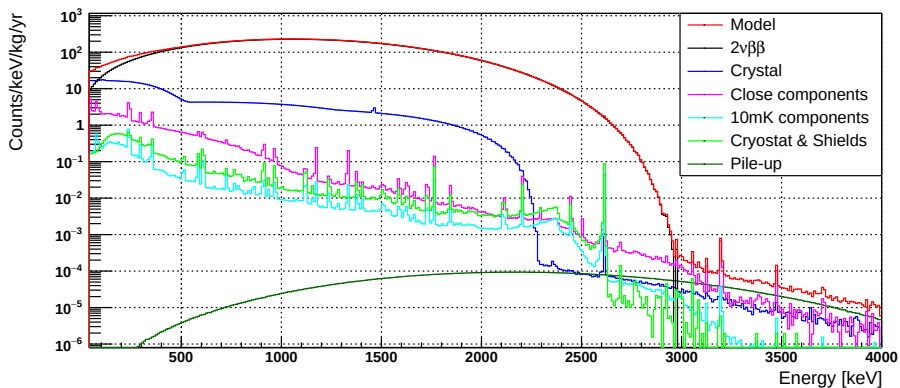
Alternative option for light detectors: TES readout

CUPID Background estimation



- Using past experiments achievements: $1.36 \times 10^{-4} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{y})$
- Plan to reach BI baseline = $10^{-4} \text{ counts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$ by:
 - Further reduction of surface contaminations
 - Pile-up rejection improvements

Reconstructed background spectrum



Sensitivity to exclusion on $0\nu\beta\beta$

With flat prior on the decay rate or equivalently $m_{\beta\beta}^2$:

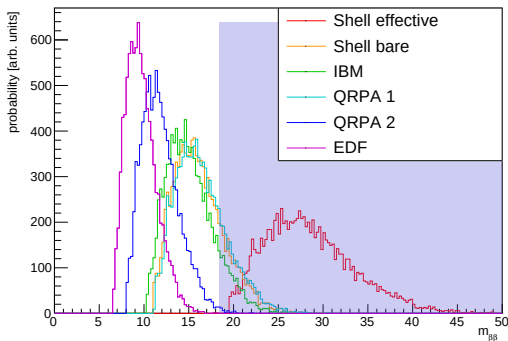
- Bayesian and Frequentist frameworks.
- Pseudo experiments generated for:

CUPID parameters:

- Total mass = 472 kg, ^{100}Mo mass = 253 kg
- ΔE 5 keV FWHM at $Q_{\beta\beta}$
- 10 years livetime
- $\text{BI} = 10^{-4}$ cts/(keV·kg·yr)

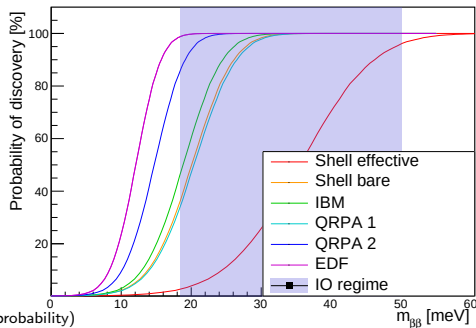
$T_{1/2}^{0\nu}$ limit, Bayesian at 90% c.i. =
 1.6×10^{27} y

↓ limit on $m_{\beta\beta}$



Sensitivity to discovery on $0\nu\beta\beta$

$T_{1/2}^{0\nu}$ discovery, Frequentist at $3\sigma = 1.0 \times 10^{27}$ y



- CUPID can rule out the Inverted Ordering 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 Inverted Ordering.

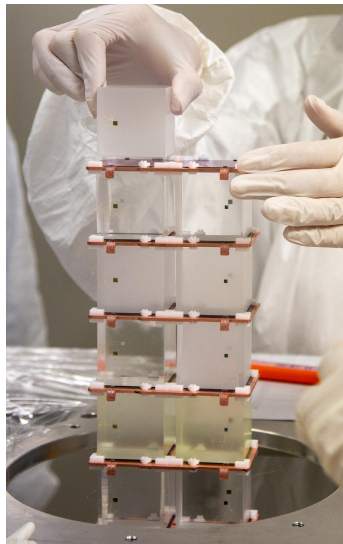
Conclusions

- CUPID will cover the Inverted Ordering down to ~ 10 meV
- Based on successful precursors CUPID-Mo, CUPID-0 and CUORE
- The collaboration has operational experience at LNGS for ton-scale bolometric experiment and utilizes the existing CUORE infrastructure
- Data driven background model reaches $BI \sim 10^{-4}$ cts/(keV·kg·yr)
- CUPID is proceeding towards construction

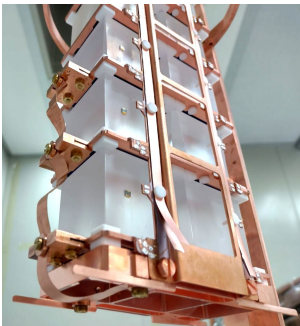
Back-up slides

Detector structure

Baseline design:



- Gravity stacked structure
- Innovative approach with respect to CUORE and CUPID demonstrators
- Reduction of copper mass wrt CUORE and demonstrators



Nuclear models used for mbb

Model	NME	Reference
Shell (effective operator)	2.240	[20]
Shell (bare operator)	3.962	[20]
pn-QRPA	3.90	[21]
pn-QRPA	5.850	[22]
IBM-2	4.22	[23]
EDF	6.58/6.588	[24, 25]

- [20] L. Coraggio, N. Itaco, G. De Gregorio, A. Gargano, R. Mancino, and F. Nowacki. Shell-model calculation of ^{100}Mo double- β decay. *Phys. Rev. C*, 105(3):034312, 2022.
- [21] Juhani Hyvärinen and Jouni Suhonen. Nuclear matrix elements for $0\nu\beta\beta$ decays with light or heavy majorana-neutrino exchange. *Phys. Rev. C*, 91:024613, Feb 2015.
- [22] Fedor Šimkovic, Vadim Rodin, Amand Faessler, and Petr Vogel. $0\nu\beta\beta$ and $2\nu\beta\beta$ nuclear matrix elements, quasiparticle random-phase approximation, and isospin symmetry restoration. *Phys. Rev. C*, 87(4):045501, 2013.
- [23] J. Barea, J. Kotila, and F. Iachello. $0\nu\beta\beta$ and $2\nu\beta\beta$ nuclear matrix elements in the interacting boson model with isospin restoration. *Phys. Rev. C*, 91(3):034304, 2015.
- [24] Nuria López Vaquero, Tomás R. Rodríguez, and J. Luis Egido. Shape and pairing fluctuation effects on neutrinoless double beta decay nuclear matrix elements. *Phys. Rev. Lett.*, 111:142501, Sep 2013.
- [25] J. M. Yao, L. S. Song, K. Hagino, P. Ring, and J. Meng. Systematic study of nuclear matrix elements in neutrinoless double- β decay with a beyond-mean-field covariant density functional theory. *Phys. Rev. C*, 91(2):024316, 2015.