

NTL light detectors as the baseline technology for the CUPID experiment



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1 BOLOMETERS FOR $\beta\beta$ DECAY: BEYOND CUORE

Bolometric technology
⇒ powerful method to study **neutrinoless double β decay ($0\nu 2\beta$)**

CUORE experiment (LNGS, Italy)
⇒ one of the most sensitive of the current generation

CUORE detector
988 TeO_2 bolometers
⇒ pure heat readout

CUORE supplemental material

Particle identification (PID) to reject the α component is mandatory to improve CUORE's performance

Isotope: ^{130}Te

2 CHANGE ISOTOPE + ADD A LIGHT DETECTOR: CUPID

Isotope: ^{100}Mo *Eur. Phys. J. C 85, 737 (2025) H. Khalife, Poster #307*

- $^{130}\text{TeO}_2 \rightarrow \text{Li}_2^{100}\text{MoO}_4 \Rightarrow$ move ROI from 2527 to 3034 keV ⇒ ~~γ background~~
- Weak scintillator: use **heat+light readout** for effective PID ⇒ ~~α background~~

HEAT SIGNAL → **Scintillating bolometers can reject α background**

Natural approach: LD is an ordinary Ge bolometer ⇒ thin Ge wafer + NTD

3 BEYOND ORDINARY LIGHT DETECTORS

Ordinary NTD-based LDs

- Simple construction
- Warm electronics
- High radiopurity

⇒ Successfully used in CUPID-0, CUPID-Mo and CUPID prototypes

LD and the crystal placed in an **optical reflective cavity**

We need:

- Open structure ⇒ **surface background rejection** via anticoincidence
- High SNR ⇒ rejection of **pile-up events** induced by random coincidence of two-neutrino events - $T_{1/2}^{2\nu} = 7.07 \times 10^{18}$ yr

Necessity to improve substantially the light detector performance

Rev. Lett. 126, 181802 (2021)

4 UPGRADE LIGHT-DETECTOR TECHNOLOGY: NTL

Alternatives: *V. Berest, Poster #339 Phys. Rev. Applied 20, 064017 (2023)*

- Change phonon sensors: from **NTD Ge thermistor** to superconductive **Transition Edge Sensor (TES)** ⇒ fast response ~ 0.1 ms
- Keep NTDs and their advantages and amplify signal by exploiting the **Neganov Trofimov Luke (NTL) effect** *Nucl. Instrum. Meth. A 940 320-327 (2019)*

Baseline solution for CUPID

- Set of **Al electrodes on wafer**
- ⇒ **electric field** in the wafer
- Drift of electron-hole pairs created by light ⇒ **additional heat**
- Amplification** of the thermal signal by **10-50**

$$E_{tot} = E_0 \left(1 + \frac{q \cdot V_{el} \cdot \eta}{\epsilon} \right)$$

5 ELECTRODE PRODUCTION AND PATTERNS

Electrodes are deposited by **electron beam evaporation / sputtering**

- Electrode structures defined by **shadow masks / photolithography**
- Ar-ion bombardment** to clean surface
- Amorphous 50-nm-thick Ge:H layer** ⇒ saturation of Ge dangling bonds
- Deposition of **100-nm-thick 0.2-mm wide Al electrodes**
- Increase electrode thickness up to 160 nm in some parts for **bonding**
- Coating by **70-nm-thick SiO** antireflective layer

CUPID baseline shape Squared shapes adopted in demonstrators (CROSS, BINGO) and for optimization studies

6 REQUIREMENTS FOR NTL LIGHT DETECTORS

LD-related **background objectives** for CUPID:

- Achieve a **rejection efficiency $\geq 99.95\%$**
- Achieve **pile-up background index $\leq 0.5 \times 10^{-4}$ counts/(keV·kg·y)**

LD requirements

Total detectors	2000
Baseline Resolution (σ)	< 100 eV for 0 V NTL HV-bias.
Light Collection	≥ 0.36 keV/MeV
Effective timing resolution	< 0.17 ms
Rise time	< 0.5 ms
Radiopurity	^{226}Ra (^{238}U) < 20 $\mu\text{Bq/kg}$ ^{228}Th (^{232}Th) < 10 $\mu\text{Bq/kg}$
Signal-to-Noise(σ) Ratio	> 140
Regeneration to charge-reset	Once a month

Typical NTL bias on adjacent electrodes (~ 4 mm pitch):
 $V_{el} \sim 80 - 100$ V

- Maximize **SNR**
- Avoid development of **harmful leakage currents** if bias it too high
- Necessity to **individual pre-characterization** to validate bias sustainability

7 VALIDATION OF THE NTL APPROACH IN CROSS

Detector ID	SNR at ^{100}Mo $Q_{\beta\beta}$			
	(I)	(II)	(III)	(IV)
LD-2	81(1)	138(1)	128(1)	166(1)
LD-3	60(1)	102(1)	94(1)	122(1)
LD-4	115(1)	196(2)	179(2)	235(3)
LD-5	154(5)	261(8)	239(8)	313(10)
LD-9	114(3)	194(5)	178(4)	233(6)
LD-10	64(1)	108(2)	100(2)	130(2)
LD-11	69(1)	118(1)	109(1)	142(2)
LD-12	51(1)	86(1)	79(1)	103(1)
Mean	78(1)	132(1)	122(1)	159(2)

JINST 21 P01035 (2026)

- Mean SNR: **159(2)**
- Mean rise time: **0.62(3) ms**

Close to CUPID requirements

8 light detectors

- CROSS setup in LSC (Spain)
- Concentric rings on **45x45 mm wafer** (**56%** electric-field filling factor (FF))
- Extrapolated to **CUPID shape, 100%** filling factor

8 RISK MITIGATION STRATEGY: SI WAFERS

Si intrinsic high-purity wafers

- + Less prone to leakage currents than Ge
- + Low cost
- + Readily available supply
- + Lower reflection in bare samples than Ge

Lower bolometric sensitivity than Ge

- Radiopurity to be checked
- Anti-reflective coating needs optimization

CROSS demonstrator and IJCLab data

- Si/Ge sensitivity: $\sim \times 0.5$
- Si/Ge optimum NTL voltage: $\sim \times 2$

Similar overall performance in NTL mode for bare Si and SiO-coated Ge

9 LIGHT DETECTOR PRODUCTION IN CUPID

Light Detector Production Preparation: 2026-2027

Milestone - confirm Ge or shift Si: 2027

Light Detector Production - Stage I: 2027-2030

Light Detector Production - Stage II: 2028-2034

Shared production between France and US: 2028-2034