Frequency multiplexed TES-based light detectors for CUPID and beyond

Vladyslav Berest on behalf of CUPID collaboration

Department of Physics, University of California, Berkeley, Berkeley, USA

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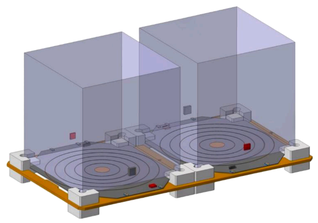
CUPID: CUORE Upgrade with Particle ID

- **CUPID** [1] is the next generation experiment for neutrinoless double beta decay search *[See Poster #307]*
- Built on **CUORE**, the largest bolometric array ever built and demonstrated stable and reliable operation over multiple years of exposure. *[See Poster #224]*



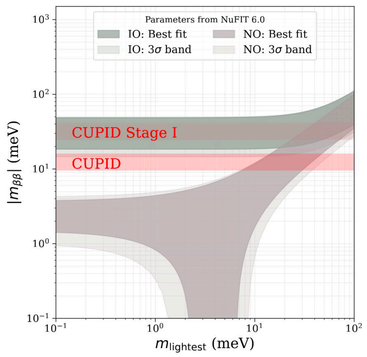
- **1596 $Li_2{}^{100}MoO_4$** enriched crystals arranged in 57 towers of 14 floors
- 240 kg of ^{100}Mo
- **1710 Ge light detectors** instrumented with Aluminum electrodes for **Neganov-Trofimov-Luke amplification** *[See Poster #312]*
- Goal **energy resolution**: 5 keV FWHM @ 3034 keV

- **Background** goal: 10^{-4} counts/keV·kg·year
- Discovery **sensitivity**: $T_{1/2} = 10^{27}$ years ($m_{\beta\beta}$ = 12-21 meV)

Germanium light detectors operating as bolometers are **crucial components for efficient background rejection** via particle identification. To achieve this, they must meet the following requirements:

- High radiopurity
- Low heat capacity
- High photon collection efficiency
- **Energy resolution** <100 eV for efficient $\alpha/\beta(\gamma)$ separation
- Excellent timing resolution to discriminate the $2\nu\beta\beta$ pile up events from $0\nu\beta\beta$ events.

- **Staged Approach:** CUPID will be deployed in two phases, allowing for ongoing R&D and hardware optimization during both the preparation phase and initial operations. **Stage I** will run 1/3 of the detector providing first results by the beginning of the next decade and will create a window for possible improvements



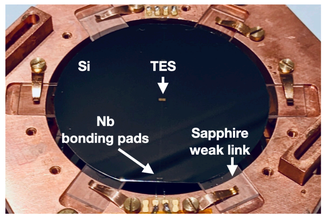
- One of the most promising technological upgrades currently under development is the transition to **TES-based light detectors.**

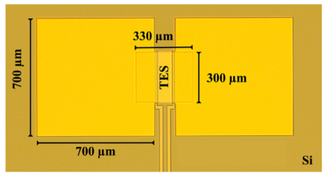
Transition-edge sensor based light detectors

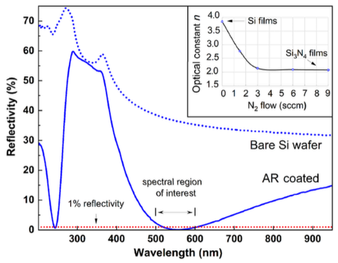
To meet the rigorous timing and energy resolution requirements of CUPID, **Transition-Edge Sensors (TES)** are being developed as a high-sensitivity alternative to conventional CUORE-like NTD-Ge thermistors.

Sensor Design & Material Composition

- **Absorber:** Utilizes a 2" Silicon wafer as the primary optical photon absorber.
- **Bilayer Sensor:** The sensor itself is a 300 μm×300 μm square Iridium/Platinum (Ir/Pt) bilayer (e.g., 100 nm/60 nm thick) equipped with Niobium (Nb) electrical traces.
- **Transition Temperature (T_c):** While intrinsic Iridium becomes superconducting at ~140 mK, utilizing the proximity effect of a normal metal like Platinum reduces the T_c to an operational range of **30–40 mK** (typically ~37 mK).





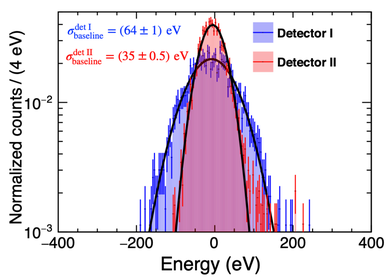


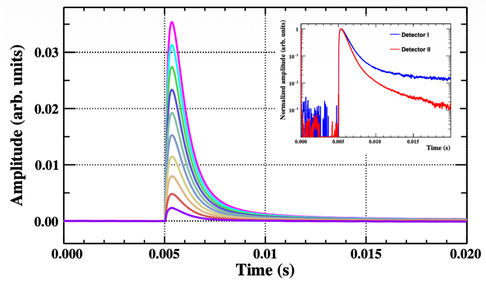
Enhanced Signal Collection

- **Au Phonon Coupling:** Deposited Gold (Au) pads couple the TES directly to the Silicon wafer, which drastically improves the signal-to-noise ratio by enhancing phonon collection efficiency.
- **Anti-Reflective Coating:** A 68 nm Si_3N_4 coating is applied to minimize photon reflectance without degrading detector performance.
- **Stability:** Negative electrothermal feedback naturally keeps the TES stable and decreases the sensor's time constant.

Detector Performance [2]

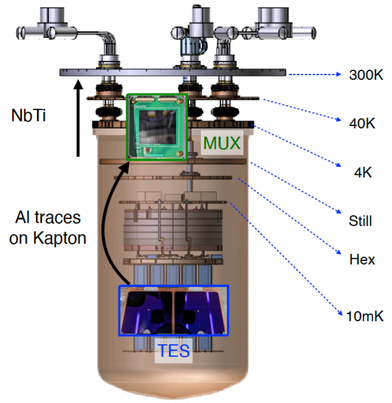
- **Superior Sensitivity and energy resolution:** Because of the exceptionally steep slope in their biased region, TES devices offer much larger sensitivity than standard thermistors.
- **Fast Timing:** Demonstrates extremely fast pulse kinetics with typical risetimes of ~175–200 μs. The timing resolution ranges from Δt<20 μs down to ~5 μs.





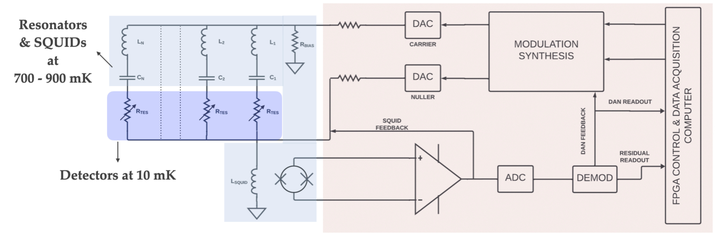
Frequency multiplexing (fMUX) [3]

Scaling to the full CUPID array requires a robust readout system that minimizes the heat load on the cryogenic stages while maintaining strict timing and noise requirements. **Frequency Domain Multiplexing (fMUX)** is the chosen solution, allowing multiple TES channels to be read out on a single coaxial line.



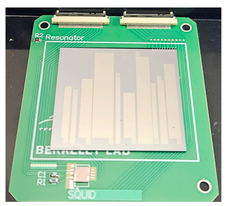
Readout Architecture

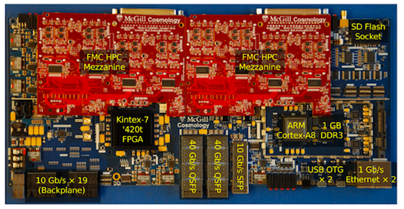
- **Cold Stage (mK):** The TES array and LC filters are coupled to a SQUID series array, which serves as a low-noise summing amplifier for the multiplexed signal.
- **Warm Electronics (300 K):** Advanced FPGA-based systems, such as the **ICEboard**, perform digital synthesis of MHz carrier tones and real-time demodulation of the incoming signals, enabling high-precision signal reconstruction.



Performance & Validated Results:

- **High Yield:** Recent resonator board fabrications have demonstrated a sensor yield of **~97%**.
- **Crosstalk Suppression:** Precise spacing of resonant frequencies ensures that cross-talk between adjacent channels is kept **< 0.5%**.
- **Timing Resolution:** Frequency-multiplexed signals maintain a timing resolution within a factor of **2x of traditional DC readout**, preserving the pulse-shape discrimination (PSD) needed for background rejection.





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[1] CUPID Collaboration, CUPID, the CUORE upgrade with particle identification. *Eur. Phys. J. C*85, 737 (2025)
[2] Singh, V., et al. "Large-area photon calorimeter with Ir-Pt bilayer transition-edge sensor for the CUPID experiment." Physical Review Applied 20.6 (2023): 064017.
[3] Adamič, M., et al. "High-bandwidth frequency domain multiplexed readout of transition-edge sensors for neutrinoless double beta decay searches." arXiv preprint arXiv:2601.23106 (2026).
[4] Adamič, Michel, et al. "Readout noise of digital frequency multiplexed TES detectors for CUPID." IEEE Transactions on Nuclear Science (2025).

Acknowledgements

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