TRANSITION-EDGE SENSOR BASED PHOTON CALORIMETER FOR THE CUPID EXPERIMENT
Vivek Singh, UC Berkeley

The Cryogenic Underground Observatory for Rare Events

CUPID: CUORE UPGRADE WITH PARTICLE ID

• Next generation calorimetric search for $0\nu\beta\beta$ experiment.
• Cryogenic calorimeters at deep cryogenic temperature
  • Synergy with HEP experiments

Tonne scale cryogenic detector
• Operates at $\sim 10$ mK (coldest cubic meter in the known universe!)
• Demonstrated operation and analysis of 1000 calorimeters

arXiv:1907.09376
• Dominant background is degraded alphas from surface contamination
• Leverage energy loss mechanism in the crystal to tag particle type
• Use auxiliary low temperature calorimeter to detect light.

Should have

- High radiopurity
- Low heat capacity
- High photon collection efficiency
- Very low threshold (~ 100 eV)
- Excellent timing resolution to discriminate the $2\nu\beta\beta$ pile up events from $0\nu\beta\beta$ events (~ 100 μs)
CUPID:

- ~ 1600 crystals with ~ 250 kg of $^{100}$Mo
- ~ 1700 photon detectors needed

• Li$_2$MoO$_4$ detectors recognized as baseline
• Enrichment > 95%
• Demonstrated active background rejection.
Ir/Pt Transition-edge Sensors (TES)

- Device fabrication at ANL
- Device testing at ANL and UCB

square Ir/Pt bilayer TES in the middle with Au pads on both sides

Detector with TES

Device specification:
- 2” Silicon wafer as optical photon absorber
- Ir/Pt (100 nm/60nm) bilayer with Nb traces as electrical leads.
- Transition temperature of ~ 42 mK
- Sensor dimension 300 $\mu$m x 300 $\mu$m
- Deposited Au pads, coupling the TES to the wafer for better phonon collection efficiency
- $T_c$ relatively unchanged with addition of Au pads but signal-to-noise improves drastically.
EFFECT OF GOLD PADS

- Transition temperature of \( \sim 34 \text{ mK} \)
- Sensor dimension 300 \( \mu \text{m} \times 300 \mu \text{m} \)
- Larger gold pad area increases thermal coupling between sensor and absorber.
- There is an optimum. Too large of a normal metal (Au) will increase the heat capacity.

4 sensors with
- No gold
- 300 \( \mu \text{m} \times 300 \mu \text{m} \)
- 600 \( \mu \text{m} \times 600 \mu \text{m} \)
- 900 \( \mu \text{m} \times 900 \mu \text{m} \)

\[
I^2R(T) = k \cdot (T_{tes}^n - T_b^n)
\]

\[
G(T_c) = k \cdot n \cdot T_{tes}^{(n-1)}
\]

Conductance not a linear function of Au pad area
TES transition characteristics

- Transition temperature of $\sim 42$ mK
- $\alpha \equiv (T/R) \frac{dR}{dT} > 100$ at operating bias point. High sensitivity
- Can be operating negative-electrothermal feedback mode at lower temperature. Stable against thermal runaway.

\[
\begin{align*}
\text{N} \rightarrow \text{SC}: R_n &= 388.29 \pm 4.87 \text{m}\Omega \\
\text{N} \rightarrow \text{SC}: R_D &= 0.00 \pm 4.87 \text{m}\Omega \\
\text{N} \rightarrow \text{SC}: T_c &= 42.41 \pm 0.38 \text{mK} \\
\text{N} \rightarrow \text{SC}: \Delta T_c &= 0.15 \pm 0.10 \text{mK}
\end{align*}
\]
TIMING RESOLUTION

• Generate a train of blue LED light pulse with known separation time $\gg$ decay time
• Examine distribution of trigger time between the subsequent pulses in detector response
• Timing resolution of $\Delta t \sim 14 \mu s$
• Detector satisfies the criteria for rejecting $2\nu\beta\beta$ pile up events for CUPID ($\sigma_t < 150 \mu s$)

Detector response to train of LED pulses injected every 15 ms

distribution of $\Delta t$ between two consecutive pulses
PILE-UP IDENTIFICATION

Two LED pulses injected 150 $\mu$s apart

- Pile-up rejection dependent on SNR
- High energy light pulses can be rejected on simple pulse shape variable (rise time, decaytime, chi2, etc)
- Developing machine learning algorithm to detect pile-up for low energy events.
Energy Response

- Excited the wafer with varying amplitudes of blue LED (475nm) pulses.
- Pulse height is proportional to the number of photons impinging on the wafer.
- Used photon statistics to calibrate the LED spectra and cross-calibrated it against Fe-55 x ray too.
Energy resolution

- Baseline resolution ($\sigma$) ~ 145 eV
- It meets the CUPID criteria but can be much better
- Vibrational/EMI noise in our Pulse Tube based cryostat a limiting factor for now.
Anti-Reflective coating

- Increase light collection efficiency for better responsively.
- CUPID baseline design uses SiO layer on Ge to reduce reflectance to 7-10% in LMO scintillation region.

We are studying different absorbers and AR coating layer to have minimum reflectance for the light detectors.
Multiplexing

• Testing feasibility of frequency-domain multiplexing readout of TES
• Multiple sensors readout through single SQUID.
• Reduce number of wires going to the cryogenic stage from room temperature.
• CUPID can do with a modest factor ~ 10 for multiplexing

Technological Challenges

• MUX has not been demonstrated at 10 mK
• Radio-purity of the materials used for MUX a concern (cables, resonators, etc)
• May require additional magnetic/emi shielding
CONCLUSIONS

➤ Heat + Light channel most favorable technique for particle ID.

➤ Ir-based bilayer TES has shown promising results for meeting the criteria of CUPID light detectors.

➤ Excellent timing resolution demonstrated.

➤ Optimization of sensor coupling to the absorber is a work in progress -> towards the goal of achieving baseline energy resolution of <100 eV.

➤ Active U.S. involvement in R&D for CUPID