TRANSITION EDGE SENSORS (TES) FOR PHOTON DETECTION

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OUTLINE

- Drivers for low energy (single) photon detection (and energy resolution)
  - Dark matter detection
- Introduction to TES photodetectors
  - Detector configuration, energy resolution
- Examples of TES photodetector researches and applications
  - Large area TES photodetectors, single photon counting TES sensors, and Quasiparticle-trap-assisted Electrothermal-feedback Transition-edge-sensor (QET)
- Example of future directions:
  - Ir/Pt bilayer TES photodetectors
- Summary
Sapphire and gallium arsenide crystals are optimal for electron recoils (ER) – Hidden sector dark matter

Measure athermal phonons in sapphire with TES detectors on surface – 0.35 eV

Measure scintillation photons from gallium arsenide with TES photon detectors – 1.4 eV

Measure athermal phonons in gallium arsenide with TES detectors on surface – 0.35 eV
DARK MATTER DETECTION WITH SUPERFLUID HELIUM AND LARGE AREA PHOTON (PHONON) DETECTORS

- Optimal for nuclear recoils (NR)
  - Light helium nucleus
- TES detectors in liquid helium
  - Triplet excimers, UV and IR photons, and quasiparticles (phonons and rotons)
- TES detector above liquid helium
  - Evaporated helium atoms kicked off by quasiparticles at surface

Hertel et al., arXiv, 1810.06283
OTHER PARTICLE DARK MATTER DETECTION CANDIDATES

- Interactions with molecular targets
  - Bosonic DM interacting with molecular gas (A. Arvanitaki et al., Phys. Rev. X 8, 041001)
  - Light DM scattering off CO gas (R. Essig et al., PRR 1, 033105 (2019))
  - Spin-dependent light DM interaction with molecular crystals (G. Wang et al., arXiv:2201.04219)

- Interactions generate long wavelength photons
  - Faint signal requires low DCR
  - Well defined energy motivates spectral resolution for background rejection
WAVE DARK MATTER

- Conversion of wave dark matter (higher mass axions/dark photons) into a long wavelength photon
  - Faint signal requires low DCR
  - Well defined energy motivates spectral resolution for background rejection

M. Baryakhtar et al., Phys. Rev. D 98, 035006

J. Liu et al., PRL 128, 131801 (2022)
SUPERCONDUCTING TECHNOLOGIES

- Multiple drivers and applications for good detectors at long wavelengths
  - Dark matter
  - Space applications
  - Terrestrial imaging

- Long wave photons are challenging to detect
  - Superconducting systems are an attractive approach with typical excitation in superconducting systems is smaller than photon energy

- Transition Edge Sensor (TES) is a mature technology
  - Well developed noise theory
  - Thermal operating principles
  - Demonstrated multiplexing for scaling up mass and/or channels
VINTAGE TRANSITION EDGE SENSOR

Attenuated Superconductors

I. For Measuring Infra-Red Radiation


Chemistry Department, The Johns Hopkins University, Baltimore, Maryland

(Received February 27, 1942)

An apparatus for measuring infra-red radiation has been constructed of fine tantalum wire, operating at a temperature of 3.22–3.23°K in the transition zone between superconduction and normal conduction. The tantalum coil is mounted on a thermostated plate with temperature electrically controlled and operates in a special self-regulating shunt circuit by which its own temperature is automatically maintained constant. The ratio of developed electrical potential to radiation flux received is 150 v (erg cm<sup>-2</sup> sec<sup>-1</sup>)<sup>–1</sup>. Minimum detectable flux is ca. 10<sup>-3</sup> erg sec<sup>–1</sup>. Absolute measurements of intensity of radiation from sources at temperatures between 24° and 55° are consistent with the Stefan-Boltzmann law showing that instrument corrections for reflectivity, window-absorption, and changes with wave-length are very small.
MODERN TES

- Heat capacity thermally stood-off from heat sink
- Voltage bias into superconducting transition
- Low-impedance current measurement via SQUID
ELECTROTHERMAL FEEDBACK

- Shape of R(T) curve together with voltage bias establishes natural negative feedback
- TES temperature stabilizes at $T_c$
- Increases bandwidth
- Linearizes response:
  - $\Delta P_{\text{absorbed}} \approx \Delta P_{\text{bias}} = V_{\text{bias}} \times \Delta I_{\text{TES}}$
- “Loop gain” determined by slope of R(T), which can be steep making feedback strong.

$$\delta P_{\text{Joule}} = \delta \left( \frac{V_0^2}{R(T)} \right) = - \left( \frac{V_0}{R} \right)^2 \frac{dR}{dT} \delta T$$
SENSITIVITY

- Fundamental noise comes from thermal fluctuations (∼kT), which can be made small by choosing suitable $T_c$
- Energy resolution:
  $$\Delta E \approx 2\sqrt{2 \ln 2} \sqrt{\frac{4k_BT_c^2C}{\alpha} \frac{n}{\sqrt{2}}}$$

- Improve by reducing $T_c$
- Incorporating athermal techniques can further reduce volume
A LARGE AREA PHOTON DETECTOR IN CRESST

Cryogenic Rare Event Search with Superconducting Thermometers

- Evaporated W TES thermometer with a Tc of 15 mK
  - Measure heat of target calcium tungstate
  - Measure scintillation light with a silicon-on-sapphire light detector of $20 \times 20 \times 0.4$ mm$^3$
  - The light yield is used to discriminate between electron recoils and nuclear recoils in the target
- Baseline noise energy resolution lies between 4.1 eV and 6.7 eV
TES SINGLE PHOTON DETECTOR AT 1550 NM

- 25 µm × 25 µm x 35 nm single-mode fiber-fed W TES
- Pulse height proportional to photon number. The inset shows the measured probability distribution. ∆E=0.12 eV
- The graph on the right shows the measured distribution with a Au/Ti (10/20 nm) bilayer TES (8 µm × 8 µm and a Tc of 115 mK). ∆E=0.067 eV
- Ultra-low DCR: detection threshold > 2.3∆E + pulse shape discrimination

K. Hattori et al., arXiv:2204.01903v1
LARGE AREA PHOTON DETECTOR WITH A SUB-EV THRESHOLD

- Quasiparticle-trap-assisted Electrothermal-feedback Transition-edge-sensor (QET)
  - Superconductor Al as photon absorber + TES as quasiparticle readout sensor
  - Originally developed in the CDMS collaboration measuring phonon with a large area coverage

Detector sensitivity depends on
- TES volume (heat capacity)
- TES Tc
IR/PT BILAYERS

Fabricated at Argonne and tested at UC Berkeley

Tc of 100 nm Ir film: 195 mK

R. Hennings-Yeomans, C. L. Chang, J. Ding, et al., J. Appl. Phys. 128, 154501 (2020);
A LARGE AREA TES PHOTON DETECTOR FOR NLDBD

- Working with the CUPID collaboration, to develop a large area photon detector to measure the scintillation light from Li2MoO4 crystals
  - Measure heat & light to reject background
- 45nm/20nm Ir/Pt TES at the center of a 2-inch silicon wafer, Tc~33 mK, Rn=0.75 Ω
- Two large Au pads (900 µm × 900 µm × 0.2 µm) thermalize contact between the Si wafer and the TES
PERFORMANCE OF THE LARGE AREA TES PHOTON DETECTOR

- Operated at a bath temperature of 15 mK and at R=0.3Rn
- Excited back of 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
  - Statistics derived energy resolution is better than 40 eV

Graph credit: Vivek Singh at UC Berkeley
IR/PT QET

Developing athermal coupling
- Reduce TES Tc and volume.
  - Thin IrPt bilayers
  - Narrow TES lines
- Al QP collector fins
SUMMARY

- Applications:
  - particle & wave dark matter searches
  - single photon spectroscopy

- TES photodetector has a high resolution and low dark counting rate

- Reviewed three kinds of TES photodetectors
  - A large area TES photodetector: a large dielectric photon absorber + a TES sensor for temperature readout
  - Sensitive large area QET: Superconducting photon absorbers + TES sensors for quasiparticle readout
  - Single photodetector: TES is used both as an absorber and a readout sensor

- Future development aims to use lower Tc materials to improve detector sensitivity
THANK YOU.