Progress on a KID-Based Phonon-Mediated Dark Matter Detector

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Abstract:
• Status of a prototype dark matter detector being developed at Caltech
• Designed for use with crystalline target m35s
• Utilizes highly-multiplexable kinetic inductance detectors (KIDs) as phonon sensing pixels
• First-pass single-KID resolution measurement of 12. 6 eV for in-KID quasiparticle energy

Motivation
• Using astronomical observations, it can be shown that 85% of matter is dark (non-interacting with EM)
• Direct detection experiments seek to observe dark matter passing through local target masses
• For some targets, dark matter interaction would produce propagating athermal phonons
• Athermal phonons can be observed using detectors such as KIDs
• Direct detection experiments want to maximize search time, mass, and sensitivity while minimizing background events
• Backgrounds which cannot be avoided at runtime should be removed during analysis
• Background removal is aided by additional event information, such as the location of the interaction
• Also of interest is the search for sub-GeV dark matter, where low thresholds (< 1 eV) are required

Multiplexability
• Position reconstruction of a phonon-producing event requires a high detector density
• KIDs are highly multiplexable with simple cryogenic readout
• Fabricate many high-Q KIDs with varying resonant frequencies on one substrate
• Read them all using one feedline and a cryogenic amplifier

Design
• 80 KIDs coupled to 1 coplanar waveguide feedline
• KIDs are aluminum
• \( \Delta \omega = 0.2 \text{ meV} \)
• Feedline is niobium
• \( \Delta \omega_B = 1.5 \text{ meV} \)
• Want phonon energy to be absorbed by KIDs, not feedline
• < 1% of phonons are above \( \Delta \omega_B \) (for NTL phonons) [1]
• 3.0 GHz \( \lesssim f \lesssim 3.5 \text{ GHz} \)
• For CASPER ROACH readout (potential large-scale deployment)
• Overcoupled KIDs
• \( q_1 < q_0 \)
• \( q_0 < q_2 \)
• Need bandwidth > 30 kHz to preserve phonon rise time
• High-resistivity silicon substrate
• 75 mm diameter
• 1 mm thick

Readout
• Flexible GPU and SDR-based readout
• Software developed by Lorenzo Minutolo of Caltech/JPL
• See Lorenzo’s poster (129-49 Session A)
• Uses a server GPU to interface with an Ettus Research SDR
• Low-noise cryogenic HEMT amplifier
• \(~ 2.5 \text{ K} \) noise temperature
• Plan to precede LNA with parametric amplifier currently being developed between Caltech/JPL
• See Peter Day’s poster (156-306 Session B)
• Quantum-limited performance would give \( \tau_N = 150 \text{ ms} \) at 3 GHz

Device Under Test
• Cooled to \(~ 50 \text{ mK} \) in OR
• Can fit 74/80 KID resonances from our current device
• 31 have good fits to Mattis-Bardeen theory
• Describes resonance change with temperature
• Gives kinetic inductance fraction (\( \eta \)) and band gap (\( \Delta \))

Energy Resolution
• Readout is designed to be cryogenic-amplifier-noise limited
• TLS noise is subdominant due to large resonator size, high power-handling capacity, and expected signal timescale (~1 ms arrival and < ~1 ms fall)
• E-h noise is subdominant due to a lack of continuous quasiparticle creation mechanisms
• Expect dissipation change to dominate signal
• Measured using a new in-array self-calibration technique
• See Yen-Yung Chang’s poster (94-407 Session B)
• Found energy resolution \(~ 12 \text{ eV} \) for a single KID on our detector
• Resolution on absorbed quasiparticle energy within that KID
• For an array of \( N \) KIDs, the resolution would degrade by \( \sqrt{N/\Delta \text{min}} \)
• Energy splits among \( N \) KIDs
• \( \eta_\text{min} \): a phonon-to-quasiparticle efficiency factor
• The measured KID has \( \tau_q ^{-1} \approx 23 \text{ ms} \)
• This is low for aluminum
• We believe black-body leakage may be the issue
  • Can be improved with well-designed shielding

Conclusion and Future
• Have taken first device energy resolution measurement for large-array detector type
• Suitable for 10s-100s kg target mass
• Found a single-KID quasiparticle energy resolution of 12.6 eV
• Plan to:
  • Repeat measurement in multiple KIDs and compare
  • Check absolute calibration on energy deposited in substrate using radioactive spectral line
  • Install lower noise parametric amplifier
  • Improve fridge black body shielding to enhance \( \tau_N \)
  • 100 \( \mu \text{s} \) is typical for aluminum
• Also, beginning development of a design optimized for threshold rather than background rejection
• Single KID on a smaller substrate to avoid energy splitting
• Use niobium KIDs for self-calibration technique


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