Snowmass2021 - Letter of Interest

Phonon-Mediated KID-Based Detectors for Low-Mass Dark Matter Detection and Coherent Elastic Neutrino-Nucleus Scattering

Topical Group(s): (check all that apply by copying/pasting ☐/☑)

☑ (CF1) Dark Matter: Particle Like
☑ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☑ (Other) *[Please specify frontier/topical group]*

IF1: Quantum Sensors

NF10: Neutrino Detectors

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Abstract:
Detection of keV-scale, eV-scale, and eventually meV-scale interactions can open up vast new parameter space in the search for dark matter and in the use of coherent elastic neutrino-nucleus scattering to test for non-standard interactions of neutrinos. Athermal (meV-scale) phonons in sub-Kelvin target materials can be produced by such small energy depositions, and superconducting kinetic inductance detectors (KIDs) can sense these meV phonons, with long-term potential for even single-phonon sensitivity. The inherent multiplexability of KIDs also makes them ideal for recovering position information from phonons. Different architectures are appropriate for different applications. In the case of low-mass dark matter (sub-GeV nuclear- and electron-scattering particles and sub-eV dark photons and axion-like particles (ALPs)), thresholds at the meV scale are eventually needed, motivating small individual detectors with a single KID sensor, exploiting the energy resolution potential of KIDs. For GeV-scale nuclear-scattering dark matter and coherent elastic neutrino-nucleus scattering of solar and reactor neutrinos, information about recoil type (nucleus or electron) and position are as important as energy resolution, motivating larger individual detectors instrumented with many KIDs to provide this additional information. In this LOI, we summarize the current status of our work to develop these types of phonon-mediated, KID-based particle detectors.

Scientific Motivation and Technical Requirements

Sub-GeV Dark Matter: Due primarily to the lack of signals in searches for the classic weakly interacting massive particle (WIMP), including WIMPs motivated by supersymmetry, the past decade has seen an explosion of interest in alternative particle dark matter models. Many of the new ideas for dark matter involve a Hidden Sector populated by at the very least a dark photon, the gauge boson of a new U(1) symmetry, along possibly with other more massive particles whose interactions it mediates. New scalar axion-like particles have also been considered. On the experimental side, these models have motivated extending the search for fermionic thermal relic dark matter down to the few keV large-scale-structure mass limit and expanding it to include the search for direct absorption of light (meV-keV mass) bosonic mediators. This parameter space is so unexplored, and the backgrounds relevant for such low-energy interactions so different from those considered for $\gtrsim$ keV depositions, that *gram-scale detectors with sub-eV to meV energy thresholds* providing kg-year total exposures could have substantial constraining power[1].

GeV-scale Dark Matter to the Neutrino Floor: Part of the above expansion has been a reconsideration of dark matter $\lesssim$10 GeV, previously ruled out in the context of minimal supersymmetry. This reconsideration motivated the SuperCDMS SNOLAB G2 experiment, which will cover enormous new parameter space down to 0.5 GeV. Its projected sensitivity does, however, leave about a decade above the so-called neutrino floor[2] unexplored because the nuclear-recoil discrimination of its iZIP detectors stops at about 1 keV deposition. To reach the neutrino floor would require a detector with *background rejection via nuclear-recoil discrimination and position fiducialization down to 100 eV while maintaining kg individual detector mass to enable exposures approaching 1 ton-yr.*

Neutrino Non-Standard Interactions (νNSI) via Coherent Elastic Neutrino-Nucleus Scattering (CEνNS): CEνNS is a Standard Model process[3] that has only recently been detected[4]. The Standard Model predictions are well understood, so precise cross section measurements would test for new physics such as non-standard neutrino interactions (perhaps driven by a neutrino magnetic moment). The requirements for solar or reactor neutrino CEνNS are identical to those for GeV dark matter detection.

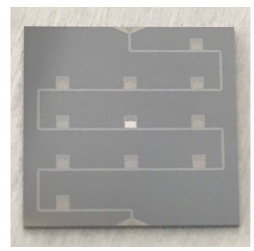
Technical Approach

The core concept is to use kinetic inductance detectors (KIDs) to detect the athermal (meV) phonon(s) produced directly by a particle interaction[5], by a recoiling particle, or by the drift in an electric field of the electron-hole (eh) pairs those recoils create.

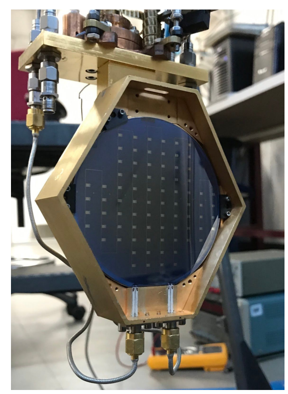
Kinetic Inductance Detectors: The basic idea of a KID is to sense the change in the surface impedance of a superconducting thin film (tens of nm thick) when Cooper pairs are broken by absorbed energy[6,7]; the reactive component is the “kinetic inductance.” By patterning the superconductor into a lumped-element or transmission-line LC resonator, the impedance change modifies the resonator frequency f_r and quality factor Q_r. Superconductivity provides KIDs with high intrinsic Q (low loss), known as the “internal quality factor," $Q_i > 10^5$-10^7. This high Q_i motivated the development of KIDs, enabling frequency-domain multiplexing at GHz (RF) frequencies, much like AM/FM radio, via simultaneous monitoring of KIDs at different f_r on the same feedline. Aside from a readily available GHz cryogenic low-noise amplifier, the complexity is all in the 300K electronics.

KIDs and TESs: The leading technology for athermal phonon signals is the SuperCDMS technology of transition-edge sensors (TESs) coupled to large superconducting phonon collection fins[5,8,9,10]. Calculations imply KID-based detectors should have competitive energy resolution, confirmed by results to date on 1-10 gram substrates[11,12]. KIDs have characteristics, however, that may be essential to meet the above technical requirements:

- KIDs are fundamentally athermal sensors, with many of the same advantages of athermal over thermal phonons: weak sensitivity to operating temperature, exponential suppression of thermally generated excitations at the energies of interest. In particular, there are signs that TESs may have begun to depart from their scaling laws due to unaccounted-for, thermally active modes[13].
- The cryogenic electronics needed for $O(10^3)$ multiplexing are the same as needed to read out a single KID, while, for TESs, a complex cryogenic multiplexer is required.
- KIDs are fundamentally non-dissipative devices, while TESs are stabilized via dissipation. This renders KIDs particularly amenable to quantum measurement techniques that may emable meV resolutions, where dissipation must be minimized for quantum-limited readout and quantum state squeezing. Such techniques may even enable a quasi-particle counting mode that could circumvent such limits.



Low-Mass DM Architecture: An architecture for low-mass DM searches uses a single KID on a substrate small enough that athermal phonons may be collected with high efficiency before decay but large enough to have macroscopic mass (20mm x 20mm x 1mm, 1 gm, see figure). A variety of substrates beyond Si are possible, with sapphire being an excellent polar target ideal for absorption of or scattering mediated by dark photons[4] and having substantial KID heritage. The challenges are two-fold: improve energy resolution as much as possible; and, address new backgrounds, such as blackbody/RF power, vibration, etc., as they become limiters.



GeV-Scale DM/CEνNS Architecture: This architecture adapts the complex electric field configuration of the SuperCDMS iZIP detectors[10], but, rather than measuring the ionization signal of eh pairs, it detects the Neganov-Trofimov[14]-Luke[15] (NTL) phonons produced while those eh pairs drift. Because nuclear recoils (NRs) due to dark matter or neutrinos produce fewer eh pairs than electron recoils (ERs) due to most backgrounds, and because the NTL phonons are produced mainly near the phonon sensors on the detector surface due to the field configuration, recoil type is mapped to position dependence of the phonon signal, dependence that is distinct from that due to interaction location. KIDs are thus ideal because their multiplexability would pixellize the phonon sensor 10x more finely than has been done with TESs. The goal is kg-scale Ge and/or Si substrates (∅75-100mm x 10-33mm; ∅75mm x 1mm in figure).

Energy Resolution Goals: We are engaged in a staged program to improve the device energy resolution to satisfy the above requirements. Current demonstrations are for a design that has not been optimized for a single-KID architecture, so reoptimization is the first step. Mitigation of excess quasiparticle (qp) creation by RF and blackbody power should improve the qp lifetime by x10. A quantum-limited parametric amplifier will reduce readout noise. Reducing the KID film superconducting transition temperature will provide x5-10 increase in qp yield. Finally, QIS techniques to circumvent the standard quantum limit may improve resolution by another x10.

stage	resolution (rms)	
	low-mass	GeV DM/CEνNS
current (estimated)	20 eV	240 eV
single-KID optimized	1-7 eV	—
increase qp τ to 1 ms	0.3-2 eV	80 eV
quantum-limited amplifier	45-360 meV	25 eV
AlMn (T_c = 0.1K/0.2K)	5-70 meV	5 eV
quantum-limit evasion	0.5-7 meV	—

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