Snowmass2021 - Letter of Interest

Improving the Sensitivity of Athermal Phonon Sensors for Light Mass Dark Matter

Thematic Areas:
■ (IF1) Quantum Sensors
■ (IF2) Photons
■ (CF1) Dark Matter: Particle Like

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Abstract: Dark matter with mass in the range from 100meV - 1GeV are expected to produce very small energy excitations when interacting with matter. As such the primary design driver for any experimental search for dark matter within this range is the development of zero dark count, ultra sensitive detection technology.

Athermal phonon detection technology is a natural candidate for this application since the necessary sensitivity is theoretically possible without the use of large E-fields for either drifting or amplifying small electronic excitations that have at least historically correlated with large dark count rates (from electronic tunneling,etc.) Below, we sketch out both the current technical capabilities as well as the R&D work program that is necessary to meet the experimental requirements.

1 Science Motivation and Design Drivers

Due to its small relative velocity with respect to the earth (O(10^{-3}c)) and small mass, only very small energy excitations are produced during interactions with light mass dark matter (DM).

In particular, we expect that for semiconductors the frenkel defect pair energy (O(15eV)) sets an electronic excitation threshold for ionization production from elastic nuclear recoils .Thus, we expect that for masses below O(300MeV), semiconductor searches for nuclear recoils must be done using phonon sensing technology. Above 300MeV, phonon sensors based searches are still well motivated even though non-phonon based techniques are conceptually sensitive, In particular, searches that combine the detection of an electronic excitation (ionization in Si/Ge or scintillation photons in GaAs [1;2]) with phonon sensing can be used to discriminate hypothetical DM nuclear recoils from electronic recoil backgrounds) [?] .

The narrative above broadly holds true for superfluid He. On the one hand, the lighter mass of He significantly increases the fraction of energy transferred to the nuclei relative to higher mass semiconductors in elastic nuclear scatters. On the other hand, the larger electronic bandgap increases the threshold. Thus, it's expected that DM below O(100 MeV) will not produce electronic excitations and thus must must be sensed using phonon detection technology. Just as with semiconductor targets, above this threshold simulaneous measurement of both the phonon and photon production should allow for nuclear recoil discrimination as well. In summary, the use of phonon sensing technology is highly motivated for nuclear interaction DM searches for all masses $<$ 6 GeV.

DM may also interact with bound electrons, exciting them to the conduction band (crystals) / lowest unoccupied orbital (atoms/molecules). Due to the presence of the nuclei as a momentum sink, such interactions can transfer nearly all of the kinetic energy of the dark matter (though with large rate suppressions for greater momentum transfer)[3]. As such, for the lowest semiconductor bandgap materials, electronic excitations can be produced by dark matter with masses down to O(1 MeV) in commonly used low gap semiconductors. Such excitations can be directly sensed (CCDs in SENSEI/DAMIC, SNSPDs for GaAs).

Even for this application phonon sensors are well motivated and deserve significant consideration. For CCDs, the E-fields used to drift charge could potential produce dark count events that are indistinguishable for example. Likewise, the lack of O(μs) timing information in CCD pixel arrays limits the ability to remove single electronic excitation events that are time coincident but spatially separate from a large energy background event[4].

3 experimental concepts that use athermal phonon sensors have been proposed that search for inelastic electronic recoils. Most simply, phonon sensors could instrument low bandgap semiconductors with no external E-field across the detector (SuperCDMS)[5]. Such devices would have eV scale thresholds, but wouldn't be susceptible to dark counts induced via E-field and would still have O(10us) scale timing for discrimination. Alternatively, an external E-field could be used to drift the charge converting the electrostatic potential energy into phonons (SuperCDMS[6]). Such a experiment is sensitive to leakage induced dark counts. However, with sub-eV sensitivities, dark count events could be discriminated against by looking for the excess phonon recoil energy from a true inelastic electronic recoil (i.e. a 3eV inelastic electronic recoil produces 1 e/h that drifts across a 100V potential producing a 103eV signal. A charge leakage event produces precisely a 100eV signal). Though more complex, such an experiment, has the benefit of being less susceptible to hypothetical darkcounts produced by microfractures in the crystal that release stress. Additionally, nuclear recoil backgrounds within the region of interest should be decreased by the ratio of the phonon sensitivity to the electrostatic potential energy of a single excitation. Alternatively, a GaAs crystal can be instrumented with phonon sensors and placed in the same optical cavity with an Ge wafer instrumented with phonon sensors as well[7]. In this experimental setup, an electronic recoil in the GaAs will produce coincident signals in both devices, leading to discrimination of any backgrounds that produce events in only one detector.

Finally, for DM interactions where the momentum transfer length scale is similar to the atomic spacing in the crystal, the paradigm of 2 body elastic nuclear scattering isn't valid. Instead, the DM interacts with the entire crystal. Polar crystals (SiO2, Al2O3) instrumented with phonon sensors capable of detecting single optical phonons (O(100 meV) thresholds) are sensitive to electronically interacting dark matter, while high sound speed crystals (diamond, SiC, SiO2) are sensitive to scalar interactions that produce single acoustic phonons (O(100 meV) thresholds required)[8? ;9].

In summary, numerous experimental concepts have been proposed that require 100meV-1eV phonon sensor thresholds to search for both electronic and nucleonic interacting dark matter throughout the mass range from 100meV to 6 GeV.

2 Athermal Phonon Sensor Technology

The athermal phonon detector principle uses a 2-step process. First, phonons from the crystal are collected with superconducting aluminum fins fabricated on the surface. In these fins, the phonon energy is converted into quasi-particle kinetic and potential energy (by breaking Cooper pairs). These quasi-particles then diffuse into an attached small volume Transition Edge Sensor (TES),where the energy is thermalized and measured. Equivalently, a small volume QUBIT or MKID could be also be used to directly sense the produced quasi-particles. This process of collecting and concentrating the diffuse phonon energy from the crystal volume into a very small TES/MKID/QUBIT volume is not perfectly efficient. At each stage losses can occur. A reliable estimate of these losses comes from the measured performance of the cryogenic photon detector (CPD). It has 2.5% of the surface covered with aluminum fins and achieves 18% phonon concentration efficiency[5].

Only a small fraction of the crystal surface is instrumented because the the energy resolution scales with the number and volume of the ultimate phonon sensors within the array. The small coverage means that most athermal phonons will reflect off un-instrumented crystal surfaces many times before being collected. This places strict requirements on the probability of athermal phonon thermalization on bare crystal surface. Thus, crystal surface treatment is very important for collection efficiency.

3 Future R&D Program

To achieve the requisite energy sensitivity requires shared R&D for all eventual sensor techniques including:

- development of environmental vibration mitigation strategies
- development of low stress structural support to minimize stress induced microfracture events than can mimic dark matter events
- measurement of athermal phonon down conversion probability on bare crystal surfaces for a variety of different crystals and surface preparation processes.

Additionally, TES based athermal phonon detectors require these TES specific improvements:

- lower TES transition temperature
- development of improved EMI and DC magnetic field mitigation
- optimization of the TES/Al collection fin to improve quasi-particle transport and collection efficiency
- decreased TES linewidth

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