Materials Design of Quasiparticle Transduction Channels for Direct Detection of Light Dark Matter

Thematic Areas:

- TF09. Astro-particle physics & cosmology.
- TF10. Quantum Information Science.
- CF01. Dark Matter: Particle-like.

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Many direct detection proposals of keV-MeV dark matter (DM) rely on the efficient transduction and readout of quasiparticle signals generated by scattering events. The types of quasiparticles generated depends on the type of coupling between dark and target materials. The range of quasiparticles created from sub-GeV DM interactions include phonons [1–4], electrons and excitions [2, 3] and magnons [5]. For all proposed DM-material couplings, we need to understand how DM creates the initial population of quasiparticles in a detector, and how these quasiparticle populations evolve before and during readout. Therefore, a key feature for a realistic detection proposal is that the energy contained in the quasiparticle distribution must be efficiently transduced into measurable signals.

One of the most prominent readout schemes for keV-MeV DM particles is the transition edge sensor. There, the DM generates an athermal distribution of phonons in a target material (e.g. Si or Ge in CDMS experiments), these phonons propagate to an interface with a transducer material (e.g. superconducting Al), which is connected to the transition edge sensor (TES). The TES is a material held at the edge of its transition to the superconducting phase – any variation in the internal energy results in a large change in the electrical properties of the material. Losses occur at each stage of the readout scheme; phonons decay during propagation to an interface, the interface scatters the phonons, the conversion from phonons to broken Cooper pairs incurs a loss, and the TES itself has noise. This combines to elevate the threshold for detection to energy scales much greater than that of a single phonon ($\mathcal{O}$(10 eV)) [6]. To drive this threshold down, novel material systems, including new chemistries, combinations of materials, and material architectures, must be developed to maximize the efficiency of energy transport in these devices.

To create design rules for new DM detectors, we need to understand the materials-specific processes and properties that give rise to quasiparticle transduction in detector materials. First-principles descriptions of the energy transfer processes in materials is possible using state-of-the-art Density Functional Theory (DFT) calculations. DFT is the work-horse for the *ab initio* description of materials at a quantum mechanical level and has been used to accurately describe the electronic, phononic and magnonic dispersion relationships in a wide variety of materials [7–9]. With this LoI, we propose two themes for developing a theoretical program for understanding, and ultimately optimizing, quasiparticle transduction in DM experiments.

I. TARGET QUASIPARTICLE TRANSDUCTION

While several proposals exist for coupling DM to materials, the detection readout depends on the generation of a detectable signal. Many of these schemes involve tranduction to phonons which can be readout using TES and MKID technolologies, for example DM coupling to magnons which can converted to detectable phonons. Therefore, proposals for DM-quasiparticle coupling schemes ultimately rely on an understanding of the quasiparticle transduction prcoesses in the target material. This first theme proposes to explore quasiparticle transduction couplings, and the resulting lifetimes and spectrum of the created excitations in the target material. One example of this is the calculation of anharmonic phonon-phonon interactions which cause the thermatlization of the initial phonon population. While anharmonic phonon-phonon interactions are more computationally demanding [7], recent developments in compressive sensing techniques [10] have allowed the efficient calculation of the relevant anharmonic processes in materials.

II. QUASIPARTICLE LIFETIMES AND DETECTION

On the other hand, the rate of energy transfer from the target material to the transducer material depends on the phonon propagation velocity, and the transmission coefficient across that interface. The phonon propagation velocities are accurately determined with DFT, but the transmission coefficient is more challenging. One often considers two limits: phonon propagation across the interface is (1) coherent, or (2) incoherent. In the former case, phonon transmission follows analogies from optics, and the transmission equations are called the Acoustic Mismatch Model (AMM) [11], and can be derived from Fresnel's equations and Snell's law. In the latter case, the phonons are assumed to scatter incoherently into all other phonon channels at the same frequency, and transmission equations based on this assumption are called the Diffuse Mismatch Model (DMM) [11]. Despite the assumptions and approximations, use of both of these limiting cases provides valuable insight into the energy transfer rates between two different materials, fully *ab initio* without any external inputs. The detector is efficient when the time scale associated with energy transfer is shorter than the timescale associated with thermalization. Therefore, the efficiency of the sensor comes down to a comparison of timescales: the rate of anharmonic decay, and the rate of energy conversion to the TES. Determination of material-specific rate-limiting factors for either time-scale is critical to pushing this technology forward.

In this Letter of Intent, we propose topics on:

- The study of quasiparticle transduction in detector targets for optimzing DM-material couplings and readout.
- The calculation of material parameters related to quasiparticle thermalization rates with DFT and compressive sensing.
- The identification of materials (or meta-materials) with minimal thermalization rates.
- The calculation of quasiparticle energy transfer rates between two distinct materials using both the AMM and DMM.
- The optimization of material interfaces for quasiparticle energy transfer.

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