Snowmass2021 Letter of Interest:
Light dark matter direct detection at the interface with condensed matter physics

Thematic Areas:

- TF09. Astro-particle physics & cosmology.
- TF10. Quantum Information Science.
- TF02. Effective field theory techniques.
- CF01. Dark Matter: Particle-like.
- CF02. Dark Matter: Wave-like.

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For decades now, theoretical and experimental probes have been focused on the weak scale in the search for answers to Nature's deepest mysteries, including the nature of the dark matter (DM). The weak scale is a theoretically compelling space to start the hunt for DM: in addition to connecting the problem of the DM to the weighty question of the natural mass scale for the Higgs boson, the relic abundance of DM falls out naturally from the freeze-out paradigm.

However, theoretical developments over the last decade have led to the realization that compelling models of new physics, including those of the dark sector, may be naturally below the weak mass scale. These paradigms of hidden sector DM include Hidden Valleys [1] with composite DM (whether dark mesons [2], atomic DM [3], or glueballs [4]), WIMPless DM [5], Secluded DM [6], Asymmetric DM [7], supersymmetric hidden sector DM [8–11], strongly interacting massive particles [12], and self-interacting DM [13–15]. These hidden sector theories have also given rise to new approaches to deep questions, such as models for baryogenesis [16–18] and "neutral naturalness" [19] solutions to the hierarchy problem.

Along with the theoretical development new experimental probes have been proposed and are under development. Sensitivity to lighter DM requires both better energy resolution sensors and qualitatively new ideas. The original idea of Goodman and Witten [20] to use nuclear recoils has limitations: once the mass of the DM drops below that of the nucleus, the interaction suffers from a kinematic suppression that allows extraction of only a small fraction of the DM kinetic energy. (This is because the energy deposition on the target is $E_D = q^2/2m_T$, where m_T is the target nucleus mass, and q is the momentum transfer, which is at most twice the DM momentum.) We know, however, that condensed matter systems have a range of small-gap excitations, as well as gapless and effectively massless modes. They would enable efficient extraction of a large fraction of the DM's kinetic energy even for DM much lighter than ordinary nuclei.

This project ultimately seeks to develop the theory for DM interactions with excitations in condensed matter systems, especially collective modes such as in superfluid helium [21, 22], (polar) crystals [23–27] and magnetically ordered materials [28]. Until these works, these collective excitations (including in common materials like semiconductors and superconductors [29, 30]) were not utilized to reach sub-GeV DM. It has been shown that by utilizing these excitations, the sub-MeV DM mass reach can be extended by several orders of magnitude, while conventional processes in the same targets still allow to probe the MeV to GeV range.

These new directions offer the exciting possibility of covering well-motivated but yet unexplored DM theory space. For example, axion DM in the 1-100 meV mass window has been poorly constrained previously but can be searched for via phonon polariton and magnon excitations [31]. Development of low-threshold energy sensors, including quantum information science (QIS) related devices, further motivates us to continue in these and related directions and explore a broader range of condensed matter systems for light DM direct detection.

Progress in this field hinges upon interdisciplinary theoretical research to accurately compute signal and background processes. On the condensed matter side, density functional theory (DFT) plays a key role in *ab initio* calculations of material properties, while (semi)analytic methods are also useful in many cases when solving weakly coupled systems. To bridge the condensed matter knowledge with DM detection ideas, calculations of material responses to DM interactions are needed, with a combination of analytic and numerical tools. In particular, effective field theory (EFT) methods [32–35] are useful both for classifying DM interactions and identifying condensed matter systems and excitations with favorable response to each type of interaction, and for generally formulating calculations of DM scattering and absorption rates to facilitate automation. Meanwhile, it is important to theoretically examine a broad range of candidate materials for each detection path, in order to find the optimal targets for further experimental investigation [26].

With this letter of interest (LoI), we propose theoretical studies on topics including, but not limited to

- Continued exploration of novel condensed matter systems for small-gap excitations for DM direct detection.
- EFTs for DM interactions with collective excitations (including phonons, magnons, plasmons etc.).
- DFT calculations of multiphonon excitations, relevant for near future experiments where detector thresholds have not reached single phonon energies.
- Optimization of detector target choice, including identification of anisotropic targets that would allow for directional detection.
- Improved DFT calculations and semianalytic tools for electron excitations in semiconductors, including all-electron reconstruction of electron wavefunctions, and core electron effects.
- Automation of detection rate calculations for various ongoing and proposed experiments.

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