Snowmass2021 - Letter of Interest

Low-gap charge detection for fundamental physics searches

Thematic Areas: (check all that apply □/■)

■ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (IF1) Quantum Sensors
■ (IF2) Photon Detectors
■ (IF7) Electronics/ASICs

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Abstract: The search for sub-GeV dark matter (DM) scattering from electrons has benefited greatly from experimental advances in single-charge detection using conventional semiconductors, and theoretical ideas for using narrow-gap ($\sim$ meV) semiconductors to extend the sensitivity down to dark matter masses of 10 keV. This Letter of Interest describes a readout scheme which can leverage both of these advances simultaneously: a contactless charge amplifier which can allow rapid prototpying of novel detector materials for keV-MeV DM detection, and can also enhance the charge multiplicity for MeV-GeV DM searches in low-gap materials. Such detectors could also find immediate use as single-THz photon detectors for axion searches or astrophysical applications.

Introduction. Dark matter (DM) may have a mass anywhere from 10^{-22} eV to 10^{19} GeV; there is no one-size-fits-all solution to detecting DM over such a broad mass range. In particular, DM which deposits energy from ~ 10 meV $-$ 10 eV is difficult to detect because these energies are comparable to, or smaller than, typical detector excitation energies and detector thresholds. Several theoretically-motivated benchmark models exist for DM which deposits these energies, including freeze-in DM [1, 2] with masses ~ 10 keV $-$ 10 MeV detected through scattering, or axion-like DM [3] with masses ~ 10 meV $-$ 10 eV detected through absorption, and these models offer concrete predictions for the coupling of DM to ordinary matter. In recent years, a broad suite of proposals utilizing novel condensed matter systems with sub-eV excitation energies has greatly improved the prospects for light DM detection [4–34]. In many of the benchmark models, electronic excitations induced from DM-electron scattering are quite generic. By operating the detector as a *charge amplifier* (as opposed to, say, a calorimeter or bolometer), the detection threshold is set intrinsically by the excitation energy rather than extrinsically by the amplifier because the signal can always be amplified by a sufficiently large applied voltage. The threshold is thus on the order of the band gap in semiconductor-like materials, and can be lowered to the meV scale with a suitable choice of material.

This Letter of Interest makes the case for *developing a universal contactless charge amplifier package suitable for a sub-Kelvin cryostat which may be coupled to systems with meV-scale band gaps*. Rather than collecting charge directly into metallized electrodes, such an amplifier utilizes a small vacuum gap as a capacitive voltage divider to prohibit leakage across the charge collection interface [35, 36], and thus does not require a metallized contact, or can be used with a contact that does not have a strong Schottky barrier [37]. This amplifier would greatly accelerate the pace of DM detection by bypassing the R&D required to engineer surface contacts on a number of novel materials, some of which have only recently been synthesized in materials science laboratories and do not have any of the industrial infrastructure of common semiconductors such as silicon and germanium. Low-gap materials can also improve the signal-to-noise performance of more standard MeV-scale DM-electron scattering searches by increasing the number of charge pairs produced for a given DM kinetic energy. Finally, since photoabsorption generates electron/hole pairs in much the same way as DM-electron scattering or DM absorption, detectors with a meV-scale gap coupled to our charge amplifier could be repurposed as single-THz photon detectors, which have numerous applications in both astrophysics and industry. This program would greatly accelerate dark matter science, and allow for rapid evaluation/testing of new meV-gap crystals for applications as THz photon sensors.

Sub-MeV dark matter searches. Due to screening effects from conduction electrons, the sensitivity to freeze-in DM is typically enhanced with insulating rather than conducting detectors [5]. The first study of narrow-gap insulators for sub-MeV detection [9] proposed the Dirac semimetal $ZrTe_5$, and several subsequent proposals have identified promising compounds (e.g. Yb_3PbO, PbTe) and noted the directional detection possibilities of anisotropic narrow-gap materials [14, 19, 27]. Dirac materials were originally the subject of study because of their simple electronic structure near the band edge, but any material which is a zero-temperature insulator will have unsuppressed DM interactions. Electronic correlations are also known to renormalize electronic energy scales, which may result in very narrow-gap materials with a large phase space for low energy particle-hole excitations across the gap. Notably, some f-electron materials have particularly small energy scales such as Kondo insulators (e.g. SmB_6 and YbB_{12}) [38, 39]. There is a wide-ranging effort to systematically search databases of molecular compounds and crystal structures to find detector materials ideally suited to DM searches [14, 40]; such searches may identify compounds which have not yet been synthesized which could be optimal detectors (e.g. $ZrSe_5$ [9] or $SrSn_2As_2$ [40]).

Despite this exciting progress, a low-gap detector with single-charge readout has not yet been demonstrated. Much of the difficulty lies in the fragile nature of these compounds, many of which are quasi-low-dimensional and grow as "flakes" [41] or sheets rather than bulk crystals. Furthermore, impurities are present in any laboratory crystal, and it is not clear a priori which samples will perform well enough for the charge readout scheme to succeed. As a result, experimental groups are reluctant to commit the extensive resources to developing a detector from a single choice of material, but diversifying the risk by using multiple materials would require bespoke surface engineering to apply the required electrical contacts to each material. As such, a universal contactless amplifier could allow rapid prototyping and down-selection of a number of candidate materials.

Enhanced charge multiplicity from low-gap materials. The main advantage of meV-gap materials lies in the ability to leverage highly mature, scalable, and robust charge readout architectures from years of research and development of science-grade CCDs and tracking detectors. In a typical point-contact detector, charge is collected across a capacitive junction and read out as a voltage, and nominal conversion of absorbed energy to charge depends on the gap energy E_g and avalanche gain G as $q = G(E_r/E_g)$. The energy resolution for a generic charge integrator readout is [42]

$$\sigma_E = \frac{\sigma_q E_g}{G} \approx \frac{N_v(C_{det} + C_{amp})E_g}{\epsilon_q G\sqrt{\tau_q}} \tag{1}$$

where N_v is the typical flat voltage noise power and τ_q is the integration time. Ge- and Si-based detectors can achieve single-charge resolution for $G = 1$ and $E_{gap} \approx 0.5 - 1.2$ eV by employing integrated charge amplifiers and long (ms-s) readout times for small capacitance, while faster single-charge detectors require high avalanche gain G to attain comparable resolution, at the expense of high levels of doping and very high dark rates. In contrast, materials with meV-scale gaps can achieve comparable energy resolution with substantially less stringent noise requirements, faster readout without avalanche gain, or intrinsic avalanche gain without an artificially fabricated avalanche region. This is an enormous advantage for DM with masses from MeV-GeV, which would typically produce $\mathcal{O}(1)$ e/h pairs in a conventional semiconductor like Si with an eV-scale bandgap, but could produce $\mathcal{O}(100)$ in a low-gap material. The downside of using new materials is a lack of experience fabricating devices with them; a platform which is material agnostic can thus easily test many materials for a given application, and lends itself to a massively multiplexed readout which can be applied to multiple materials in e.g. an imaging spectrometer. Development of a platform for testing new materials will open up new windows into dark matter, and is synergistic with the growing field of designer compounds for quantum sensing [43].

Applications as single-THz photon detectors. Single THz photodetectors are increasingly in demand for a variety of applications, including quantum computing, direct searches for axion-like particles, and as imaging sensors for THz astronomy. Many technologies based on superconductors have recently been proposed, including transition edge sensors [44], microwave kinetic induction devices [45], nanowires [46], and qubit-based technologies such as quantum capacitance detectors [47]. The major drawbacks to superconducting detectors are the limited quantum efficiency of these devices without coupling to a resonant cavity, and the strict operating requirements including operation in a dilution refrigerator and low light levels. Novel insulating materials with meV-scale band gaps may be operated at less demanding temperatures, and are not intrinsically sensitive to the thermal photon bath at temperature below the gap energy. In addition, charge-based readout is more easily adapted to existing imaging applications due to the standard readout technologies and techniques employed.

Conclusion. DM which deposits sub-eV energies is theoretically well-motivated but completely unprobed experimentally. The universal contactless charge amplifier we propose here will allow rapid prototyping of narrow-gap detectors where DM creates electron/hole pairs. This technique could immediately be applied to conventional semiconductors with eV-scale gaps as well as single-THz photon detection for astronomy and quantum computing applications.

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