
Snowmass 2021 Letter of Interest
Cryogenic Carbon Detectors for Dark Matter Searches

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Topical Groups:

- (CF1) Dark Matter: Particle Like
- (CF2) Dark Matter: Wavelike
- (IF2) Photon Detectors
- (IF3) Solid State Detectors and Tracking
- (IF6) Calorimetry
- (IF9) Cross-Cutting and Systems Integration
- (NF10) Neutrino Detectors

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Uncovering the nature of dark matter (DM) is one of the primary P5 science drivers [1]. More recently, the Cosmic Visions community report [2] and the Basic Research Needs report on new small-project initiatives for dark matter [3] dramatically expanded the DM hunting ground to include a much broader range of potential DM particle masses, with a particular emphasis on the very low-mass range in which the mass of the dark matter particle is less than the mass of the proton ('sub-GeV'). The expansion of DM searches to sub-GeV physics targets, and the growing interest in coherent neutrino scattering, has led many in both fields to re-think typical solid-state targets employed as detector media. The requirements of these new research areas are distinct; energy transfers are small, and physics reach is threshold driven. For dark matter in particular, the maximum elastic energy transfer to a target nucleus from DM of mass m_χ is [4]

$$\Delta E \approx \frac{2\ \text{meV}}{A_T}\left(\frac{m_\chi}{1\ \text{MeV}}\right)^2 , \tag{1}$$

with A_T the atomic number of the target; coherent neutrino scattering suffers from similar kinematic constraints. In addition to required advances in macro-calorimeter resolution to achieve meV-scale thresholds, use of lighter targets enhances reach by improving kinematic matching between the target particle and the detector. Carbon ($A_T = 12$) and carbon-based crystals are thus much preferred to typical targets (e.g. Ge, Si, Xe) which have much higher nuclear masses. Carbon-based targets for DM searches in particular have been the focus of recent studies, with Diamond [5] and SiC [4] identified as ideal crystals for DM detection when compared against a broad spectrum of crystal systems [6].

In addition to the kinematic matching to DM and neutrinos, Diamond and SiC are superior detector targets in many ways. They have good isotopic purity, outstanding radiation hardness, and excellent phonon properties and dynamics due to the particularly strong carbon bonds. In their tetrahedral forms—the same crystal polytype as Si and Ge—they have the highest sound speeds and most energetic optical phonons of any known crystals. These phonon properties make energy transport and collection faster and more efficient than comparable designs using Si, Ge, or sapphire. Diamond and SiC are also able to hold large applied electric fields due to exceptionally large dielectric strengths. These properties are expected to yield a significant improvement in energy sensitivity relative to more conventional semiconductors, thus enabling detection thresholds in the meV to eV energy range [5, 4]. Finally, much of the thin-film phonon-readout technology developed for germanium and silicon (see, e.g., Refs. [7, 8]) can be applied to diamond with minimal modification. Initial work on diamond and SiC particle detectors is promising, and an athermal-phonon—Transition Edge Sensor (TES)—readout on a CVD diamond sample was recently demonstrated with comparable performance to sapphire [9].

Recent advances with cryogenic silicon calorimeters instrumented with high-resolution phonon sensors have demonstrated sensitivity to single electron-hole pairs and corresponding eV-scale energy thresholds [10, 8]. As discussed in Refs. [5, 4], direct application of these techniques to carbon-based substrates should immediately yield eV-scale phonon resolution. Sensitivity to such small energy depositions will provide access to dark matter candidates with masses below $0.1\,\text{GeV/c}^2$. Further advances in the sensor technology are expected to give an additional factor of $\sim$100 improvement in phonon resolution, which would continue to extend the mass reach below $0.01\,\mathrm{GeV/c^2}$. Also, our carbon-based detectors will be sensitive to electronic interactions, which enables searches for dark matter, dark photons, and axion-like particles through additional physics channels, some of which have the potential to probe the sub-eV/c^2 mass scale. The higher dielectric strength of these materials will allow kV-scale voltage biases, which translates to charge resolution of better than $10^{-3}e^-$. The higher bandgaps also ensure deeper impurity traps, making these detector less susceptible to absorption of infrared photons causing excess charge backgrounds.

High-purity Diamond and SiC are also emerging as promising platforms for Quantum Information Science (QIS). Within the last two decades, improved methods for growth of synthetic diamond—in particular, high-purity diamond grown via Chemical Vapor Deposition (CVD)—have enabled progress with a broad range of advanced QIS applications, including quantum computing, microelectronics, communications, and various types of quantum sensors (e.g., high-speed quantum information processing as in Ref. [11]). As a result, there is a common need for high-quality, low-cost diamond growth and thin-film fabrication and characterization R&D to benefit both QIS and high energy physics (HEP).

To broadly capitalize on the promise of carbon-based crystals, significant work and investment is needed over the next decade. In particular:

1. Assays of ^{14}C are needed for different crystal-growth processes. CVD can be made ^{14}C-free via additional processing steps to purify the input gas used for crystal growth, and both ^{12}C- and ^{13}C-enhanced crystals have been produced via this method. It is currently slow (growth of microns/hour) and expensive but is rapidly advancing due to industry investment. Academia-industry partnerships will be particularly fruitful in this respect. SiC is largely grown by the same process as Si, but the ^{14}C content will depend on the purity of the seed material and needs to be investigated.

2. Tungsten TES sensors have already been fabricated on a diamond substrate [9], which alleviates some concerns of T_c spoiling via creation of tungsten carbide and pollution of sputtering targets. Superconducting resonators have also been fabricated on Diamond and SiC substrates, and Diamond and SiC themselves can be made superconducting via boron doping [12], which would allow for complex on-device readout structures with high energy efficiency.

3. The large bandgap of diamond (5.5 eV), and to some extent SiC (2–3.4 eV), make calibration more difficult due to the lack of UV single-photon sources and the difficulty of coupling both UV and long-wave IR sources into cryostats. To some extent, the promise of operating these detectors at 4 K via charge readout may partially solve this issue, as optical windows are more readily available for such cryostats.

Basic research support and broad adoption across the various interested communities will enable this technology to grow, led by existing programs in beam monitoring[13] and the dark matter and coherent neutrino scattering applications discussed here.

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