1 Progress toward a solid-state directional dark matter detector

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1.1 Introduction

The next generation of WIMP dark matter detectors are expected to approach the "neutrino fog," where coherent scattering of solar neutrinos will be observable, making it challenging to extract the WIMP signal [1]. However, due to the differing expected angular distributions of the WIMP and solar neutrino fluxes, the capability to determine the direction of an incoming particle would allow the rejection of solar neutrinos and provide insights into the cosmological origin of a WIMP signal [2, 3]. This could be performed by a hybrid "conventional-directional" solid-state dark matter detector where nuclear recoils are registered in real-time by conventional readout techniques and directional information is extracted by high-resolution imaging of the resulting crystal damage track inside the material [4–6]. Such a detector is particularly promising due to its higher target density compared to gaseous or emulsion detectors [7–9], the availability of materials with favorable semiconductor properties and low nuclear mass [10, 11], and the ability to utilize color centers in the material for fast and precise identification and characterization of the damage track [5, 6].

1.2 Detector scheme

The detector would consist of a $\sim$m^3 volume of diamond or silicon carbide (SiC) divided into numerous removable millimeter-scale segments. Occasionally, a WIMP or neutrino interacts with the detector mass. Simulations with diamond indicate that a $\sim$1-100 GeV WIMP particle would lead to a $\sim$10-100 keV nuclear recoil, producing a $\sim$10-100 nm long-lasting damage track [4]. Localization and measurement of this signal would proceed in three stages (Fig. 1). In stage 1, the nuclear recoil is recorded in real-time using charge, phonon, or photon collection similar to those in existing semiconductor-based detectors [12, 13]. The location of the interaction is also identified and the corresponding detector segment is removed for further analysis.

In stage 2, the location of the damage track within the mm-scale detector segment is identified with micron-scale precision. Two readout strategies are possible [6]. The first is optical strain spectroscopy of pre-existing color centers in the material, looking for a strain spike in color centers located near the damage track. The second is to use material with few existing color centers and detect the fluorescence from new centers created by the damage track. Both of these methods can be applied to color centers such as nitrogen vacancies (NVs) in diamond [14–16] or divacancies in SiC [17–20].

Having identified the $\sim\mu$m^3 voxel containing the damage track, we proceed to stage 3, where nanometer-scale imaging techniques such as X-ray diffraction spectroscopy [21, 22] or superresolution spectroscopy of color centers [5, 23, 24] are applied to measure the shape,

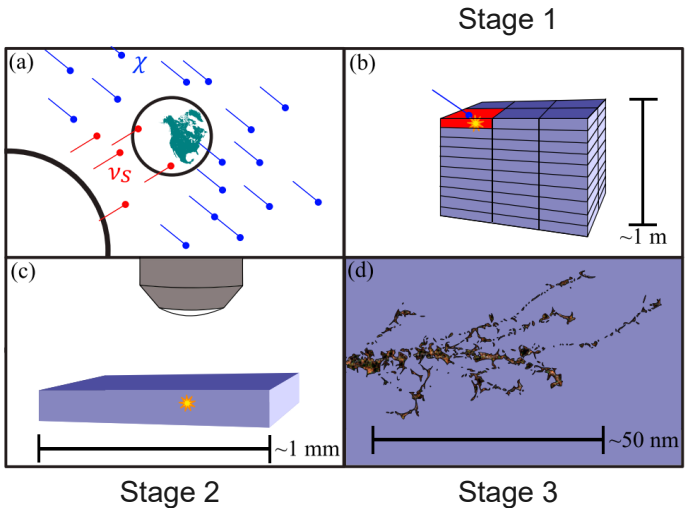


Figure 1: Multi-stage detection in a solid-state directional matter detector. a) Solar neutrinos and WIMPs stream through the earth with distinct preferred directions. b) Stage 1: WIMP or neutrino particles interact with a macroscopic detector, causing a nuclear recoil recorded in real-time with conventional readout methods. c) Stage 2: micron-scale localization with a QDM. d) Stage 3: nanoscale imaging of the damage track. Figure adapted from [5].

orientation, and length of the damage track. This information can then be correlated with stage 1 real-time data to determine the direction and origin of the signal. In order to keep up with the anticipated event rate of a full m^3-scale detector, stages 1-3 need to be completed within a conservative benchmark time of 3 days [6].

1.3 Recent experimental progress and future outlook

Here, we report recent progress and future outlook toward developing such a detector at the Quantum Technology Center (QTC) at the University of Maryland. Due to the maturity of conventional (stage 1) detection techniques with semiconductor materials [12, 13] and ongoing efforts on implementing similar techniques in diamond detectors [10, 25–28], our research has focused on stage 2 and 3 detection using NV centers in diamond, a leading platform for quantum sensing [14, 29].

1.3.1 Stage 2: micron-scale localization

For stage 2, precise, high-throughput optical strain spectroscopy can be performed with a quantum diamond microscope (QDM) [30]. To localize a damage track from a 10 keV nuclear recoil, a strain sensitivity of at least $1 \times 10^{-7}/\sqrt{\text{Hz } \mu\text{m}^{-3}}$ with 1 μm^3 voxel size is required [5]. In 2022, we demonstrated strain sensing on a confocal QDM with a sensitivity of $5(2) \times 10^{-8}/\sqrt{\text{Hz } \mu\text{m}^{-3}}$, exceeding this requirement [16]. For higher imaging throughput, 2D strain sensing was also performed on a wide-field QDM with 150×150 μm^2 field of view and similar levels of strain sensitivity. With chemical vapor deposition, NV-rich

diamonds can be synthesized with low background strain [31], favorable for localization of strain spikes caused by damage tracks.

However, 2D strain imaging lacks depth resolution, and WIMP damage tracks can randomly occur within the entire volume of the diamond detector segment. Our current research is focused on developing full 3D strain imaging capability using light sheet microscopy [32, 33]. By shaping the excitation laser light, a light sheet QDM (LS-QDM) would permit interrogation of a μm-scale-thick layer of NV centers [34]. As an initial demonstration, we aim to construct an LS-QDM with $\sim$5 μm resolution, $\sim 100 \times 100$ μm^2 field of view, and strain sensitivity comparable to Ref. [16]. In the longer term, achieving 1 μm resolution is feasible [35]. For the alternative stage 2 readout method, which looks for fluorescence from NV centers created in the vicinity of the damage track, conventional LSMs akin to those used in other mineral detectors [36, 37] will be useful.

1.3.2 Stage 3: nanoscale track imaging

For stage 3, nanoscale imaging of diamonds using scanning X-ray diffraction microscopy (SXDM) has been explored at the Argonne National Laboratory. In this technique, a beam of X-rays is focused to a 10-25 nm spot inside a sample held at a Bragg angle [38]. As the beam is scanned, local differences in the resulting diffraction pattern encodes the crystal structure of the diamond. In the 2021 experiment [22], strain sensitivity of 1.6×10^{-4} was achieved, which would be sufficient to detect 10 keV recoils. A limited survey of low-strain regions of the sample found no natural strain features which would impede detection of nm-scale damage tracks. Future efforts will be geared towards performing SXDM of artificial damage tracks with similar spatial and strain resolution.

An alternative stage 3 readout method is to perform super-resolution imaging of color centers using techniques such as spin-RESOLFT [23]. This technique has been used to perform 2D magnetometry with $\sim$20 nm resolution [24], and is relatively straightforward to extend for strain sensing. Z-resolution can be obtained by combining this technique with super-resolved Fourier magnetic gradient imaging [5, 39]. By mapping the position of all the color centers inside the region of interest, pattern recognition algorithms can be used to reconstruct the damage track [4]. Compared to X-ray microscopy, a significant advantage of this readout method is that it can be performed locally at the detector site with a tabletop setup. Super-resolution NV imaging techniques have been previously developed in our group [23, 24, 39, 40], and construction of a super-resolution-enabled confocal QDM at the QTC is currently in the preliminary stages.

1.3.3 Artificial damage tracks for sensitivity characterization

To characterize the sensitivity of the aforementioned imaging techniques, it is crucial to have methods to generate injected signals in a diamond sample. We have an ongoing collaboration with the Ion Beam Lab at Sandia National Laboratory, where their microbeam facility can implant low numbers of carbon ions on the surface of a diamond sample with a spot size of $\sim$1 um and minimum energy of 0.8 MeV [41]. In situ ion counting can be used

to significantly reduce the ion intensity uncertainty in an ion pulse, allowing for deterministic implantion of single ions [42, 43]. Another method to produce artificial tracks is to irradiate the diamond sample with energetic neutrons [44]. Preliminary simulations with MCNP [45] indicate that irradiation with a monoenergetic 14 MeV neutron source would produce a small but sufficient number of > 0.1 MeV nuclear recoils in diamond. Unlike ion implantation, which is restricted to the surface, neutron irradiation can create tracks inside the sample and would be useful to study the effects of neutron backgrounds which are common in mineral detectors [37, 46].

1.4 Conclusion

In conclusion, a three-stage conventional-directional solid-state dark matter detector is a promising prospect for detecting WIMP dark matter beyond the neutrino fog, by combining techniques in conventional real-time nuclear recoil detection and quantum sensing with color centers. Current research at the QTC aims to extend and fine-tune state-of-the-art quantum sensing techniques to demonstrate the technical feasibility of such a detector within the next few years, including determining the best readout method for each detection stage. Although current research has predominantly concentrated on NVs in diamond, development of similar techniques with color centers in silicon carbide should also be explored in the future, given its potential for easier scalability.

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References

[1] C. A. J. O'Hare, *New Definition of the Neutrino Floor for Direct Dark Matter Searches*, *Physical Review Letters* **127** (Dec., 2021) 251802.

[2] F. Mayet, A. M. Green, J. B. R. Battat, J. Billard, N. Bozorgnia, G. B. Gelmini et al., *A review of the discovery reach of directional Dark Matter detection*, *Physics Reports* **627** (Apr., 2016) 1–49.

[3] S. E. Vahsen, C. A. O'Hare and D. Loomba, *Directional Recoil Detection*, *Annual Review of Nuclear and Particle Science* **71** (2021) 189–224.

[4] S. Rajendran, N. Zobrist, A. O. Sushkov, R. Walsworth and M. Lukin, *A method for directional detection of dark matter using spectroscopy of crystal defects*, *Physical Review D* **96** (Aug., 2017) 035009.

[5] M. C. Marshall, M. J. Turner, M. J. H. Ku, D. F. Phillips and R. L. Walsworth, *Directional detection of dark matter with diamond*, *Quantum Science and Technology* **6** (Mar., 2021) 024011.

[6] R. Ebadi, M. C. Marshall, D. F. Phillips, J. Cremer, T. Zhou, M. Titze et al., *Directional detection of dark matter using solid-state quantum sensing*, *AVS Quantum Science* **4** (Nov., 2022) 044701.

[7] S. E. Vahsen, C. A. J. O'Hare, W. A. Lynch, N. J. C. Spooner, E. Baracchini, P. Barbeau et al., *CYGNUS: Feasibility of a nuclear recoil observatory with directional sensitivity to dark matter and neutrinos*, Dec., 2020. 10.48550/arXiv.2008.12587.

[8] T. Shimada, S. Higashino, T. Ikeda, K. Nakamura, R. Yakabe, T. Hashimoto et al., *Direction-sensitive dark matter search with 3D-vector-type tracking in NEWAGE*, *Progress of Theoretical and Experimental Physics* **2023** (Oct., 2023) 103F01.

[9] A. Umemoto, T. Naka, T. Shiraishi, O. Sato, T. Asada, G. De Lellis et al., *First direction sensitive search for dark matter with a nuclear emulsion detector at a surface site*, Oct., 2023. 10.48550/arXiv.2310.06265.

[10] N. Kurinsky, T. C. Yu, Y. Hochberg and B. Cabrera, *Diamond detectors for direct detection of sub-GeV dark matter*, *Physical Review D* **99** (June, 2019) 123005.

[11] S. M. Griffin, Y. Hochberg, K. Inzani, N. Kurinsky, T. Lin and T. C. Yu, *Silicon carbide detectors for sub-GeV dark matter*, *Physical Review D* **103** (2021) 075002.

[12] E. L. Asamar and f. t. S. Collaboration, *SuperCDMS SNOLAB: status and prospects for measuring the coherent neutrino scattering*, *Journal of Physics: Conference Series* **1216** (Apr., 2019) 012020.

[13] DAMIC Collaboration, A. Aguilar-Arevalo, D. Amidei, I. Arnquist, D. Baxter, G. Cancelo et al., *Characterization of the background spectrum in DAMIC at SNOLAB*, *Physical Review D* **105** (Mar., 2022) 062003.

[14] M. W. Doherty, N. B. Manson, P. Delaney, F. Jelezko, J. Wrachtrup and L. C. L. Hollenberg, *The nitrogen-vacancy colour centre in diamond*, *Physics Reports* **528** (July, 2013) 1–45.

[15] P. Kehayias, M. J. Turner, R. Trubko, J. M. Schloss, C. A. Hart, M. Wesson et al., *Imaging crystal stress in diamond using ensembles of nitrogen-vacancy centers*, *Phys. Rev. B* **100** (Nov, 2019) 174103.

[16] M. C. Marshall, R. Ebadi, C. Hart, M. J. Turner, M. J. Ku, D. F. Phillips et al., *High-Precision Mapping of Diamond Crystal Strain Using Quantum Interferometry*, *Physical Review Applied* **17** (2022) 024041.

[17] S. Castelletto and A. Boretti, *Silicon carbide color centers for quantum applications*, *Journal of Physics: Photonics* **2** (Mar., 2020) 022001.

[18] W. F. Koehl, B. B. Buckley, F. J. Heremans, G. Calusine and D. D. Awschalom, *Room temperature coherent control of defect spin qubits in silicon carbide*, *Nature* **479** (Nov., 2011) 84–87.

[19] A. L. Falk, P. V. Klimov, B. B. Buckley, V. Ivády, I. A. Abrikosov, G. Calusine et al., *Electrically and Mechanically Tunable Electron Spins in Silicon Carbide Color Centers*, *Physical Review Letters* **112** (2014) 187601.

[20] P. Udvarhelyi and A. Gali, *Ab Initio Spin-Strain Coupling Parameters of Divacancy Qubits in Silicon Carbide*, *Physical Review Applied* **10** (Nov., 2018) 054010.

[21] R. P. Winarski, M. V. Holt, V. Rose, P. Fuesz, D. Carbaugh, C. Benson et al., *A hard X-ray nanoprobe beamline for nanoscale microscopy*, *Journal of Synchrotron Radiation* **19** (Nov., 2012) 1056–1060.

[22] M. C. Marshall, D. F. Phillips, M. J. Turner, M. J. H. Ku, T. Zhou, N. Delegan et al., *Scanning X-Ray Diffraction Microscopy for Diamond Quantum Sensing*, *Physical Review Applied* **16** (Nov., 2021) 054032.

[23] P. C. Maurer, J. R. Maze, P. L. Stanwix, L. Jiang, A. V. Gorshkov, A. A. Zibrov et al., *Far-field optical imaging and manipulation of individual spins with nanoscale resolution*, *Nature Physics* **6** (Nov., 2010) 912–918.

[24] J.-C. Jaskula, E. Bauch, S. Arroyo-Camejo, M. D. Lukin, S. W. Hell, A. S. Trifonov et al., *Superresolution optical magnetic imaging and spectroscopy using individual electronic spins in diamond*, *Optics Express* **25** (May, 2017) 11048–11064.

[25] A. Tarun, S. J. Lee, C. M. Yap, K. D. Finkelstein and D. S. Misra, *Impact of impurities and crystal defects on the performance of CVD diamond detectors*, *Diamond and Related Materials* **63** (Mar., 2016) 169–174.

[26] L. Canonica, A. H. Abdelhameed, P. Bauer, A. Bento, E. Bertoldo, N. Ferreiro Iachellini et al., *Operation of a Diamond Cryogenic Detector for Low-Mass Dark Matter Searches*, *Journal of Low Temperature Physics* **199** (May, 2020) 606–613.

[27] A. H. Abdelhameed, G. Angloher, A. Bento, E. Bertoldo, A. Bertolini, L. Canonica et al., *A low-threshold diamond cryogenic detector for sub-GeV dark matter searches*, *The European Physical Journal C* **82** (Sept., 2022) 851.

[28] C. Collaboration, G. Angloher, S. Banik, G. Benato, A. Bento, A. Bertolini et al., *Light Dark Matter Search Using a Diamond Cryogenic Detector*, Oct., 2023. 10.48550/arXiv.2310.05815.

[29] J. F. Barry, J. M. Schloss, E. Bauch, M. J. Turner, C. A. Hart, L. M. Pham et al., *Sensitivity optimization for NV-diamond magnetometry*, *Rev. Mod. Phys.* **92** (Mar, 2020) 015004.

[30] E. V. Levine, M. J. Turner, P. Kehayias, C. A. Hart, N. Langellier, R. Trubko et al., *Principles and techniques of the quantum diamond microscope*, *Nanophotonics* **8** (Nov., 2019) 1945–1973.

[31] A. M. Edmonds, C. A. Hart, M. J. Turner, P.-O. Colard, J. M. Schloss, K. S. Olsson et al., *Characterisation of CVD diamond with high concentrations of nitrogen for magnetic-field sensing applications*, *Mater. Quantum Technol.* **1** (2021) 025001.

[32] O. E. Olarte, J. Andilla, E. J. Gualda and P. Loza-Alvarez, *Light-sheet microscopy: a tutorial*, *Adv. Opt. Photon.* **10** (Mar, 2018) 111–179.

[33] N. Vladimirov, F. F. Voigt, T. Naert, G. R. Araujo, R. Cai, A. M. Reuss et al., *The Benchtop mesoSPIM: a next-generation open-source light-sheet microscope for large cleared samples*, *bioRxiv : the preprint server for biology* (2023) .

[34] A. Horsley, P. Appel, J. Wolters, J. Achard, A. Tallaire, P. Maletinsky et al., *Microwave device characterization using a widefield diamond microscope*, *Phys. Rev. Appl.* **10** (Oct, 2018) 044039.

[35] A. Glaser, J. Chandrashekar, J. Vasquez, C. Arshadi, N. Ouellette, X. Jiang et al., *Expansion-assisted selective plane illumination microscopy for nanoscale imaging of centimeter-scale tissues*, *eLife* **12** (Oct., 2023) .

[36] B. K. Cogswell, A. Goel and P. Huber, *Passive low-energy nuclear-recoil detection with color centers*, *Phys. Rev. Appl.* **16** (Dec, 2021) 064060.

[37] S. Baum, P. Stengel, N. Abe, J. F. Acevedo, G. R. Araujo, Y. Asahara et al., *Mineral detection of neutrinos and dark matter. A whitepaper*, *Physics of the Dark Universe* **41** (Aug., 2023) 101245.

[38] M. Holt, R. Harder, R. Winarski and V. Rose, *Nanoscale Hard X-Ray Microscopy Methods for Materials Studies*, *Annual Review of Materials Research* **43** (2013) 183–211.

[39] K. Arai, C. Belthangady, H. Zhang, N. Bar-Gill, S. J. DeVience, P. Cappellaro et al., *Fourier magnetic imaging with nanoscale resolution and compressed sensing speed-up using electronic spins in diamond*, *Nature Nanotechnology* **10** (Oct., 2015) 859–864.

[40] H. Zhang, K. Arai, C. Belthangady, J.-C. Jaskula and R. L. Walsworth, *Selective addressing of solid-state spins at the nanoscale via magnetic resonance frequency encoding*, *npj Quantum Information* **3** (Aug., 2017) 1–8.

[41] M. Titze, *Focused Ion Beam Capabilities at the Sandia Ion Beam Laboratory.*, Nov., 2022.

[42] J. L. Pacheco, M. Singh, D. L. Perry, J. R. Wendt, G. Ten Eyck, R. P. Manginell et al., *Ion implantation for deterministic single atom devices*, *Review of Scientific Instruments* **88** (Dec., 2017) 123301.

[43] M. Titze, H. Byeon, A. Flores, J. Henshaw, C. T. Harris, A. M. Mounce et al., *In Situ Ion Counting for Improved Implanted Ion Error Rate and Silicon Vacancy Yield Uncertainty*, *Nano Letters* **22** (Apr., 2022) 3212–3218.

[44] *Neutron generators for analytical purposes.* Radiation technology reports. Internatinoal Atomic Energy Agency, Vienna, 2012.

[45] J. K. Shultis and R. E. Faw, *An MCNP primer*, 2011.

[46] A. K. Drukier, S. Baum, K. Freese, M. Górski and P. Stengel, *Paleo-detectors: Searching for dark matter with ancient minerals*, *Phys. Rev. D* **99** (Feb, 2019) 043014.