Snowmass 20201 Letter of Intent: Hidden Orders in Quantum Matter and Dark Matter Detection

Contact: A.Balatsky(Nordita/Uconn), balatsky@hotmail.com; Authors: Sang-Wook Cheong (Rutgers U), sangc@physics.rutgers.edu, J. Conrad (Stockholm U), conrad@fysik.su.se, Sinead Griffin (LBL, Berkeley), SGriffin@lbl.gov Rohit Prasankumar(Los Alamos), rpprasan@lanl.gov; N. Spaldin (ETH Zurich), nicola.spaldin@mat.ethz.ch

CF2 primary, IF1, TF10 secondary

Abstract. The nature of DM is one of the most pressing questions in contemporary fundamental physics. Contemporaneously, the rise of quantum materials reveals the gap in our understanding of HO. We propose an intertwined research forum connecting the search for answers to DM challenge and the discussion on the nature of quantum HOs.

State-of-the-art DM particle detectors use nuclear and electron recoil/excitation as their detection principle with sensitivity down to GeV masses. Next-generation detectors extend the sensitivity to sub-GeV masses by exploring the interaction with phonons, Dirac electrons and magnons in crystals. Here we discuss a new, unexplored route for dark matter (DM) detection using quantum materials with multiple orders. We explore extensions to the current DM paradigm: First the target responses of the material are hidden orders (HO), which appear with distinct responses to perturbations, and can potentially uncover the hidden 'quantum numbers' of dark matter. Second, we use the quantum advantage of coherent orders in materials (Avogadro scaling) making tabletop experiments feasible.

Coupling axion DM to hidden coupled orders in multiferroics is a new proposal for axion search in solid-state systems. This approach has the advantage of multiple coupling channels for DM impinging on the detector, can extend the sensitivity range down to even lower DM masses (meVs), and to potentially reveal hidden properties of DM. This allows us to evaluate coupling strengths, make suggestions for next-generation experiments, uncover new HOs, and design materials with enhanced responses. This research would gather expertise from across the fields of hidden orders, multiferroics and quantum materials, DM detection at a crucial time for designing next-generation DM experiments.

Background and Results. Despite comprising over 75% of the universe's mass-density, DM has so far escaped detection. This suggests that the nature of DM is fundamentally different from previous assumptions, and new DM detection ideas are needed.

Concurrent with DM developments has been the discovery of exotic orders in quantum materials. There, electrons arrange their charges or spins in ways that cannot be detected by conventional probes but that cause unexpected properties. Several examples of hidden orders (HO) are known and many more await discovery, including complex, composite, entangled or dynamical HOs [1]. Quantum materials have a rich space of coupled and hidden orders that are entirely unexplored for their interactions with DM.

We invite the community to develop discussions and collaborations at the intersection of **HO in quantum materials and the search for (hidden) DM**. Hidden orders imprint a particular entanglement, e.g. on magnetization M and polarization P modes that can be used to sense DM. Avogadro scaling of entangled HO states in materials is the quantum advantage we will pursue. We will i)discuss the search for quantum materials with suitable properties for DM detectors with the possibility of uncovering the unknown 'quantum numbers' of DM; ii)explore our newly proposed idea that the interaction of DM with materials could reveal new kinds of hidden order in materials that could not be detected by conventional probes [2]. The search of DM and search of novel HO are interconnected and reflect our growing understanding of the dark sectors both in quantum materials and in high-energy physics. . Previously, we identified how DM interacts with charge, spin and phonons in crystals [3-6]. However, DM interactions with HOs are entirely unexplored.

We recently developed the first ab initio description of DM-electron interactions, replacing the standard paradigm based on phenomenological interactions [2]. Our calculations showed that the rate at which DM can kick electrons out of atoms depends on four independent atomic responses, three of which have not been previously identified and are specific to DM. Our goal will be to set up a framework to analyze the behavior of these three new responses in real materials to determine what kinds of new hidden electronic orders they could reveal.

We also will discuss in this forum the ideas on applications of machine learning tools to identify materials with the desired properties (gaps, magnetization) for new HO materials for DM [7].

Ideas on the quantum materials -dark matter nexus and materials informatics were presented at Nordita workshops: Asia Pacific-Nordita meet https://tqmatter.org/asia-pacific-nordita-meeting-on-quantum-matter/, Quantum Materials for Dark Matter detection, https://indico.fysik.su.se/event/6660/.

Impact of this forum. This program enables: i)The establishment of a new concept of HO-based detection of DM, ii) Materials-specific estimates of new detection schemes for DM based on multiferroic crystals. This will allow us to evaluate their use as a next-generation detector for DM and potentially begin preparing for the construction of such a detector, iii) The optimization and development of multi-modal quantum sensors that couple to several orders at the same time. The design of such quantum sensors has applications outside of DM including quantum computing and post-CMOS electronics.

References

[1] G. Aeppli, A. V. Balatsky, H. Ronnow, and N. A.Spaldin, Nat. Rev. Mater. 5, 477 (2020),

[2] R. Catena, et.al, Phys. Rev. Res. 2, 033195 (2020),

[3] Y. Hochberg, S. Griffin, et al , Phys. Rev. D 97,015004 (2018),

[4] S. M. Griffin, et al, Phys. Rev. D 98, 115034 (2018),

[5] S. M. Griffin, et.al., Phys. Rev. D 101, 055004(2020),

[6] K. Inzani, A. Faghaninia, and S. M. Griffin, arXiv arXiv:2008.01075 (2020),

[7] R.M. Geilhufe, et.al , Phys. Stat. Sol. RRL 12, 0293 (2018).