Snowmass2021 - Letter of Interest

The TESSERACT Dark Matter Project

Thematic Areas:

- IF1 Quantum Sensors
- IF8 Noble Elements
- CF1 Dark Matter: Particle-like
- CF2 Dark Matter: Wavelike

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Abstract:

The TESSERACT project will search for individual galactic DM particles below the proton mass through interactions with advanced, ultra-sensitive detectors. Currently TESSERACT is in a design phase aiming to produce fully defined experiments (dubbed HeRALD and SPICE) that will explore DM mass parameter space down to 10 MeV, with upgrade paths to sub-MeV. It will be sensitive to both nuclear recoil DM (NRDM) and electron recoil (ERDM). An initial period of targeted R&D is needed to make technical choices and retire technical risks, leading to a well-defined set of design parameters with baseline values.

Multiple target materials will be used, sharing identical readout. In addition to maximizing sensitivity to a variety of DM interactions, this provides an independent handle on instrumental backgrounds. The HeRALD experiment will use superfluid helium as a target material. Helium, with its light mass, has good NRDM sensitivity, but minimal sensitivity to low-mass dark photons. The SPICE experiment will use polar crystals, which will ultimately have the best sensitivity to dark photon mediated DM, but require lower energy thresholds than LHe for the same NRDM reach. Scintillating crystals such as GaAs have sensitivity to ERDM with kinetic energy greater than the electronic bandgap of the material.

Project overview: The "Basic Research Needs for Dark-Matter Small Projects New Initiatives" report [1] reviews the strong theoretical motivation for searching for particle Dark Matter (DM) in the mass range below the proton mass, continuously down to small fractions of an eV. Elucidating the nature of DM is one or the most compelling problems of high energy physics, as identified in the P5 roadmap.

The TESSERACT (Transition Edge Sensors with Sub-EV Resolution And Cryogenic Targets) project will consist of a liquid helium (LHe) experiment (HeRALD), as well as GaAs and Sapphire-based experiments (SPICE), read out by Transition Edge Sensor (TES)-based phonon sensor technology sensitive to phonon, roton, and light signals from LHe, phonon and light signals from GaAs, and phonon signals from sapphire. This project ultimately seeks to detect collective excitations from DM interactions in both superfluid helium [2, 3] and a polar target [4] in addition to searching for ERDM on low bandgap scintillator [5]. The total mass for each target type is between 100 g and 1 kg, but segmented into multiple small pixels with independent readout. The multiple targets will be instrumented with identical sensors and readout technology. This commonality provides a powerful tool to assess backgrounds and systematics, and also simplifies the design and construction, allowing the use of multiple targets with minimal extra effort. TESSERACT is funded for a project planning phase under the DOE Dark Matter New Initiatives program.

The absence of electric fields is a hallmark of TESSERACT. Most detector and readout technologies use E-fields to either amplify (photomultiplier tubes, 2 phase TPC, etc.) or to drift an electronic signal (semiconductor ionization detectors, TPC). Unfortunately, E-fields necessarily cause backgrounds, if nothing else then by quantum mechanical tunneling of electrons. Such "dark count" or "dark current" backgrounds currently limit to some extent all ERDM searches [6, 7, 8, 9]. By having zero E-field we avoid such backgrounds, but require higher sensitivity detectors. Said a different way, extremely low noise detectors enable operation without an E-field.

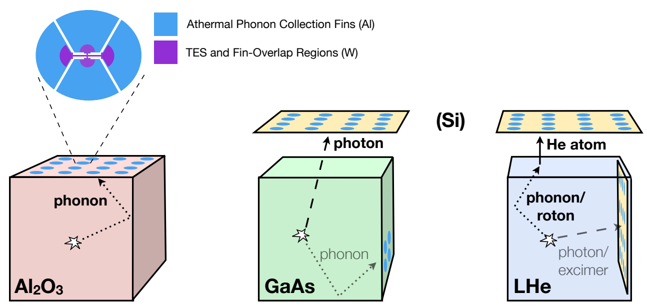

FIG. 1: Conceptual schematic of the target materials and signal pathways. Three target materials are used (Al_2O_3, GaAs, and LHe), with complementary DM sensitivity.

The target mass will be composed of cm^3 scale identical replicas (see Fig. 1), each with its own cm^2 scale athermal phonon sensor array that is fabricated directly on the surface of crystal targets, or on 1 mm-thick Si substrates that collect photon and quantum evaporation signals from scintillator or LHe targets. This signal energy is converted into athermal phonons in the 1 mm-thick Si and measured.

The athermal phonon detector principle uses a 2-step process. First, phonons from the crystal are collected with superconducting Al fins fabricated on the surface. In these fins, the phonon energy is converted into quasi-particle energy (by breaking Cooper pairs). Second, these quasi-particles then diffuse into an attached small volume Transition Edge Sensor (TES), where the energy is thermalized and measured. Only a small fraction of the crystal surface is instrumented because the energy resolution scales with the number of TES sensors within the array (the total TES volume). The small coverage means that most athermal phonons will reflect off un-instrumented crystal surfaces many times before being collected. This places strict requirements on the probability of athermal phonon thermalization on bare crystal surface. Thus, crystal surface treatment is very important for collection efficiency. A technology based on *athermal* phonon collection will be more sensitive than any *thermal* sensor technology, assuming the phonon sensor bandwidth is appropriately matched to the athermal collection time.

LHe targets will be read out using the detectors built on 1 mm-thick Si as depicted in Fig. 1. Details of the proposed experimental setup specific to LHe, and evaluation of expected science can be found in [10]. The LHe is held in a passive container, and an active volume within is enclosed with detectors submerged in the liquid and above the liquid. Energy deposited in the LHe can be partitioned into multiple excitation modes, including light as well as phonons/rotons. The detector suspended above the LHe surface will detect quantum evaporation signals. In this mechanism, a photon or roton ejects a He atom from the liquid surface into the vacuum above, which is almost perfect due to the extremely low vapor pressure of He-4. When the He atom lands on the surface of the suspended detector it releases heat of adsorption which exceeds the energy that went into ejecting it from the fluid. This is therefore a gain mechanism. This readout mechanism would not only work for a LHe target, but can be applied by coating the surface of any solid target with He.

Scintillating crystal targets will produce light in addition to phonons, and the crystal scintillation mode is sensitive to ERDM. The detectors built on 1 mm-thick Si serve as zero dark count photodetectors. Incident photons will be absorbed in the Si, producing phonons.

The experiments will require support, cooling, control and readout, shielding and veto, and calibration. R&D is needed to optimize detector performance, investigate veto technology and to establish the most suitable calibration methods. The underground siting of the experiments will influence final design.

Scientific Reach: The experiments will have sensitivity to both nuclear recoil DM (NRDM) and electron recoil (ERDM) interactions. DM parameter space sensitivity for NRDM (ERDM) is given for 100 g-yr (1 kg-yr) exposure at an underground site. Sensitivity projections assuming present technology (solid lines) and assuming baseline goals (dashed lines) are shown in Figure 2. These sensitivities show the power of a low-threshold TES-based sensor, and they make clear the useful complementarity between the three target materials' various sensitivities. GaAs exhibits efficient scintillation and lack of dark counts, enabling interesting electromagnetic sensitivities at the photon energy scale and above. LHe posseses a low-mass target nucleus, enabling interesting NR sensitivities at 1 MeV and above, along with phonon modes that enable direct phonon excitation at lower masses. In addition to the relatively light O nucleus, Al_2O_3 exhibits a highly polar unit cell, with numerous optical phonon modes extending to $\sim$100 meV, enabling interesting sensitivities at the lowest energies.

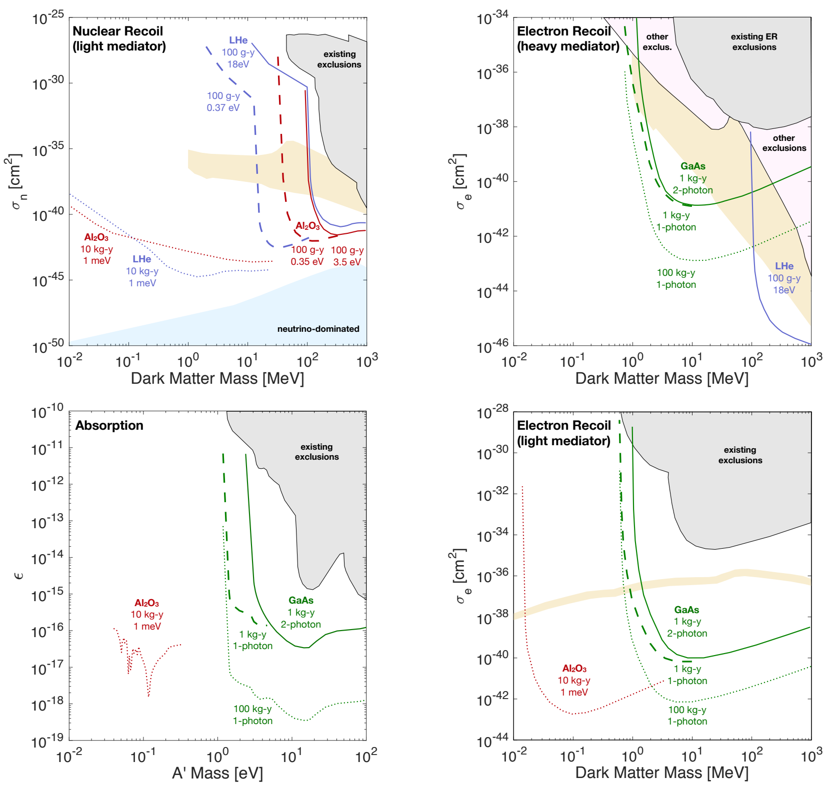

FIG. 2: Sensitivity projections for the target materials and TES sensitivities described here. Interaction type is listed in the top left corner of each plot. Grey and pink regions have already been excluded, light orange regions indicate model regions of interest, and the light blue region indicates parameters for which solar neutrino coherent nuclear scattering will dominate the nuclear recoil rate. Sensitivity curves come in three stages: Solid curves assume current technology (based on a TES with 40 meV baseline resolution), dashed curves assume the baseline goals, and dotted lines describe some future 'ultimate' experiment for each technology.

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