Snowmass2021 - Letter of Interest

A Scintillating n-type GaAs detector for sub-GeV Dark Matter Direct Detection

Thematic Areas:

■ (CF1) Dark Matter: Particle Like
■ (Other) *[IF1:Quantum Sensors]*

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Abstract: Sub-GeV dark matter can interact with electrons or nuclei in a n-type gallium arsenide (GaAs) target suitably doped with silicon and boron and produce 1.33 eV scintillation photons. These photons can be detected with a sensitive photodetector such as a Transition Edge Sensor (TES) or a Superconducting Nanowire Single-Photon Detector (SNSPD). This detection concept could be successfully realized with a high-mass ($>$10 kg) target and thus probe smaller interactions between dark and ordinary matter than many other existing or proposed efforts to probe sub-GeV dark matter. In particular, no dark counts are expected, since the GaAs target has no afterglow and the 1.33 eV photons are naturally produced and easily measured without the need of an amplification mechanism (such as electric fields). We discuss the detection concept, the R&D required to realize this detection concept, and our plans.

1 Introduction and Physics Goals

A wide array of dark matter (DM) direct-detection ideas have been put forward to search for sub-GeV DM, see e.g.[1–4] and references therein. Here we highlight the role a scintillating n-type gallium arsenide (GaAs) target suitably doped with silicon and boron, coupled together with a sensitive photodetector such as a Transition Edge Sensor (TES) or a Superconducting Nanowire Single-Photon Detector (SNSPD), can play in this search. Such a detector could probe DM-electron scattering for DM masses above $\sim$1 MeV[5;6], bosonic DM (dark photons, scalars, and axionlike particles) being absorbed by electrons for DM masses down to $\mathcal{O}$(eV)[7], DM-nucleus elastic scattering for masses $\gtrsim$100 MeV, and DM-nucleus scattering via the Migdal effect[8;9] for masses $\gtrsim$1 MeV. The potential sensitivity of such a search for DM-electron scattering is shown in Fig. 1.

N-type GaAs(Si,B) produces scintillation photons when (1) an electronic excitation event leaves one or more holes in the valence band that are (2) trapped by acceptor atoms and (3) radiatively recombine with n-type donor band electrons. Preliminary studies show that the concentrations of n-type electrons, boron acceptors, and silicon complex acceptors are important in maximizing the luminosity and minimizing the trapping of valence band holes on non-radiative centers.

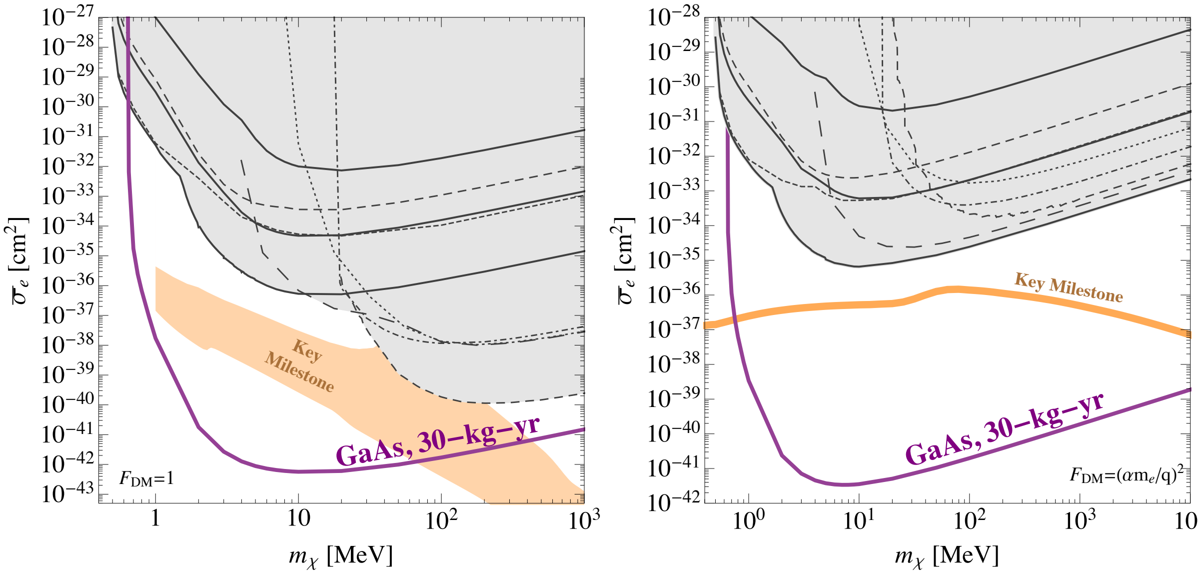

Figure 1: Projected sensitivity (thick magenta line) to dark-matter-electron scattering mediated by a heavy mediator (**left**) or light mediator (**right**) of a GaAs target assuming a 30 kg-year exposure. We assume zero background events for events with one or more photons, a radiative efficiency of 1, and a photon detection efficiency of 1. Existing constraints are shown in gray from SENSEI, DAMIC at SNOLAB, XENON10, XENON100, XENON1T, DarkSide-50, EDELWEISS, and CDMS-HVeV[10–21]. Orange regions labelled "Key Milestone" are from[4].

2 Status and Required R&D

2.1 Gallium Arsenide Target Properties

N-type GaAs suitably doped with silicon and boron is a luminous cryogenic scintillator[22;23] and has several properties that make it an excellent target for detecting sub-GeV DM:

- There are no naturally occurring radioactive isotopes of Ga or As.
- N-type GaAs is commercially grown as 5 kg crystals.

- The donor electrons do not freeze out above a free-carrier concentration of 8×10^{15}/cm^{3}[24].
- Metastable radiative centers that could cause afterglow are annihilated by delocalized donor electrons, as evidenced by the lack of thermally stimulated luminescence[22].
- Luminosities >100 photons/keV are observed without anti-reflective coatings.

Additional R&D and measurements are needed both to optimize the silicon and boron doping levels in the GaAs and to measure precisely the luminosity.

2.2 Photodetectors

The photodetectors must be able to measure 1.33 eV photons with negligible dark counts. Two natural possibilities are TES and SNSPD detectors. Their current status and the required R&D for realizing a large-mass GaAs DM detector are:

- **Transition Edge Sensors.** Very large area (45 cm^2) cyrogenic photo detectors readout with TES based athermal phonon sensors have already achieved a measured 4 eV (σ_E) sensitivity[25]. Since $\sigma_E \propto \sqrt{A}$, where A is the total instrumented area, this suggests that 600 meV resolutions in 1 cm^2 detectors is already achievable. Additional improvements in the athermal phonon sensor design (lowering TES T_c, optimizing sensor geometry to improve athermal phonon collection efficiency) would allow one to further improve sensitivity and increase the instrumented area per channel past 1 cm^2.
- **Superconducting Nanowire Single-Photon Detector.** SNSPDs are the most advanced detectors available for time-resolved single photon counting from the UV to the infrared. They have demonstrated system detection efficiency as high as 98% at 1550 nm,[26] timing jitter below 3 ps,[27] energy thresholds as low as 0.125 eV, and dark count rates on the order of 10^{-5} cps. SNSPDs have recently been demonstrated with mm-scale active areas, and typically have operating temperatures between $1-4$ K. To support large-scale DM searches using GaAs targets, the active area of SNSPDs must be scaled to cm^2 and beyond. This will require the development of new fabrication processes and techniques, and new on-chip multiplexing techniques, which allow the combination of signals from many nanowire sensor elements onto a single readout line.

The two proposed readout concepts (TES based athermal phonon sensors and SNSPDs) have vastly different susceptiblities to potential backgrounds and are thus complementary. Athermal phonon sensors are fundamentally sensitive to athermal phonons produced not only by photon absorption, but also by stress induced microfracture events and frictional rubbing with the mechanical support structure. To minimize these sources of environmental backgrounds, R&D is currently ongoing to suspend the devices from a double mass suspension system. As an additional protection against spurious dark counts, the GaAs crystal will also be instrumented with athermal phonon sensors; only events with coincident signals in both the GaAs and Ge photon detector would be indistinguishable from a DM interaction.

By contrast, SNSPDs have minimal sensitivity to spurious athermal phonons, since they are absorbed non-locally, while the absorption of a photon produces an extremely localized energy deposition that causes the SNSPD to transition. Thus, SNSPDs are not sensitive to potential phonon background sources. On the other hand, an SNSPD setup would not have a coincident athermal phonon signal on the GaAs target. As such, spurious single photon events, produced by very high energy photons travelling across an interface[28] or from higher energy nuclear recoils. It may be possible to mitigate such backgrounds by using multiphoton coincidence counting.

3 Plans

Several R&D steps are necessary to realize this detection concept:

- Optimize GaAs crystal size, surface roughness, and dopant density to maximize photon production and collection in the sensor.
- Athermal Phonon Sensor: Implement suspension system to supress environmental vibrations.
- Athermal Phonon Sensor: Improve sensitivity by decreasing TES T_c and optimizing sensor geometry.
- SNSPD: increase active area from 1 mm^2 to 1 cm^2.

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