Physics Letters B 785 (2018) 386–390

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Detection of light dark matter with optical phonons in polar materials

Simon Knapen [a,b,*], Tongyan Lin [a,b,c], Matt Pyle [d], Kathryn M. Zurek [a,b]

[a] Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States of America
[b] Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, United States of America
[c] Department of Physics, University of California, San Diego, CA 92093, United States of America
[d] Department of Physics, University of California, Berkeley, CA 94720, United States of America

ARTICLE INFO

Article history:
Received 22 May 2018
Received in revised form 7 August 2018
Accepted 8 August 2018
Available online 31 August 2018
Editor: A. Ringwald

ABSTRACT

We show that polar materials are excellent targets for direct detection of sub-GeV dark matter due to the presence of gapped optical phonons as well as acoustic phonons with high sound speed. We take the example of Gallium Arsenide (GaAs), which has the properties needed for experimental realization, and where many results can be estimated analytically. We find GaAs has excellent reach to dark photon absorption, can completely cover the freeze-in benchmark for scattering via an ultralight dark photon, and is competitive with other proposals to detect sub-MeV dark matter scattering off nuclei.

© 2018 Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP³.

1. Introduction

The scope of dark matter (DM) searches in recent years has dramatically broadened beyond traditional candidates such as the weakly interacting massive particle (WIMP) and axion. Theoretically compelling candidates exist in hidden sectors consisting of DM and new light mediators, with numerous mechanisms for setting the DM relic density. These models have motivated a suite of new direct detection experiments, aimed at sub-GeV DM. SuperCDMS [1–3], DAMIC [4], SENSEI [5], NEWS-G [6] and CRESST [7] are working to detect energy depositions as small as an eV from scattering of MeV mass DM, or absorption of eV mass DM. There are also proposals for eV-scale detection with *e.g.* atoms [8], graphene [9], liquid helium [10], scintillators [11], molecular bonds [12], and crystal defects [13,14].

For DM in the 10 keV–GeV mass range, freeze-in DM interacting with an ultralight dark photon [15–19] or asymmetric dark matter [20–22] are compelling candidates. Freeze-in selects a clear target for the scattering rate, while there is also a wide parameter space of asymmetric DM. Other viable DM candidates below an MeV include DM scattering through a light scalar mediator coupled to nucleons [23,24]. In the meV–eV mass range, dark photon DM can be absorbed in the same experiment.

To be sensitive to such light DM, a target must have a sufficiently small gap to excitations, as well as favorable kinematics for DM scattering. The first proposals included detecting sub-MeV DM scattering off electrons with a superconducting target [25,26], and off nuclei in superfluid helium [27,28]. In these cases, the sensitivity to DM scattering via an ultralight dark photon was limited due to the strong in-medium screening in superconductors, and due to the limited polarizability in superfluid helium. Dirac materials have an excellent reach for this scenario [29] but such materials have not yet been produced in the quantities needed for direct detection.

In this *Letter* we argue that polar materials are an excellent target for sub-MeV DM, especially for scattering through an ultralight dark photon mediator. There are four reasons for this: first, these materials feature gapped optical phonons which can be thought of as oscillating dipoles. These dipoles have a sizable coupling to kinetically mixed dark photons; furthermore, the suppression from screening effects is much smaller than in other materials such as superconductors. Second, optical phonons are gapped excitations with typical energies of ~ 30 meV up to ~ 100 meV. This is kinematically favorable for sub-MeV DM, allowing $\gg$ meV energy depositions with low momentum transfer. Third, the anisotropy of the crystal induces a directional dependence in the DM scattering rate. Finally, similar to germanium and silicon, the technology already exists to make ultra pure polar materials in bulk.

Here we show that GaAs exhibits all of these features, with excellent sensitivity to scattering through dark photon and scalar mediators, as well as to dark photon absorption. Furthermore, GaAs has a relatively simple crystal structure, such that many results can be estimated analytically. In a future paper, we will explore sap-

* Corresponding author.
E-mail address: smknapen@lbl.gov (S. Knapen).

https://doi.org/10.1016/j.physletb.2018.08.064
0370-2693/© 2018 Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP³.

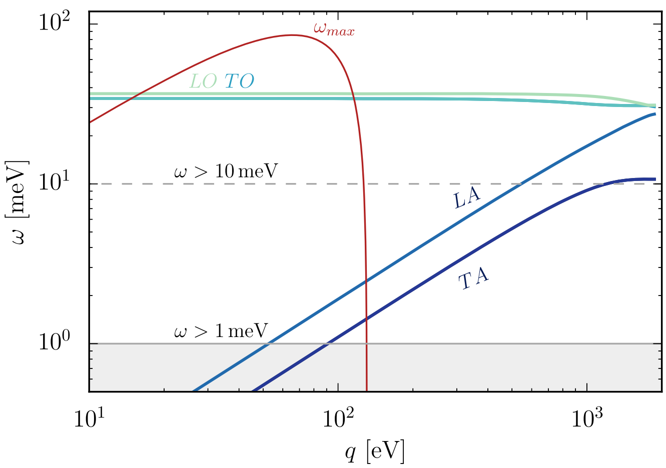

Fig. 1. Phonon modes in GaAs for **q** vectors along the direction from $\Gamma = (0, 0, 0)$ to $X = (0, 2\pi/a, 0) \approx (0, 2.21, 0)$ keV, calculated with QuantumESPRESSO [32]. For a representative DM mass $m_X = 25$ keV, we show the maximum energy deposited $\omega_{\max}$ as a function of momentum transfer q. Also shown are two possible experimental thresholds, $\omega > 1$ meV and $\omega > 10$ meV.

phire (Al_2O_3), where the more complex crystal structure is more suitable for directional detection [30].

2. Optical phonons in polar materials

Optical phonons arise when there is more than one atom per primitive unit cell of a crystal. For GaAs, with two atoms in the primitive cell, the phonons consist of two transverse acoustic (TA) modes, one longitudinal acoustic (LA) mode, and similarly two transverse (TO) and one longitudinal (TO) gapped optical modes. Given a model for the effective ion–ion potential, the phonon frequencies are derived by solving a coupled set of differential equations for the ion displacements in the primitive cell (see e.g. [31]): the acoustic modes have a linear dispersion $\omega \propto q$ as $q \to 0$, while the optical modes have non-zero frequencies $\omega_{\text{LO,TO}}$ as $q \to 0$. The acoustic (optical) modes describe oscillations where the ion displacements are in phase (anti-phase) in the $q \to 0$ limit. The dispersions of all phonons in GaAs are shown in Fig. 1; we see that the typical momentum transfers allowed for light DM, in combination with the experimental threshold, greatly reduces the phase space for scattering off acoustic modes but not for optical modes.

The presence of optical phonons is not sufficient for coupling to dark photons. If the atoms in the unit cell are identical (such as in Si or Ge), there is no net polarization associated with optical phonon oscillations. Instead, in GaAs the ions have net Born effective charges of ± 2.1 [33], resulting from the polar GaAs bond. The out-of-phase displacements of the optical mode therefore give rise to coherently oscillating dipole moments, which generate long-range dipole fields. This allows a coupling of the LO phonons to charged particles, including conduction electrons as well as DM coupled to an ultralight dark photon mediator, where in the latter case the DM effectively carries a tiny electric charge. Combined, the gapped dispersion and the dipole moment for optical phonons are crucial for polar materials to be effective targets for scattering and absorption of light DM.

The optical phonons also contribute to the optical response for energies below the electron band gap ω_g, which is an important quantity in determining the sensitivity of a target to dark photon interactions. For $\omega < \omega_g$, the permittivity of GaAs can be written as [34]

$$\hat{\epsilon}(\omega) = \epsilon_\infty \frac{\omega_{\text{LO}}^2 - \omega^2 + i\omega\gamma_{\text{LO}}}{\omega_{\text{TO}}^2 - \omega^2 + i\omega\gamma_{\text{TO}}}, \tag{1}$$

where $\gamma_{\text{TO,LO}}$ are damping parameters and ϵ_∞ is the contribution of the electrons for $\omega < \omega_g \approx 1$ eV in GaAs. This result can be generalized in a straightforward way to polar materials with more optical phonon branches, by including a product over the different branches. Note that the dielectric function becomes close to zero at $\omega = \omega_{\text{LO}}$: this reflects the fact that an LO phonon may be present in a material even without a driving external field [33].

The permittivity determines the screening of electric (and dark photon) fields, with $\epsilon_0 \equiv \hat{\epsilon}(0)$ the usual dielectric constant. We use measured values of the GaAs phonon frequencies and damping constants at $T = 4.2$ K [35], appropriate for a cryogenic experiment. In general $\hat{\epsilon}(\omega)$ is an O(1) number, *without* the strong screening that is typically present for free charges. Thus sensitivity to dark photon interactions is achieved due to the possibility of coupling to the polarizability and due to the relatively mild screening.

3. Experimental concept

The success of polar materials for light DM searches requires the development of detection technology that can trigger on 30 meV–100 meV of vibrational excitations with minimal dark count rate. Traditional semiconductor and scintillation sensor techniques are not feasible since the energy depositions are below the electron excitation energies. Likewise, traditional low temperature calorimeters, where phonons are allowed to fully thermalize within the target before measurement in the temperature sensor, are not practical because the coupling of $\mathcal{O}(10$ mK) phonons to the electronic system of the thermometer is extremely poor. One would need very large volume and heat capacity thermal sensors, which have large thermal noise [36].

Consequently, only detector concepts wherein athermal phonon excitations are collected and sensed before thermalization are viable. One option is to absorb athermal phonons into a few-monolayer thick layer of superfluid He film on the target surface, which leads to evaporation of a He atom with some probability. These evaporated He atoms could then be either absorbed onto the bare surface of a small volume calorimeter (depositing both the kinetic energy and the binding energy of the He atom [37,38]) or ionized with large E-fields near a sharp metal tip and subsequently accelerated onto a calorimeter (depositing the total electrostatic potential energy [39]).

A second possibility is to instrument the surface of a polar absorber with athermal phonon sensors [40,41], which have been employed by CDMS and also proposed for superconducting DM detectors [26]. High energy phonons produced by DM interactions quickly decay anharmonically into $\mathcal{O}(10^2)$ acoustic phonons with energies around $\mathcal{O}$(meV). At this energy scale, both isotopic scattering and anharmonic decay timescales become long [42] compared to travel times across the crystal. The athermal phonons are thus either thermalized via surface down-conversion processes or collected by superconducting collection fins; in the latter case they produce quasiparticles which are detected in a small volume (and thus sensitive) Transition Edge Sensor (TES) or Microwave Kinetic Inductance Device (MKID).

Clean, well-polished crystal surfaces have been shown to have an athermal phonon surface thermalization probability of less than 10^{-3} at 10 mK [43], so only a small fraction ($< 1\%$) of the total detector surface area must be instrumented to collect nearly all athermal phonons. Conceptually, this allows for O(1–10 meV) sensitivity with a 125 mm^3 absorber volume as shown in [26].

Radiogenic backgrounds (Comptons, ^{3}H, ^{210}Pb decay products) have typical energy scales that are much larger than the energies

Download English Version:

https://daneshyari.com/en/article/10136715

Download Persian Version:

https://daneshyari.com/article/10136715

Daneshyari.com