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Sub GeV DM-Nucleon Scattering via Collective Excitations: The Inelastic Regime.

Thematic Areas:

■ (CF1) Cosmic Frontier: Dark Matter: Particle Like
■ (TF9) Theory Frontier: Astro-particle physics and cosmology

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Abstract: The existing theoretical formalism to calculate differential scattering rates for the direct detection of dark matter (DM) scattering with nucleons fundamentally relies on the single-particle (or isolated atom) treatment of detector nuclei. This treatment is valid in semiconductors for momentum transfers much larger than 1 MeV, but breaks down for sub-GeV DM which cannot elastically provide enough energy to displace a nucleus. In this regime, elastic scattering signals, especially in detectors measuring ionization, become strongly suppressed to the point where inelastic scattering can produce a stronger signal. We argue that theoretical and experimental developments are needed to properly model detector response to nuclear recoils in this *inelastic regime* in order to fully understand detector sensitivity to sub-GeV DM.

Dark matter (DM) scatters with nuclei in three kinematically distinct regimes. The standard formalism of direct detection, on which all of the G2 particle dark matter experiments are based, treats the nucleus as a free particle and the scattering as elastic[1]. This *elastic regime* picture is valid for DM much heavier than 1 GeV, where both the energy and momentum transfer are large compared to any relevant atomic or molecular scales. In recent years, the low-energy *phonon regime*, where DM scattering is best described through the collective oscillation of many nuclei in a solid or superfluid, has been identified as a promising direction to search for sub-MeV DM[2]. Since phonon energies are at the meV scale and can in principle extend to arbitrarily low energy, more sensitive detectors with lower thresholds will always uncover new parameter space, and the theoretical treatment is on solid footing because it concerns the energy scales well-studied in condensed matter physics. However, the *inelastic regime*, with energy transfers at the $1 - 100$ eV scale and momentum transfers at the $\sim 10\,\mathrm{keV} - 10\,\mathrm{MeV}$ scale, are not well described by treating the nucleus as a free particle nor as part of a long-wavelength oscillation, because the energy deposits are comparable to lattice displacement and/or the ionization energies and momentum transfers are comparable to the inverse lattice spacing (or Bohr radius). This is precisely the kinematic regime relevant for MeV$-$GeV-mass DM, and thus nuclear scattering in the inelatic regime requires a qualitatively new formalism where many-body effects are accounted for from the beginning. Furthermore, these kinematics are maximally distinct from existing calibration experiments, being too high-energy for thermal neutrons and too low-energy for neutrons from radioactive decay, for example. As such, very little data exists to guide theoretical predictions.

In the past few years, significant effort has been made to extend the existing formalism for elastic scattering to inelastic scattering of sub-GeV DM. A key step was the rediscovery of the Migdal effect[3] and its relevance for DM scattering. The Migdal effect is a form of inelastic scattering where a hard scattering event with an atomic nucleus can result in some of the energy and momentum transfer to be given to the (kinematically favorable) electronic system through the coupling between the nucleus and the atomic electrons. Many efforts have been made to expand and improve on Migdal's original anlysis[4–11], concluding in a reasonably accurate theoretical prediction for differential scattering in noble liquids which can be directly calibrated with photoabsorption data[12]. In parallel, efforts have been made to extend this formalism to semiconductors[11], correctly accounting for the delocalized electrons, but still assuming a free and isolated nucleus as the scattering target.

However, at the energy and momentum scales relevant for the inelastic regime, treating a condensed matter system as consisting of isolated nuclei with single-particle electron wavefunctions misses several important qualitative and quantitative effects. One such effect which should become relevant at $\mathcal{O}(10)$ eV energy deposits is a collective resonance in the dielectric function known as the plasmon[13;14]. The plasmon is a well-studied effect in condensed matter systems, generic to all ordered crystals, and can be observed with electron energy-loss spectroscopy[15] or X-ray scattering experiments[16]. Notably, these measurements only observe the scattered probe, and thus are agnostic to the eventual fate of the energy and momentum *deposited* into the plasmon mode (i.e. into ionization or phonons). Simple models of direct excitation of the plasmon through electron scattering indicate that, for large momentum transfers (on the scale of the inverse lattice spacing), the plasmon should decay effectively to ionization due to Landau damping[17;18]. To the best of our knowledge, no measurement or theoretical modeling of the plasmon resonance exists in the condensed matter literature for the low momentum transfer regime relevant to sub-GeV DM, where the plasmon could decay anharmonically to phonons. Furthermore, the assumption of free nuclei must break down at the scale of the displacement energy, typically $\mathcal{O}(10 - 20)$ eV in silicon and germanium. This affects not only the spectrum of the primary scattering process, but also secondary processes where the recoil energy is converted to ionization and phonons, which are the end-stage detector signals. Existing calibration data[19–22] are on the verge of probing this regime, but do not yet constrain any theoretical models.

Current Status

A wide-ranging and creative theoretical program has already made substantial progress in the last year towards identifying effects in solid-state detectors in the inelastic regime which are invisible in the elastic and phonon regimes, but a complete picture is still missing. The first calculation of the Migdal effect in semiconductors which incorporates the valence electron band structure was performed in Ref.[11], but phonon contributions were not included. Ref.[23] proposed the first mechanisms for plasmon excitation through DM scattering, but rates were only computed at the order-of-magnitude level and a full calculation is lacking. Ref.[24] improved this work by developing a quantitative theory for plasmon emission, modeling the recoiling ion as a free particle. This calculation gives an excellent representation of coupling to the plasmon for sufficiently large energy transfers, but breaks down in the direct multi-phonon regime where the final state of the scattered nucleus is not well-described by either a free ion nor a single phonon. In the same vein, Ref.[25] presents a tour-de-force unified formalism of DM excitation of electronic and nuclear channels (see also Refs.[26;27]), but the analysis explicitly excludes momentum transfers of $\mathcal{O}(100)$ keV where multi-phonon production dominates.

Theoretical and Experimental Goals

Given the proliferation of semiconductor detectors searching for sub-GeV DM, it is imperative to fully understand the collective effects which contribute to both the primary DM scattering event and the end-stage readout in the inelastic regime. Recent detector advances in low threshold calorimeters[28;29] and ionization detectors[30–34] have allowed substantial access to this energy regime for this first time. Indeed, DM searches with these detectors have all revealed excesses over radiogenic backgrounds that are superficially consistent with the spectral expectation from inelastic effects despite different levels of shielding, overburden, and detector readout[23]. The similarity of these excess event profiles with either inelastic nuclear scattering or detector effects clearly motivates better understanding and modeling of low-threshold detectors.

In order to properly understand detector response to sub-GeV DM, it is imperative to foster *collaboration between condensed matter physicists and particle physicists* to bridge the gap between these respective energy regimes, and perform *dedicated calibration experiments which probe the energy and momentum transfers relevant for MeV-GeV DM and which can be compared to theoretical predictions*. While e.g. photoabsorption data can (and has) been used to calibrate dark photon absorption in condensed matter detectors[30;35–37], we emphasize that no calibration data exists for solid-state detectors which can be applied to sub-GeV DM scattering off nuclei, and no existing calculation takes into account all relevant effects in this energy regime. For example, it is unknown whether the plasmon resonance may be excited by nuclear scattering, and the energy spectrum of direct multi-phonon production is likewise unknown.

Consequently, it is important that direct detection efforts work in collaboration with theorists to extend existing nuclear and electron recoil calibrations down to lower energies. This includes, at a minimum, applying some of the techniques that have been developed in the past decade with lower threshold detectors exhibiting improved resolution, including photoneutron sources[19;21;38], backing detectors[22;39], color centers[40], and neutron capture[20]. Existing calibrations with semiconductor detectors already observe significant deviation from the Lindhard prediction[41], which should have been expected since Lindhard's original work states "a discussion of quite low energies of heavy particles, less than 100 eV say, is either unnecessary or may be made separately"[42]. Indeed, the lack of calibration data and theoretical modeling in the regime relevant to sub-GeV DM at the time of Lindhard's work is unsurprising, since no Standard Model probe has the same dispersion relation as sub-GeV DM and the evidence for DM itself was certainly not unambiguous. Revisions to Lindhard's model have only recently been made accessible through theoretical and experimental advances, and the time is ripe to continue the progress to even lower energy scales.

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