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Light dark matter detection: new ideas and new tools

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Abstract. We discuss possibile ways to probe dark matter in the keV to GeV range with direct detection experiments.

1 Introduction

There is today overwhelming evidence that the majority of matter in the Universe is dark matter, feebly interacting with ordinary matter. Despite the crucial role it plays in our understanding of the Universe, we still know very little about its nature. In particular, its possible mass ranges over more that sixty orders of magnitude. Following stringent constraints on heavy WIMPs [e.g., 1–5], there is now increasing interest in models for sub-GeV dark matter [e.g., 6–8], motivating new detection ideas. In particular, dark matter candidates in the keV to GeV range cannot release appreciable energy via standard nuclear recoil, and thus require detectors with low energy thresholds, such as semiconductors [e.g., 10–12], superconductors [e.g., 13–15], lower dimensional materials [e.g., 16, 17], and so on [e.g., 18–20].

Here we focus on some possible ways to push the sensitivity of direct detection experiments down to masses of order keV. Specifically, for the range 1 MeV $\lesssim m_\chi \lesssim$ 1 GeV, we discuss the so-called Migdal effect in semiconductors [21–24]. For the range 1 keV $\lesssim m_\chi \lesssim$ 1 MeV we, instead, discuss signatures involving phonons in superfluid ^{4}He [e.g., 25–32] or magnons in anti-ferromagnetic materials [33]. We describe the processes above using effective field theory (EFT) methods, which allow to bypass some difficulties encountered in the more traditional approaches, and simply the theoretical treatment.

2 MeV to GeV: Migdal effect in semiconductors

Semiconductors, like Si or Ge, have bandgaps of the order of a few eV, making them promising targets to hunt for dark matter particles as light as an MeV. When the dark matter couples mostly to the nuclei, it can promote an electron from the valence band to the conduction one via the Migdal effect: the dark matter interacts with a nucleus, which in turns interacts with the electrons through lattice excitations. Computing the rate for this event in a realistic material is complicated by the many-body, strongly interacting dynamics of both nuclei and electrons. So far, the problem has been treated under some simplifying approximations, namely the impulse [21] and harmonic [22, 23] ones. The former is reliable for $m_\chi \gtrsim 50$ MeV, while the latter for $m_\chi \simeq 1$ MeV. It is necessary to develop a formalism for the general description of the phenomenon, which allows for sound predictions for all dark matter masses.

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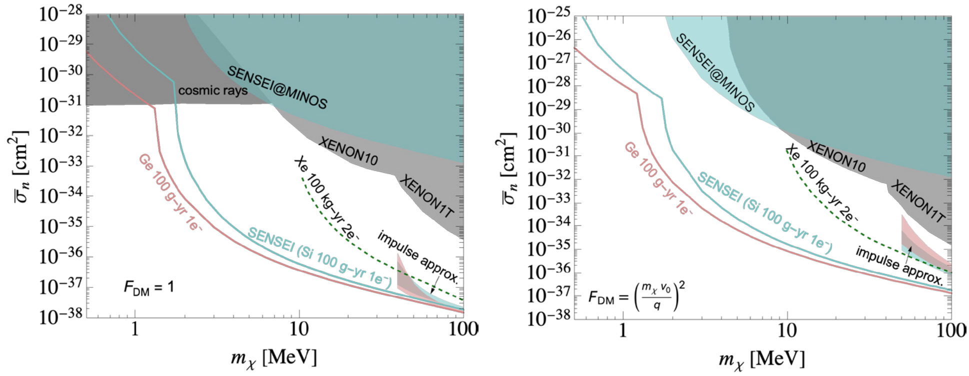

Figure 1. Projections for the dark matter–nucleon cross section using the Migdal effect at 90% C.L., assuming an exposure of 100-g-year of both Si (**cyan**) and Ge (**red**). In both cases, we assume a detector sensitive to single electrons excitations, as well as zero background. For details see [24].

As noticed in [24], the problem at hand is charachterized by a separation of scales: the energy of the Migdal electron is O(eV), much larger than the typical energy of the excitations of the crystal, which is $O(1 - 100\ \text{meV})$. This allows to bypass the complicated description of the crystal dynamics by writing a low energy EFT, which describes the Migdal emission by the dark matter via the following effective Hamiltonian [24]:

$$H_{\text{eff}} = \frac{1}{m_{\text{N}}\omega^2} \nabla H_{\chi\text{L}} \cdot \nabla H_{e\text{L}} + O\left(1/\omega^3\right), \tag{1}$$

where ω is the energy of the outgoing Migdal electron, $H_{\chi\text{L}}$ the Hamiltonian coupling the dark matter to the nuclei in the crystal, and $H_{e\text{L}}$ the one coupling the nuclei to the electrons. Thanks to this, it is possible to show that the rate for Migdal emission, differential both in the electron energy, ω, as well as in the energy released to the crystal, E_{ph}, is [24],

$$\frac{d^2\Gamma}{d\omega dE_{\text{ph}}} \propto \sum_{\boldsymbol{k}} \sum_{\boldsymbol{K},\boldsymbol{Q}} \frac{\boldsymbol{q}\cdot(\boldsymbol{k}+\boldsymbol{K})\,\boldsymbol{q}\cdot(\boldsymbol{k}+\boldsymbol{K})}{|\boldsymbol{k}+\boldsymbol{K}||\boldsymbol{k}+\boldsymbol{Q}|} \text{Im}\left(-\epsilon^{-1}_{\boldsymbol{KQ}}(\boldsymbol{k},\omega)\right) S\left(\boldsymbol{q}-\boldsymbol{k}-\boldsymbol{K}, E_{\text{ph}}\right). \tag{2}$$

Here $\boldsymbol{q}$ is the momentum transfer by the dark matter, $\boldsymbol{K}$ and $\boldsymbol{Q}$ are momenta belonging to the reciprocal lattice, and $\boldsymbol{k}$ is the crystal momentum of the outgoing electron (belonging to the first Brillouin zone). The electron response of the material is encoded in the energy loss function (ELF) [e.g., 34–36], $\text{Im}\left(-\epsilon^{-1}_{\boldsymbol{KQ}}(\boldsymbol{k},\omega)\right)$, while the crystal response in the so-called structure factor [e.g., 37], $S(\boldsymbol{q}, E)$. Both these quantities are, a priori, measurable from data, thus bypassing the need for an accurate modelling of the nuclei and electrons in the semiconductor.

With this result at hand, one can compute the projected limits obtained from the Migdal effect in case of SENSEI [e.g., 38], which employs Si, as well as of a possible detector based on Ge. The results are reported in Figure 1. For measurements which are inclusive on the energy released to the crystal, the rate is insensitive to the details of the crystal under consideration [24]. Possible future measurements, sensitive also to E_{ph}, could instead be used as background discrimination, making it imperative to have reliable predictions based on Eq. (2), and, consequently, to precisely measured both the ELF and the structure factor.

3 keV to MeV: superfluid ^{4}He and anti-ferromagnets

When looking for dark matter with masses $m_\chi \lesssim O(\text{MeV})$, the typical momentum exchange is $1/q \gtrsim O(\text{Å})$, larger than the interparticle separation in the target material. Consequently, the interaction with dark matter likely produces collective excitations, rather than single particle ones. Depending on the type of interaction of dark matter with the Standard Model, it can couple more efficiently to different kinds of collective excitations. Here we discuss the possibility of probing spin-independent interactions using phonons in superfluid ^{4}He [28, 29, 31, 39], as well as spin-dependent one using magnons in anti-ferromagnetic materials [33]. Our theoretical description relies on the fact that these collective modes, at low energies, are Goldstone bosons associated to some spontaneously broken symmetries. As such, their interactions can be solely described in terms of symmetries and a handful of effective parameters.

3.1 Phonons in superfluid ^{4}He

The ground state of a superfluid (like ^{4}He) spontaneously breaks boosts, time translations and the particle number symmetry, preserving a linear combination of the last two [e.g., 40]. The associated Goldstone is the phonon, $\pi(x)$, corresponding to the material density perturbations. At low energies, its self-interactions are described by an effective Lagrangian [e.g., 39],

$$\mathcal{L}_\pi = \frac{1}{2}\dot{\pi}^2 - \frac{c_s^2}{2}(\nabla\pi)^2 + \frac{\lambda}{6}\dot{\pi}^3 + \frac{\lambda'}{2}\dot{\pi}(\nabla\pi)^2 + O\left(\pi^4\right), \tag{3}$$

where c_s is the speed of sound in the superfluid, and λ and λ' are effective coefficients that can be determined from the equation of state [28, 29, 31]. As far as the dark matter–phonon interaction is concerned, many natural dark matter models lead, in the non-relativistic limit, to a simple coupling between the dark matter and the superfluid density, n, [e.g., 28, 31]:

$$\mathcal{L}_{\text{int}} \propto \chi^\dagger\chi n(\pi) \propto \chi^\dagger\chi\left[\alpha\dot{\pi} + \frac{\beta_1}{2}(\nabla\pi)^2 + \frac{\beta_2}{2}\dot{\pi}^2 + O\left(\pi^3\right)\right], \tag{4}$$

with χ the non-relativistic dark matter field, and α and $\beta_{1,2}$ given by the equation of state [31].

With this at hand, the event rate for the emission of any number of low energy phonons can be computed with standard diagramatic methods. This has been used to determine the rate of emission of two phonons, as first suggested in [26, 27], which allows to find the projected exclusion plots for masses down to $m_\chi \sim O(\text{keV})$ [28, 29]. A similar analysis has also been performed for a model of dark matter which interacts with the Standard Model via a new Abelian vector mediator [39]. Finally, it has been used to compute the rate of a more involved process: the emission of three phonons [31]. While the latter is expected to be suppressed with respect to a two-phonon event, it offers an intriguing possibility for background discrimination. Indeed, it allows for a configuration with two back-to-back phonons, which can be used for coincidence, and one phonon emitted in the same direction as the incoming dark matter, which can instead provide directional information. The previous EFT can be used to determine the angular distributions of such an event, as well as its total rate, showing that it actually dominates over the two-phonon event in the $0.7\ \text{MeV} \lesssim m_\chi \lesssim 1\ \text{MeV}$ range [31].

3.2 Magnons in anti-ferromagnets

If dark matter, instead, features dominant spin-dependent interaction, a more suitable class of target materials is anti-ferromagnets:[1] the dark matter couples to the individual spins in the

[1] Ferromagnets have also been considered [41–44]. Anti-ferromagnets, however, can probe masses an order of magnitude lighter [33].

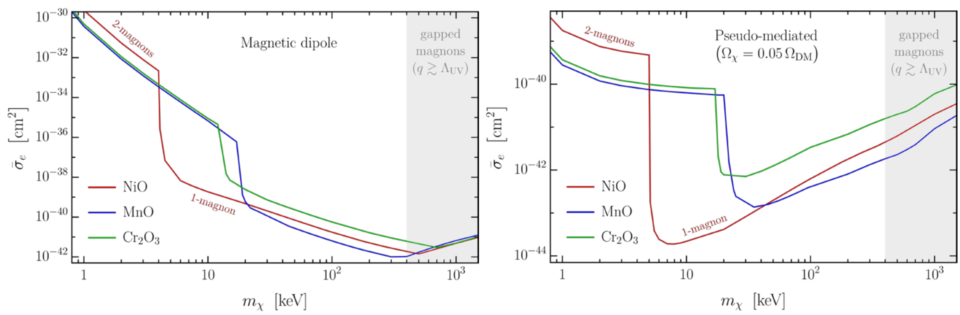

Figure 2. Projected exclusion limits for the dark matter–electron cross section at 90% C.L. for three different anti-ferromagnets and two benchmark dark matter models, assuming zero background. See [33] for details.

material, causing the emission of spin waves, called magnons. When gapless, they too are Goldstones, following from the fact that the ground state of an anti-ferromagnet (all spins are anti-aligned in one direction) spontaneously breaks the internal $SO(3)$ spin symmetry, down to an unbroken $SO(2)$. Similarly to the case of phonons in a superfluid, low energy magnons in an anti-ferromagnet can be described by the following effective Lagrangian [45, 46],

$$\mathcal{L}_\theta = \frac{c_1}{2}\left(\dot{\theta}^a\right)^2 - \frac{c_2}{2}\left(\partial_i \theta^a\right)^2 + O\left(\theta^3\right), \tag{5}$$

with $\theta^a(x)$ the magnon field ($a = 1, 2$), and $c_{1,2}$ effective coefficients which are determined from the magnon speed of propagation together with neutron scattering data [33]. The coupling between dark matter and magnons, instead, happens via the spin density operator, $\boldsymbol{s}(x)$:

$$\mathcal{L}_{\rm int} \propto \left(\chi^\dagger \hat{\Gamma}^i \chi\right)\left(\hat{\mathcal{D}}_{ij} s^j(\theta)\right) = c_1 \left(\chi^\dagger \hat{\Gamma}^i \chi\right)\left[\hat{\mathcal{D}}_{ij}\left(\delta^j_a \theta^a + \delta^j_3 \epsilon_{ab}\theta^a\dot{\theta}^b + O\left(\theta^3\right)\right)\right], \tag{6}$$

where $\hat{\Gamma}$ is a possible spin operator and $\hat{\mathcal{D}}$ a possible differential operator. Both of them depend on the particular dark matter model under consideration.

Again, we can now use textbook techniques to evaluate the event rate for the emission of any number of magnons. In Figure 2 we report the projected exclusion plots fro three different anti-ferromagnets and two benchmark dark matter models. Firstly, all anti-ferromagnets allows to probe masses as light as the keV. Secondly, one of them, NiO, feature a speed of propagation surprisingly close to the typical dark matter velocity, making it particularly efficient at absorbing most of its energy, already via the dominant one-magnon emission process.

4 Conclusion

The hunt for dark matter in the keV to GeV range requires new detectors ideas and, consequently, new theoretical tools for the description of the relevant phenomena. Taking advantage of the Migdal effect in semiconductors, one can extend the sensitivity to the dark matter–nucleon interaction down to masses $m_\chi \sim O(\text{MeV})$. Signatures involving collective modes in material such as superfluid ^{4}He and anti-ferromagnets, instead, can push the experimental sensitivity down to $m_\chi \sim O(\text{keV})$. In all these instances, one must deal with the richness and complicacy of condensed matter phenomena. One possible way to account for that is using effective field theory methods, as discussed here.

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