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Direct detection of light dark matter and solar neutrinos via color center production in crystals

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ABSTRACT

We propose a new low-threshold direct-detection concept for dark matter and for coherent nuclear scattering of solar neutrinos, based on the dissociation of atoms and subsequent creation of color center type defects within a lattice. The novelty in our approach lies in its ability to detect single defects in a macroscopic bulk of material. This class of experiments features ultra-low energy thresholds which allows for the probing of dark matter as light as $\mathcal{O}(10)$ MeV through nuclear scattering. Another feature of defect creation in crystals is directional information, which presents as a spectacular signal and a handle on background reduction in the form of daily modulation of the interaction rate. We discuss the envisioned setup and detection technique, as well as background reduction. We further calculate the expected rates for dark matter and solar neutrinos in two example crystals for which available data exists, demonstrating the prospective sensitivity of such experiments.

1. Introduction

More than 80% of the matter in our universe is yet to be understood. This astonishing fact has been established with overwhelming evidence by measurements ranging from sub-galactic to cosmological scale. Yet so far, this so called Dark Matter (DM) has been manifested via gravitational interactions only, and its particle nature remains unknown.

For over three decades there has been an extensive effort to search for DM directly with underground detectors, indirectly with the use of satellites and earth-based telescopes, and at colliders. To date there is no unambiguous, non-gravitational, experimental evidence for DM. Most of the theoretical and experimental effort, however, has been focused on a specific DM paradigm, the Weakly Interacting Massive Particle (WIMP) [1]. To date, the strongest constraint comes from the XENON1T experiment [2], constraining DM masses above several GeV. While appealing, the failure to discover the WIMP suggests that an alternative DM scenario may be at play. The last years have seen significant theoretical progress in this direction, with a particularly motivated candidate being Light Dark Matter (LDM) in the MeV to GeV mass range [3–15]. In addition, several recent proposals for experimental setups for LDM direct detection have been put forth [16–31] (for a review, see [32]), most of which offer to search for DM-electron scatterings. Perhaps the most notable ongoing search for DM-electron scattering is the SENSEI experiment, which utilizes Skipper CCDs [33] and has 2-electron sensitivity. In this study, we propose a novel experimental technique to directly search for LDM with masses below a GeV via DM-nucleon interactions. Our suggested setup will allow to significantly expand the experimental effort beyond current capabilities.

The main shortcoming of current experiments arises from the search for the elastic recoils of DM off nuclei. With a typical $\mathcal{O}$ (keV) sensitivity to nuclear recoil energies,[1] the suppression due to the target mass does not allow to search for DM much below the GeV scale. However, searching for inelastic processes, and specifically bond-breaking phenomena, may allow to significantly lower the experimental threshold [36,37]. In crystals, such interactions can induce detectable defects. Here we explore the prospects of detecting the formation of defects known as color centers (CCs)

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[1] Note however, that some experiments, such as CRESST [34] and SuperCDMS [35], can reach significantly lower thresholds and present sensitivity to sub-GeV dark matter.

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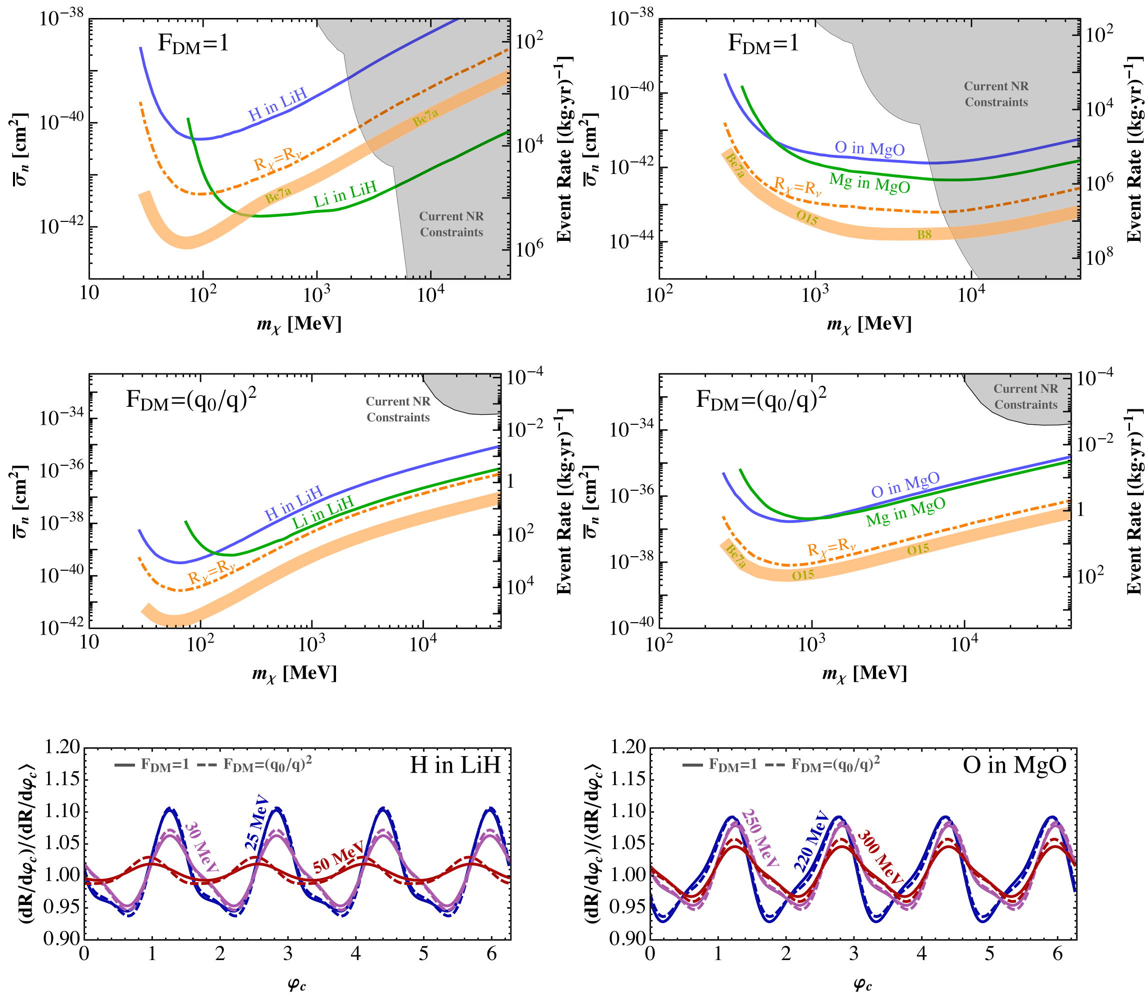

Fig. 1. Potential cross section sensitivity for 1 kg·year exposure (**top** and **center**) and daily modulation (**bottom**) for the two example crystals considered in this study, assuming a background-free experiment and single defect sensitivity. Both crystals have CCs which have been studied in the literature (see text for details), LiH (**left**) and MgO (**right**). **Top** and **center**: The cross section sensitivity, given on the left axes, has been calculated for interactions with both types of nuclei within the crystals. The right axes correspond to the expected event rate per kg·year assuming a DM-nucleon reference cross section of $\bar{\sigma}_n = 10^{-37}\mathrm{cm}^2$. **Top** panels correspond to $F_{\rm DM}(q) = 1$, **center** panels correspond to $F_{\rm DM}(q) = (q_0/q)^2$ with $q_0 = 100$ keV. The orange dotted-dashed curves correspond to the cross section for which one expects the rate of DM events to be equal to that of solar neutrino events for the lighter nucleus in each crystal (H in LiH and O in MgO). Below this line a dedicated neutrino background reduction will be necessary in order to detect DM. The thick orange curve corresponds to the prospective reach of a 100 kg·year experiment for the same targets, following a dedicated neutrino reduction analysis. Black lines/gray shaded regions show nuclear recoil bounds from CRESST II, CDMSLite, SuperCDMS, and XENON1T. **Bottom**: Daily modulation has been calculated for the lighter nucleus in each crystal (H in LiH and O in MgO). The modulation is presented as the differential rate normalized by its average for three DM masses, as a function of the angle between the crystal and the Earth's velocity in the galactic rest frame. Solid curves correspond to $F_{\rm DM}(q) = 1$ while dashed curves correspond to $F_{\rm DM}(q) = (q_0/q)^2$. The latter show slightly larger modulation due to a stronger dependence on the minimal momentum transfer, except for DM masses very near threshold. Furthermore, lower masses correspond to larger modulations while the total rate is exponentially suppressed with decreasing mass. Modulation of order $\mathcal{O}(10)$'s% is expected for these targets at these masses (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

following the dislocation of a nucleus within the crystal. These $\mathcal{O}(10)$ eV-threshold processes give rise to detectable signals, that should allow an experiment to explore an uncharted region in the parameter space of LDM as well as the low energy region of the solar neutrino spectrum.

An exciting feature of near-threshold excitations in targets with intrinsic anisotropy, is the directional dependence of the interaction rate. Consequently, a (sub-)daily modulation of the signal is expected, and would present as a striking signature of DM and a strong handle on background reduction.

The minimal cross sections which could be probed for a range of DM masses and for two example crystals considered in this study, with 1 kg·year exposures, are presented in the top and center panels of Fig. 1. Presented in the bottom panels of the figure is the expected daily modulation, i.e. the expected rates (normalized to their average) as a function of the orientation of the crystal with respect to the Earth's velocity. The momentum-transfer dependent DM Form Factor (FF), $F_{\rm DM}(q)$, parameterizes the microscopic physics of the DM-nucleon interaction. Other details of these results are given below. Here we stress the prospective two orders of magnitude improvement in DM mass sensitivity and the unique handle of daily modulation.

2. Concept

Several requirements must be fulfilled in an experiment of the type discussed above, that aims at the discovery of LDM or other feebly-interacting particles:

- **Low threshold**, typically below few tens of eV, in order to create a detectable defect.
- **Background discrimination** which allows to differentiate between low-energy (signal) and high-energy (background) events, and between nuclear (signal) and electron (back-