Dark matter electron interactions in graphene detectors

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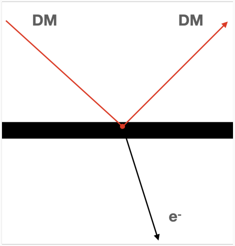
Chalmers

Introduction

- We focus on theoretical modeling of dark matter (DM) induced electron ejections from graphene sheets to be used in upcoming dark matter direct detection experiments.



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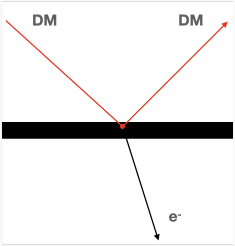

- These interactions are interesting because they can be probed for DM particles as light as a couple MeV due to the small mass of the electron.

Daily Modulation

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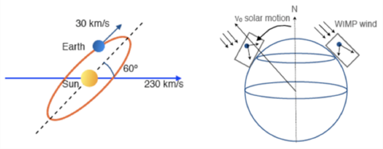

Credits: slac.stanford.edu

- The direction changes as the Earth rotates, giving rise to a time dependent signal which allows for discrimination between dark matter signals from backgrounds.

Non-relativistic effective field theory

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Non-relativistic effective field theory

- Previously the modelling of DM electron interactions has been performed with semi-analytical approximations and for the simple scenario of the dark photon model.
- We use a state of the art Density Functional Theory calculation to accurately capture the graphene physics, and employ an expansion in non-relativistic effective operators to capture all forms of non-relativistic DM electron interactions.

Non-relativistic effective field theory

$\mathcal{O}_1 = \mathbb{1}_{\chi e}$	$\mathcal{O}_9 = i\mathbf{S}_\chi \cdot \left(\mathbf{S}_e \times \frac{\mathbf{q}}{m_e}\right)$
$\mathcal{O}_3 = i\mathbf{S}_e \cdot \left(\frac{\mathbf{q}}{m_e} \times \mathbf{v}_{\mathrm{el}}^\perp\right)$	$\mathcal{O}_{10} = i\mathbf{S}_e \cdot \frac{\mathbf{q}}{m_e}$
$\mathcal{O}_4 = \mathbf{S}_\chi \cdot \mathbf{S}_e$	$\mathcal{O}_{11} = i\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_e}$
$\mathcal{O}_5 = i\mathbf{S}_\chi \cdot \left(\frac{\mathbf{q}}{m_e} \times \mathbf{v}_{\mathrm{el}}^\perp\right)$	$\mathcal{O}_{12} = \mathbf{S}_\chi \cdot \left(\mathbf{S}_e \times \mathbf{v}_{\mathrm{el}}^\perp\right)$
$\mathcal{O}_6 = \left(\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_e}\right)\left(\mathbf{S}_e \cdot \frac{\hat{\mathbf{q}}}{m_e}\right)$	$\mathcal{O}_{13} = i\left(\mathbf{S}_\chi \cdot \mathbf{v}_{\mathrm{el}}^\perp\right)\left(\mathbf{S}_e \cdot \frac{\mathbf{q}}{m_e}\right)$
$\mathcal{O}_7 = \mathbf{S}_e \cdot \mathbf{v}_{\mathrm{el}}^\perp$	$\mathcal{O}_{14} = i\left(\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_e}\right)\left(\mathbf{S}_e \cdot \mathbf{v}_{\mathrm{el}}^\perp\right)$
$\mathcal{O}_8 = \mathbf{S}_\chi \cdot \mathbf{v}_{\mathrm{el}}^\perp$	$\mathcal{O}_{15} = i\mathcal{O}_{11}\left[\left(\mathbf{S}_e \times \mathbf{v}_{\mathrm{el}}^\perp\right) \cdot \frac{\mathbf{q}}{m_e}\right]$

Rate of DM induced electron ejections

$$R = \frac{n_\chi M_{\text{target}}}{64\pi^2 m_\chi^2 m_e^2 M_{\text{cell}}} \int \mathrm{d}^3 k' \int \mathrm{d}(\Delta E) \int \mathrm{d}^3 q$$
$$\int \mathrm{d}^3 v\, f(\mathbf{v}) \delta(E_f - E_i) \overline{|\mathcal{M}'|^2} W$$

Catena, Emken, Matas, Spaldin, Urdshals; Work in progress

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For a graphene sheet lying in the xy-plane W becomes

$$W\left(\mathbf{k}' - \mathbf{q}, \frac{(\mathbf{k}')^2}{2m_e} - \Delta E\right) = \frac{A_{\text{cell}}}{(2\pi)^2} \sum_{\mathbf{G}_{xy}, i} \int_{\text{BZ}} \mathrm{d}^2 k_{xy}\, \delta^2\left(\mathbf{k}_{xy} + \mathbf{G}_{xy} + \mathbf{q}_{xy} - \mathbf{k}'_{xy}\right) \times \delta\left(E_{i,\mathbf{k}} - \left[\frac{(\mathbf{k}')^2}{2m_e} - \Delta E\right]\right) \times \left|u^{\text{cont}}_{i,\mathbf{k},\mathbf{G}}\right|^2 \Bigg|_{G_z = k'_z - q_z,\, k_z = 0}$$

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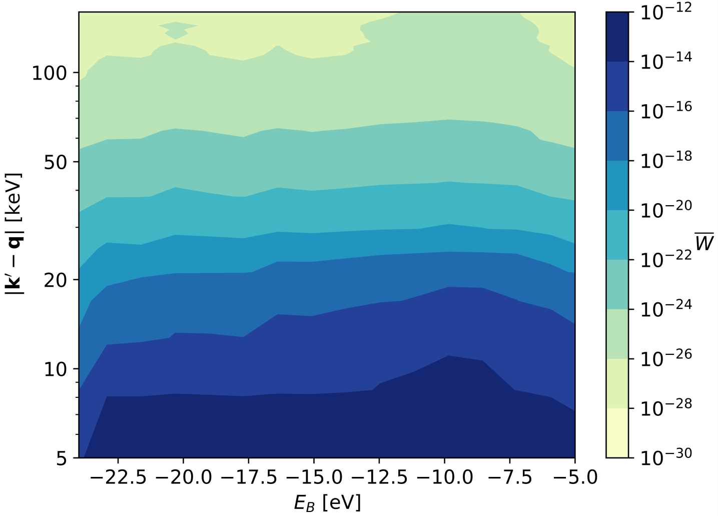
W



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Summary and Outlook

- We have shown that the matrix element for dark matter induced electron ejections from graphene factorises into a graphene response function and an expanded matrix element being a function of the properties of the free particles.
- The graphene response function we have computed using DFT methods.
- We are expecting to predict the spectrum of the ejected electrons, how it changes through the day, and how it depends on the dark matter mass and the form of the interaction.