Novel crystal responses to general dark matter-electron interactions

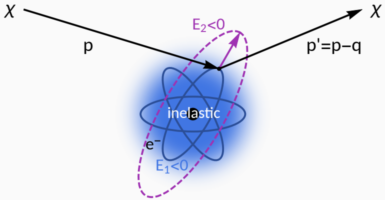
Novel responses for direct detection

Einar Urdshals

Chalmers

Introduction

- I focus on theoretical modeling of dark matter (DM) electron interactions in Silicon and Germanium crystals used in dark matter direct detection experiments.



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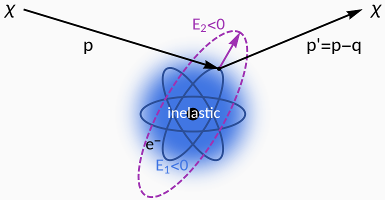

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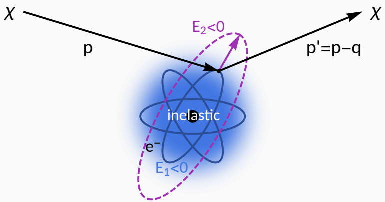

- These interactions are interesting because they can be probed for DM particles as light as a fraction of an MeV due to the small mass of the electron.
- So far this scattering has only been considered for the dark photon model. We are doing this for a much larger model space for the first time using effective non-relativistic operators.

Effective operators

$\mathcal{O}_1 = \mathbb{1}_\chi \mathbb{1}_e$	$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_e}\mathbb{1}_e$
$\mathcal{O}_3 = i\vec{S}_e \cdot \left(\frac{\vec{q}}{m_e} \times \mathbf{v}_{\mathrm{el}}^{\perp}\right)\mathbb{1}_\chi$	$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left(\vec{S}_e \times \mathbf{v}_{\mathrm{el}}^{\perp}\right)$
$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_e$	$\mathcal{O}_{13} = i\left(\vec{S}_\chi \cdot \mathbf{v}_{\mathrm{el}}^{\perp}\right)\left(\vec{S}_e \cdot \frac{\vec{q}}{m_e}\right)$
$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_e} \times \mathbf{v}_{\mathrm{el}}^{\perp}\right)\mathbb{1}_e$	$\mathcal{O}_{14} = i\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_e}\right)\left(\vec{S}_e \cdot \mathbf{v}_{\mathrm{el}}^{\perp}\right)$
$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_e}\right)\left(\vec{S}_e \cdot \frac{\vec{q}}{m_e}\right)$	$\mathcal{O}_{15} = i\mathcal{O}_{11}\left[\left(\vec{S}_e \times \mathbf{v}_{\mathrm{el}}^{\perp}\right) \cdot \frac{\vec{q}}{m_e}\right]$
$\mathcal{O}_7 = \vec{S}_e \cdot \mathbf{v}_{\mathrm{el}}^{\perp}\mathbb{1}_\chi$	$\mathcal{O}_{17} = i\frac{\vec{q}}{m_e} \cdot \boldsymbol{\mathcal{S}} \cdot \mathbf{v}_{\mathrm{el}}^{\perp}\mathbb{1}_e$
$\mathcal{O}_8 = \vec{S}_\chi \cdot \mathbf{v}_{\mathrm{el}}^{\perp}\mathbb{1}_e$	$\mathcal{O}_{18} = i\frac{\vec{q}}{m_e} \cdot \boldsymbol{\mathcal{S}} \cdot \vec{S}_e$
$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_e \times \frac{\vec{q}}{m_e}\right)$	$\mathcal{O}_{19} = \frac{\vec{q}}{m_e} \cdot \boldsymbol{\mathcal{S}} \cdot \frac{\vec{q}}{m_e}$
$\mathcal{O}_{10} = i\vec{S}_e \cdot \frac{\vec{q}}{m_e}\mathbb{1}_\chi$	$\mathcal{O}_{20} = \left(\vec{S}_e \times \frac{\vec{q}}{m_e}\right) \cdot \boldsymbol{\mathcal{S}} \cdot \frac{\vec{q}}{m_e}$

Dark matter and crystal responses

$$R_{\text{crystal}} = \frac{n_\chi N_{\text{cell}}}{128\pi m_\chi^2 m_e^2} \int \mathrm{d}(\ln \Delta E) \int \mathrm{d}q \, q \int \frac{\mathrm{d}^3 v}{v} g_\chi(v) \times \sum_{l=1}^{5} \Re\left(R_l^*(q, \mathbf{v}) \overline{W}_l(q, \Delta E)\right)$$

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- $R_l(q, \mathbf{v})$ is the dark matter response
- $\overline{W}_l(q, \Delta E)$ is the crystal response
- For the dark photon model $R(q, \mathbf{v}) = 1$ or $R(q, \mathbf{v}) = \alpha^4 m_e^4 / q^4$, and there is only one crystal response, $\overline{W}_1(q, \Delta E)$

The crystal response $\overline{W}_l$

$$\overline{W}_l(q, \Delta E) = (4\pi)^2 V_{\text{cell}} \frac{\Delta E}{q^2} \sum_{\mathbf{G}' i i'} \int_{\mathrm{BZ}} \frac{\mathrm{d}^3 k \mathrm{d}^3 k'}{(2\pi)^6} B_l \times \delta(|\mathbf{k} - \mathbf{G}' - \mathbf{k}'| - q) \delta(\Delta E - E(\mathbf{k}, i) + E(\mathbf{k}', i'))$$

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- $B_1 = \left| f'_{i,\mathbf{k}\to i',\mathbf{k}'} \right|^2$
- $B_2 = \frac{\mathbf{q}}{m_e} \cdot (f'_{i,\mathbf{k}\to i',\mathbf{k}'})(\mathbf{f}'_{i,\mathbf{k}\to i',\mathbf{k}'})^*$
- $B_3 = \left| \mathbf{f}'_{i,\mathbf{k}\to i',\mathbf{k}'} \right|^2$
- $B_4 = \left| \frac{\mathbf{q}}{m_e} \cdot \mathbf{f}'_{i,\mathbf{k}\to i',\mathbf{k}'} \right|^2$
- $B_5 = i \frac{\mathbf{q}}{m_e} \cdot \left(\mathbf{f}'_{i,\mathbf{k}\to i',\mathbf{k}'} \times \left(\mathbf{f}'_{i,\mathbf{k}\to i',\mathbf{k}'} \right)^* \right)$

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- $f'_{i,\mathbf{k}\to i',\mathbf{k}'} \sim \int \mathrm{d}^3 x \psi^*_{i',\mathbf{k}'}(\mathbf{x}) e^{i\mathbf{x}\cdot\mathbf{q}} \psi_{i,\mathbf{k}}(\mathbf{x})$
- $\mathbf{f}'_{i,\mathbf{k}\to i',\mathbf{k}'} \sim \int \mathrm{d}^3 x \psi^*_{i',\mathbf{k}'}(\mathbf{x}) e^{i\mathbf{x}\cdot\mathbf{q}} \frac{i\nabla_{\mathbf{x}}}{m_e} \psi_{i,\mathbf{k}}(\mathbf{x})$

$\overline{W}_1$

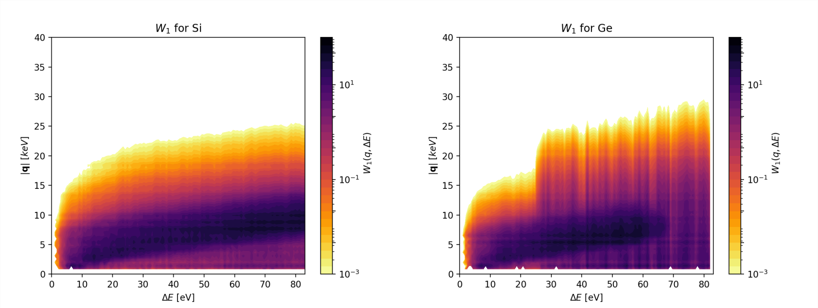

Figure 1: $\overline{W}_1$ arising from $B_1 = \left| f'_{i,\mathbf{k}\to i',\mathbf{k}'} \right|^2$

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$\Re(\overline{W}_2)$

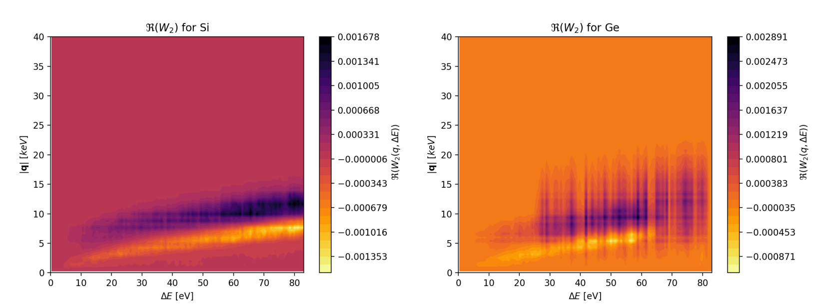

Figure 2: $\overline{W}_2$ arising from $B_2 = \frac{\mathbf{q}}{m_e} \cdot (f'_{i,\mathbf{k}\to i',\mathbf{k}'})(\mathbf{f}'_{i,\mathbf{k}\to i',\mathbf{k}'})^*$

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$\overline{W}_3$

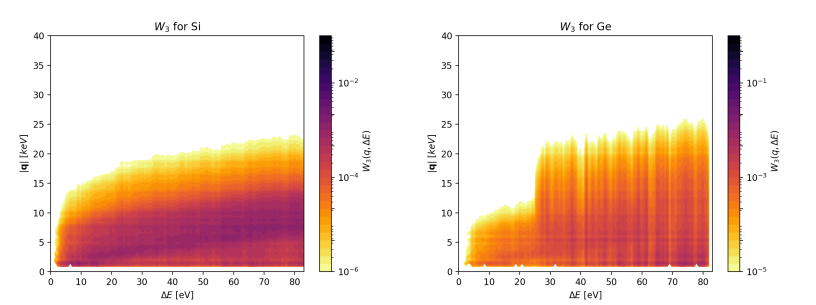

Figure 3: $\overline{W}_3$ arising from $B_3 = \left|\mathbf{f}'_{i,\mathbf{k}\to i',\mathbf{k}'}\right|^2$

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$\overline{W}_4$

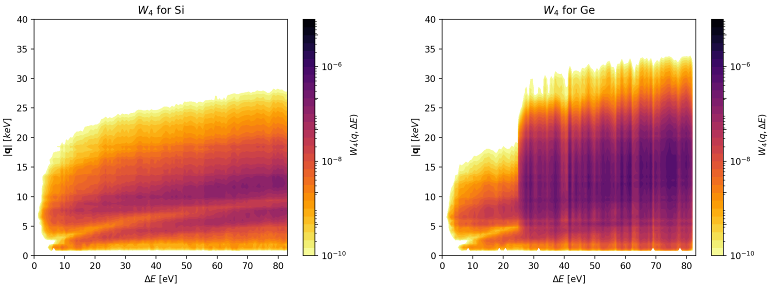

Figure 4: $\overline{W}_4$ arising from $B_4 = \left| \frac{\mathbf{q}}{m_e} \cdot \mathbf{f}'_{i,\mathbf{k}\to i',\mathbf{k}'} \right|^2$

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Expected excitation rates

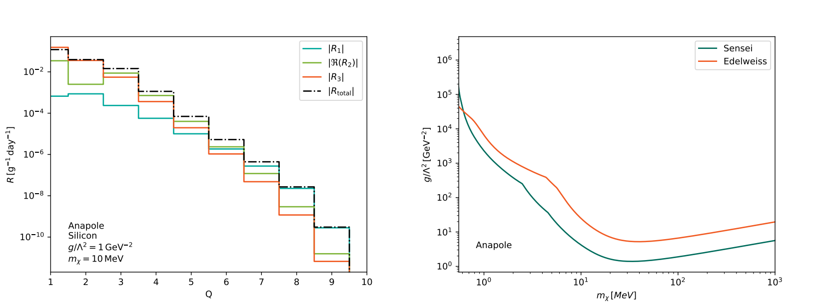

Figure 5: Rates and limits for anapole interactions, $\mathscr{L} = \frac{1}{2}\frac{g}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$ corresponding to $c_8^s = 8em_e m_\chi \frac{g}{\Lambda^2}$ and $c_9^s = -8em_e m_\chi \frac{g}{\Lambda^2}$

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Summary

- I focus on theoretical modeling of DM electron interaction in Silicon and Germanium crystals due the possibility to probe small dark matter masses.
- In this work, we derive and compute for the first time dark matter and crystal responses that can be used to model any interaction that can be probed in direct detection experiments using Silicon and Germanium crystals.