Direct detection of Light Dark Matter with Semiconducting Electrons

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What is Dark Matter?

Based on astronomical and astrophysical observations we know that only a small fraction of the Universe is made of ordinary matter (basically atoms). It has been determined that these Dark Matter particles bind gravitationally to galaxies. In particular, in the Milky Way they travel at the speeds comparable to those of stars orbiting around the galactic center of order 100 km/s, much below the relativistic regime.

Many models of DM have been proposed since its existence was hypothesized in the 50’s. Dark Matter is widely believed to be made of an unknown type of elementary particles. These particles are travelling through space, interacting gravitationally and possibly also interactin very weakly through other fundamental mechanisms.

Current status: Recent experimental evidence suggests that the WIMP paradigm, which proposes masses in the GeV-TeV range, is not a good candidate for DM. This motivates to continue the search in different regions of the DM parameter space, in particular in lower masses.

How to detect sub-GeV Dark Matter

DM particles will be subject to fundamental interactions with ordinary target particles. In the recent years nuclei have been used as target. But if DM is lighter than ~1 GeV, nuclei are too heavy to be good target particles because only small energy transfers can occur, which then requires extreme detector sensitivity. For example for m_i=10 MeV, the energy transferred to a typical nucleus is ~10 MeV. However, if we use the much lighter electrons as target, this energy transfer would be ~2 eV, reducing the required detector sensitivity by over 2 orders of magnitude.

A DM particle can scatter off an electron in a semiconductor, transferring energy E_i and momentum q, bringing the electron to a conduction state. An applied bias voltage across the semiconductor will make this excitation produce a secondary cascade of electron-hole pairs and phonons that can be measured.

This work provides theoretical guidance on what regions of Dark Matter parameter space semiconductor detectors based on electron scattering will be able to probe in the sub-GeV Dark Matter mass range.

DM-electron scattering rates

Theory

The DM-electron scattering rate is is given by the perturbative formula

$$R = N_{\text{DM}} \frac{2 \pi}{E_i} \sum_{k} \int d^3k |f_{\text{DM}}(q, k)|^2 |f_{\text{DM}}(q)|^2 \eta \left( \frac{E_i}{m_i} \right)$$

which brings together astrophysics, particle physics and solid state physics:

- **Astrophysics**
  - \(\eta\) contains information regarding the velocity distribution of DM in the vicinity of the Earth (where detectors will be located).
  - \(\sigma_q\) is the cross section of a DM particle to a free electron at momentum transfer \(q\).
- **Particle Physics**
  - \(f_{\text{DM}}(q, k)\)
  - \(f_{\text{DM}}(q)\)
  - \(\eta\)
- **Solid State Physics**
  - \(\eta\) is the crystal form-factor which is built solely from the valence and conduction wavefunctions.

Computational methods

We are interested in energy transfers up to ~40 eV, which set the detector thresholds. Large momentum transfers are kinematically relevant. This implies that large wavevector Fourier components (large \(q\)) are important, so the size of the wavefunction basis needs to be large. Additionally, a relatively fine k-vector mesh is needed to capture the low energy transitions accurately.

QEDark is an extension to the Quantum ESPRESSO code that calculates the crystal form-factor and the DM-electron scattering rates. The solid state wavefunctions are calculated using Density Functional Theory.

- **k-vector integrals are discretized**
- **Finite set of G-vectors for wavefunction expansion**
- **Integrate crystal form-factor “on the fly” to avoid storing it in memory**
- **Parallelization over k-point sums (integrals)**

Results and summary

- **Existing Dark Matter detectors can be adapted to DM-electron scattering events**
- **Semiconducting electron scattering will detectable DM masses is 3 orders of magnitude, down to the MeV-VeV regime**
- **Exclusion reaches have been calculated for various experimental thresholds to allow for direct comparison with experiment**
- **We project our data to the values for existing detectors. These detectors, once adapted, their thresholds are lowered, will be capable of exploring low-mass, low-cross section Dark Matter parameter space**

QEDark code will be available for the community to study other materials, directionality, etc.