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12/13/2021

Comparison of Simulations and Data from Small High Voltage Single Crystal Detectors for Dark Matter Searches

Abstract. *Using combined Semiconductor and Superconducting technologies, SuperCDMS has set world leading sensitivity limits to low-mass dark matter interactions. Sensitivity of the next generation SuperCDMS detectors is limited by lack of understanding of the physics of the experiment and devices. In this thesis, we focus on understanding the response of small high-resolution phonon detectors to photon interactions using simulations. We have been able to reproduce the main features of the energy spectrum using the simulations of laser source and interactions in the detector crystal. Next step is adding the simulation of sensors, data acquisition system and noise.*

Summary

Numerous observations of the large scale universe including galaxy rotation curves, gravitational lensing map of the universe and cosmic microwave background fluctuations, indicate that 85% of the universe consists of unseen massive particles called Dark Matter that have no electromagnetic interactions.

According to theoretical predictions, dark matter and normal matter interact with each other through nuclear recoil and/or electron recoil at eV to KeV energy scales. Ultra-sensitive detectors are needed for observing these interactions. Combined Semiconductor and Superconductor technologies are promising avenues for detecting very low energy interactions. SuperCDMS Experiment uses these technologies to build multiple complementary detectors for its dark matter search.

In this thesis we focus on small high-resolution phonon detectors that are called HVeV (for "High Voltage eV resolution") detectors. The sensitivity of HVeV detectors is limited by the lack of understanding of the physics of the experiment and devices. Using simulations can play a significant role in enhancing our understanding of the experiment. The goal of this thesis is to compare the simulation of HVeV detectors with well understood photon interactions from laser data to 1) Understand the physics of the detectors using simulation, 2) Validate and improve the simulation and 3) Use the simulation to obtain otherwise inaccessible information about the experiment which can suggest new ways to improve the detectors and/or analyze the data we get from them.

We simulate particle interactions using Geant4, and a custom detector simulation which simulates condensed matter physics (G4CMP). Our simulations consist of SourceSim, DetectorSim, DAQSim and NoiseSim. SourceSim simulates the laser source. DetectorSim consists of CrystalSim and TESSim which simulate the semiconductor crystal and the superconducting Transition Edge Sensors respectively. DAQSim and NoiseSim simulate data acquisition system, readout electronics and noise. After creating the raw data, we can process them by running through our reconstruction algorithm. Then we compare processed simulation results and real data.

We have finished the simulation of laser source and detector crystal and have been able to reproduce the main features of the data with simulations. We are planning to add the simulation of Transition Edge Sensors, Data Acquisition and Noise for the final defense so we can validate the full simulation of the HVeV experiment and confirm that the simulation is ready to be used in a dark matter search. Next student in our group will do the Dark Matter search with the simulation when we have the much bigger detectors for the SNOLAB payload.

Thesis Outline:

1. **Introduction and Motivation**
    - 1.1. Dark Matter Evidence
    - 1.2. Dark Matter Phenomenology and Candidates
    - 1.3. Current Dark Matter Searches and Limits
    - 1.4. Detector Concept: Making Dark Matter Detectors from Single Crystal Semiconductors and Superconducting Sensors
    - 1.5. The need for Small High-Resolution Athermal Phonon (HVeV) Detectors
    - 1.6. The need for Understanding the Physics of HVeV Detectors and Advantages of Using Simulations
    - 1.7. Overview of the HVeV Recoil Energy Measurement Experiment
    - 1.8. Overview and Outline of this Thesis

2. **Physics of Single Crystal Semiconductors and Lattice Response to Photon Interactions**
    - 2.1. Conduction and Valence Band Structure
    - 2.2. Lattice Vibration (Phonons) and Charge Creation in Single Particle Interactions
    - 2.3. Phonon and Charge Propagation in the Crystal
    - 2.4. Effects of Applying a Voltage Bias to the Crystal: Luke Phonon Creation
    - 2.5. Additional Charge Creation (Impact Ionization) and Charge Trapping
    - 2.6. Summary: Photon Interaction with the Single Crystal Semiconductors Under Voltage Bias

3. **Physics of Superconducting Sensors and Readout**
    - 3.1. Overview of Quasiparticle-assisted Electrothermal- feedback Transition Edge Sensors (QETs)
    - 3.2. Transition Edge Sensor (TES)
    - 3.3. Phonon Energy Readout by TES