Summary

Rare event search experiments like Dark Matter searches, Coherent Elastic Neutrino-Nucleus Scattering (CEνNS), and Neutrino-less Double Beta Decay (NDBD) are exciting and challenging as they address unanswered physics questions and push the boundaries of current technology. Dark Matter, constituting 26.8% of the Universe's mass-energy, remains an enigma. In direct detection experiments, Dark Matter particles scatter off target nuclei, producing signals such as light, phonons, charge, or a combination of them, depending on the detector material. The absence of GeV-scale Dark Matter signals compels the exploration of low-mass Dark Matter, requiring detectors with low-energy thresholds. CEνNS, which scatters neutrinos coherently with nuclei, faces similar challenges. Another challenge is the mitigation of high background rates from radiogenic and cosmogenic sources, necessitating underground laboratory with passive shielding, and active shielding for in-situ background reduction.

In this thesis, we discuss the development and performance of an annular, cryogenic phonon-mediated active veto detector designed to significantly reduce radiogenic backgrounds in rare event search experiments. The detector consists of a germanium veto

detector weighing approximately 500 g, with an outer diameter of 76 mm and an inner diameter of 28 mm. The veto detector can host a 25 mm diameter germanium inner target detector weighing around 10 g. Using inputs from a GEANT4 based simulation, the detector was optimized to be positioned between two germanium detectors, resulting in a $> 90\%$ reduction in background rates dominated by gamma interactions. Operating at mK temperatures in the experimental setup, the prototype veto detector achieved a baseline resolution of 1.24 ± 0.02 keV, while maintaining a functional inner target detector with a baseline resolution of 147 ± 2 eV. Experimental results closely matched simulation predictions, affirming the efficiency of the design for aggressive background reduction necessary for neutrino and dark matter search experiments.

This thesis also presents experimental results from a ~ 100 g single-crystal sapphire detector, with a diameter of 76 mm and a thickness of 4 mm, equipped with transition edge sensors (TES). Sapphire, composed of aluminum oxide (Al_2O_3), emerges as a promising candidate for light mass dark matter search experiments due to its lower atomic mass compared to materials like germanium and silicon. This novel phonon-assisted sapphire detector exhibits a baseline recoil energy resolution of 28.4 ± 0.4 eV. We combine two low-threshold detector technologies, sapphire and ~ 100 g Si High Voltage (HV), to develop a large-mass, low-threshold detector system. It simultaneously measures athermal phonons in a sapphire detector while an adjacent Si HV detector detects scintillation light from the sapphire detector utilizing NTL amplification. This setup allows for event-by-event discrimination between electron and nuclear events due to differences in their scintillation light yield. While previous systems with simultaneous phonon and light detection have employed smaller detectors, this system is designed to provide a large detector mass with high amplification for the limited scintillation light.

This thesis also discusses an ongoing study to precisely measure the decay rates of ^{32}Si

and ^{32}P using data from Cryogenic Dark Matter Search (CDMS) experiment, collected between 2003 and 2012 at the Soudan Underground Laboratory. The experiment employed 19 Ge and 11 Si cryogenic detectors in a five-tower configuration to detect recoil energy from particle interactions, measuring both phonon and charge energy. ^{32}Si, a naturally occurring isotope in Si detector material, decays to ^{32}P, which further decays to stable ^{32}S, emitting β particles contributing to background for dark matter signals. The analysis comprises three parts: (i) obtaining the main observable, the charge energy after applying all data quality cuts, (ii) modeling the beta decay spectrum of ^{32}Si and ^{32}P using Betashape software and comparing it to the Fermi theory of beta decay, and (iii) conducting GEANT4 simulations to model other relevant backgrounds present in the experimental setup. A profile likelihood analysis will be performed, utilizing the three aforementioned inputs, to determine the precise level of ^{32}Si contamination within Si detectors. The analysis is currently in progress, and this thesis will discuss the current status and future prospects of this investigation. This measurement is crucial not only for SuperCDMS SNOLAB, a future upgrade of the CDMS and SuperCDMS experiment, but also for all rare event search experiments utilizing Si detectors.