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Introduction

The Coherent Elastic Neutrino-Nucleus Scattering (CENNS) is a process predicted nearly 40 years ago. In August 2017, the COHERENT experiment reported the first keV-scale detection at the 6.7 sigma level of this process, which is a probe for the new low energy physics, opening a window on a myriad of new physics opportunities. The Ricochet experiment aims at measuring with high accuracy the CENNS process in order to probe various exotic physics scenarios in the electroweak sector. Using cryogenic bolometers operated in a cryostat 8 meters away from the core of the ILL research nuclear reactor, the experiment will benefit from an intense neutrino flux, allowing the results of COHERENT to be reproduced in a single week. The objective of an accurate measurement will be achieved after one year of data collection, by 2024. The CryoCube is a compact cubic array of cryogenic detectors developed for RICOCHET, with the following specifications: a very low energy threshold of $\mathcal{O}(10)$ eV on the thermal signal, an electromagnetic background rejection of at least 10^3 and a total target mass of 1 kg distributed among 27 germanium crystals of about 30 g each. The objective of this thesis is to propose an optimized detector design for the CryoCube, inspired by the cryogenic germanium detectors equipped with charge and temperature readings of the direct dark matter search experiment EDELWEISS.

The first chapter introduces the CENNS process in the framework of the Standard Model. It then presents multiple exotic physics scenarios that would emerge from the measure of the CENNS at low energy range. Different low energy neutrino sources as well as detector technologies are discussed in order to realize this precision measurement. We discuss the R&D program of the nuclear reactor experiment RICOCHET, joint with the direct detection dark matter search experiment EDELWEISS, based on event discrimination realized in germanium semiconductor crystals. Their specificity is their intrinsic ability to distinguish the nuclear recoils produced by the CENNS or the dark matter from the electronic radioactive background. As these recoils are of the order of $\mathcal{O}(100)$ eV, this thesis work is focused on the development of a new generation of cryogenic low threshold germanium detectors with particle identification.

The second chapter describes the working principles of these detectors featuring a double measurement of the recoil energy of an incident particle as a temperature increase measured by a GeNTD thermistor (heat channel) and as the collection of electric charges by electrodes on the surface of the crystal (ionization channel). It presents the IP2I cryogenic facility allowing the surface operation of prototype detectors at 20 mK in optimal conditions, thanks to the mitigation of the mechanical vibrations. The data collected from the RED series of prototype detectors drive the studies of the heat and ionization channels in all the later chapters, exploring how to improve the resolution in heat and ionization energy up to $\mathcal{O}(10)$ eV while maintaining a good rejection of background events.

The third chapter is dedicated to the study of the heat channel based on experimental data of RED detectors of simple design with one GeNTD thermal sensor and no electrodes. These bolometers are modeled with a system of electro-thermal equations. The noise affecting two readout electronics is characterized by adjusting this model in the frequency domain using Monte Carlo Markov Chain analysis. Similarly, a new detector is characterized based on its steady-state and the shape of heat signals. The strategy for improving the heat channel performance is then discussed based on simulation of the energy resolutions.

The fourth chapter introduces the ionization channel of the cryogenic detectors. The processes of ionization and charge drift in the semiconducting germanium crystal are described along with the theory of the signal generation on the electrodes. The electrostatic simulation of detectors in the finite element calculation software COMSOL is explained. It is used to characterize two detector designs candidate for the CryoCube by estimating their electric field, electric capacitance and fiducial volume. This chapter ends on the estimation of the ionization energy resolution from a future low-noise HETM-based electronics for the two detector designs.

The fifth chapter describes the optimization of the detector designs introduced previously. It presents a methodology based on the electrostatic simulations for studying the influence of each of the design parameters on the projected ionization channel performance.

The sixth chapter compares the projected performance from electrostatic simulations and experimental results for two prototype detectors operated in the IP2I cyrostat. It starts with the description of the simulations. It then follows with an explanation of the analysis pipeline applied to the raw experimental data. The last section discusses the comparison between experimental and simulated results, especially regarding the optimization of the designs in the previous fifth chapter.

The seventh chapter is dedicated to the measurement of the neutron background at the IP2I cryogenic facility with the prototype detector RED80. It describes the specific experimental setup used to calibrate the detector with a neutron source. An advanced analysis for the discrimination of the nuclear and electronic recoils is presented using analytical pulse simulation to estimate their associated event rate spectrum. The characterization of the neutron background is used to estimate the expected fast neutron background at the ILL site for RICOCHET.

Conclusion

This thesis is inscribed in the R&D program of the RICOCHET experiment for the precision measurement of the CENNS near the research nuclear reactor of the ILL. Its main goal was to develop a new generation of low-threshold cryogenic germanium detectors satisfying the specifications of the CryoCube detector array for RICOCHET. For this purpose, the heat and ionization channels of these cryogenic detectors were modeled and optimized based on experimental data collected from prototype detectors operated at the IP2I cryogenic facility.

This work first started with the study of the heat channel. An electro-thermal model of simple RED detectors was built. Its adjustment to experimental data is excellent and permitted the adoption of a new methodology for the characterization of new detectors. The study of their steady-state and heat response to a scattering particle can be reproduced with this model, thus constraining the thermal properties of the detector components, and in particular the GeNTD thermal sensor. Interestingly, the prototype detector RED10 showed a high 20.2 % proportion of athermal phonons, greatly contributing to sensitivity of the detector and motivating further study on the relaxation of phonons in the detector. The modelization of the heat channel helped understand the propagation of the signal into the detector and highlighted the existence of an optimal polarization current for the NTD thermal sensor. The noise PSDs of two electronics were also fitted with the electro-thermal model, hinting towards a low-frequency noise component limiting their performances. We also confirmed that the EDELWEISS electronics with cold electronics is affected by a lower noise level and should be used for the characterization of detectors and data collection. The projected energy resolution calculated from the electro-thermal model motivated the optimization of the heat channel with a lower germanium crystal mass. The most recent prototype detectors operated in the IP2I cryostat weights between 32 g and 38 g and can reliably reach heat energy resolution inferior to 30 eV.

This thesis then greatly furthered the knowledge on the ionization channel of the cryogenic detectors. The modelization of the signal generation by the drift of the electric charge carriers in the semiconductor germanium crystal was built. Thanks to its matrix formalism, this model brought attention to the influence of the cabling capacitance of the ionization polarization and readout electronics. Indeed, in the current situation, with a dominating high cabling capacitance, the sensitivities of the electrodes are almost equals and are limited by their common high cabling capacitance of their electronics. With the new low-noise HEMT-based electronics which will be installed close the detector load inside the RICOCHET cryosta, the cabling capacitance will not dominate the capacitance of the detector electrodes anymore and the ionization signal signatures will drastically change. This model of the ionization channel was validated and is now coupled to the electrostatic simulation of the detectors within the finite element calculation software COMSOL. These simulations yield precise estimation of the fiducial volume of the detector and the electric capacitance of its electrodes. The optimization of the two detector designs PL38 and FID38 was realized by scanning over the various parameters within the simulation. The comparison between simulated performance and experimental results highlighted the limitations of the electrostatic simulation: not taking into account the oblique propagation of the electrons in the germanium crystal or the charge trapping processes.

This final result of this work is the characterization of the neutron background at the IP2I cryogenic laboratory. Benefiting from the good heat and ionization performances of the detector RED80, a data collection lasting more than five days with intermittent calibration with a neutron source was realized. The in-depth analysis of the data streams permitted to exploit the intrinsic discriminitation between nuclear and electronic recoils within the semiconducting germanium crystal thanks to the double-energy measurement of the detector. Indeed, the electronic and neutronic components of the background were isolated which allowed to compute their associated event rate spectra. This measurement of the fast neutron background in the IP2I cryostat will be used to estimate the expected neutron background at ILL site. Being one of the major obstacle to the CENNS precision measurement, knowledge of the neutron background is invaluable to adapt the RICOCHET strategy.

In the end, this thesis positions itself as a solid foundation for the development of low-threshold cryogenic germanium detectors. The R&D program at the IP2I cryogenic facility is in continuation with this work with:

- the upgrade of the suspended tower for the mechanical decoupling solution of the CryoCube within the RICOCHET cryostat, soon to be tested at the IP2I laboratory,
- the study of the new low-noise HEMT-based electronics with low cabling capacitance,
- the characterization of the two new prototype detectors RED130 and RED140, assembled following the PL38 and FID38 designs, with first experimental results pointing towards excellent performances.

The RICOCHET collaboration is on the right tracks to build the CryoCube according to specifications, measure with high accuracy the CENNS at the ILL within a few years, and perhaps topple the Standard Model with new exotic physics.