PROCEEDINGS OF SCIENCE

Gamma background characterization and modeling for the RICOCHET experiment at the Institut Laue-Langevin

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The RICOCHET experiment is currently being deployed at the Institut Laue-Langevin (ILL) research nuclear reactor in Grenoble, France, with the goal of performing a precise measurement of coherent elastic neutrino-nucleus scattering (CEνNS). At reactor neutrino energies (0–8 MeV), the coherence condition is fully satisfied and the cross section benefits from the expected N^2 enhancement, where N is the neutron number of the target nucleus. A detector with a kilogram-scale target mass is therefore sufficient for a measurement. In the final configuration of RICOCHET, two cryogenic detector concepts will be deployed: an array of eighteen germanium bolometers of about 40 g each, and nine superconducting crystals inserted in a cryostat operating at a temperature of 10 mK. In the initial commissioning phase, up to nine germanium crystals were installed. The raw background level is significant due to the proximity of the reactor core (neutron and gamma) and to the positioning of the detector on the surface (cosmic background). To fight against the backgrounds, a three-fold strategy is used: an active muon veto, a passive shielding of lead and polyethylene to mitigate the gamma and neutron backgrounds, and the simultaneous measurement of ionization and heat to discriminate electron and nuclear recoils. Prior to the installation of the RICOCHET cryostat, a measurement campaign of the radiogenic and reactogenic gamma background was carried out inside the shielding with a dedicated High-Purity Germanium (HPGe) detector. This contribution will present the gamma background model derived from these measurements and highlight some comparisons with data recorded in the commissioning phase.

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1. Introduction

1.1 Scientific objective: CEνNS measurement

CEνNS results from the weak interaction and was theorized in 1974 by D. Z. Freedman [1]. During this process, the incident neutrino exchanges its energy and momentum with the nucleus as a whole rather than with individual nucleons, due to the coherence of the interaction. The scattering angle is generally very small, which means that the nucleus recoils slightly, with a low energy, and the neutrino therefore continues on a slightly deflected trajectory. Thus, despite a cross section greater than many processes involving neutrinos (Fig. 1), this process has only been observed very recently, due to the technical challenges associated with detecting very small nuclear recoils: on the order of tens of electron volts and requiring ultra-sensitive detectors. CEνNS was first observed in 2017 by the COHERENT collaboration [2].

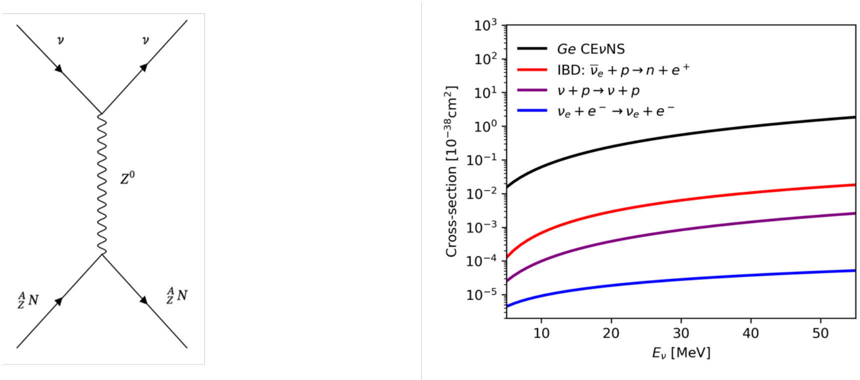

Figure 1: Feynman diagram (left) & cross section of CEνNS and various electroweak processes [3] (right).

Through its sizable differential cross section, CEνNS provides a powerful probe of possible deviations from the Standard Model of particle physics. Any discrepancy between theoretical predictions and experimental measurements could indicate new physics, such as a non-zero neutrino magnetic moment or the existence of a light Z' mediator [4]. Further, the nuclear recoils induced by coherent scattering of solar and atmospheric neutrinos closely mimic the expected signal from various dark matter models. Precise knowledge of this background, called the "neutrino floor" [5], is therefore crucial to enhance the sensitivity of future direct dark matter searches.

1.2 Experimental context: RICOCHET at ILL

CEνNS is a rare and challenging process to observe, requiring both a high neutrino flux and incident neutrino energies low enough to preserve the coherence of the interaction. For these reasons, the Institut-Laue Langevin research reactor was chosen as the site of the RICOCHET experiment. It provides antineutrinos with energies up to about 8 MeV [6], which ensures the coherence condition at the nuclear level. Moreover, the RICOCHET cryostat is located only 8.8 meters away from the reactor core of 58 MW nominal power, resulting in an intense and pure electron antineutrino flux of about $\phi_{\bar{\nu}_e} \sim 10^{12}$ cm^{-2} s^{-1}, originating directly from the beta decays of the fission products. In contrast, typical accelerator-based neutrino sources deliver fluxes below 10^8 cm^{-2} s^{-1}, energies above 10 MeV and contain a mixture of flavors ($\bar{\nu}_e$, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$).

1.3 Detection method: CryoCube

The first phase of RICOCHET relies on an array of eighteen germanium cryogenic bolometers, divided into two families: planar and Fully Inter-Digitized detectors. They are combined into the CryoCube with a total active mass close to one kilogram. The technology is based on ultrapure germanium crystals operated under an applied electric field. When a neutrino scatters off a nucleus in the target, the recoiling nucleus releases a minute amount of heat and produces an ionization signal. Both signals are read out simultaneously by Neutron-Transmutation-Doped sensors and aluminum electrodes, providing a dual measurement of the phonon energy (E_{heat}) and the ionization energy (E_{ion}). The ratio of these two quantities depends on the interacting particle and on the recoil type (E_{recoil}), allowing a discrimination between nuclear and electronic recoils via the quenching factor (Eq. 1 with ΔV the voltage bias and ϵ the energy required to produce one electron-hole pair). This dual readout significantly reduces backgrounds mimicking CEνNS events [7].

$$Q = \frac{E_{\text{ion}}}{E_{\text{recoil}}} = \frac{E_{\text{ion}}}{E_{\text{heat}} - q \times \frac{E_{\text{ion}}\,\Delta V}{\epsilon}} \begin{cases} = 1 \text{ for Electronic Recoils (ER)} \\ < 1 \text{ for Nuclear Recoils (NR)} \end{cases} \tag{1}$$

2. Background sources and shielding

2.1 Background sources

In order to reach a signal-to-background ratio close to unity and a detection rate of about 10 CEνNS events per day, per kilogram, and per keV, the experiment must be shielded from various environmental backgrounds, which can be grouped into three main categories [8]:

- **Radiogenic**: originating from naturally occurring radioactive isotopes in the surroundings of RICOCHET, such as the decay chains of uranium and thorium;
- **Reactogenic**: produced when the reactor is operating, due to its proximity to the detector, and including fast neutrons, capture gammas, and decays of activated isotopes;
- **Cosmogenic**: related to background created by cosmic particles, mainly muons that can also lead to the production of neutrons and other particles.

2.2 Background mitigation strategies

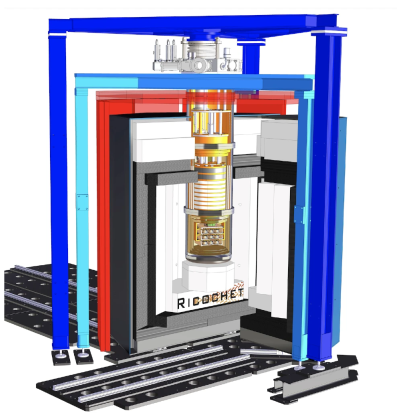

Figure 2: RICOCHET shielding [9].

The RICOCHET setup was designed to strongly suppress background and enhance sensitivity to CEνNS. The shielding (Fig. 2) combines passive layers (2 t of borated polyethylene, 20 t of lead, plus layers of lead, copper, and polyethylene inside the cryostat) with active systems (external scintillator panels and internal CryoVeto for cosmic muon rejection). The experiment also benefits from an additional 15 m.w.e. overburden provided by the ILL reactor pool. Nevertheless, background characterization remains crucial and has been carried out both with dedicated detectors prior to installation and with the cryogenic bolometers in situ. This work focuses on the gamma background component, which was partly characterized using a GEM60 High-Purity Germanium (HPGe) detector with a mass of one kilogram [10], and two RICOCHET bolometers.

3. Analysis and GEANT4 simulations comparison

3.1 Radiogenic gamma background

The characterization of the radiogenic gamma background was carried out between July and October 2023 using an HPGe detector, with the aim of identifying the main radioisotopes and their origins. The analysis revealed that most of the signals arose from the decay chains of ^{232}Th and $^{235/238}$U, as well as from ^{40}K, primarily emitted from the lead and polyethylene shielding and from the concrete slab of the reactor pool. Monte Carlo simulations were performed to reproduce these spectra by homogeneously contaminating each material with the corresponding radionuclides. For each source-material pair, a simulated spectrum was generated and subsequently combined using a chi-square minimization algorithm (Eq. 2). The goal is to determine the linear coefficients a_k, which relate the measured activities of material samples to the specific activities of each radionuclide, thereby decoupling the contributions of different sources. The chi-square algorithm incorporates a factor f to account for systematic uncertainties of the simulation. The results obtained from this minimization correctly reconstruct both the experimental spectrum (Fig. 3) and the specific activities of the radioisotopes, with a normalized chi-square $\chi^2_\nu = 1.12$, and are expected to improve the model of the radiogenic gamma background for future RICOCHET analyses.

$$\chi^2 = \sum_{i=1}^{N_{\text{bin}}} \left[\frac{S_i^{\text{exp}} - f \times S_i^{\text{sim}}(s_k^{\text{mat}}, a_k)}{\sqrt{\sigma_i^{\text{exp}\,2} + \sigma_i^{\text{sim, stat}\,2}}} \right]^2 + \left(\frac{f - 1}{\sigma_f^{\text{sim, sys}}} \right)^2 \tag{2}$$

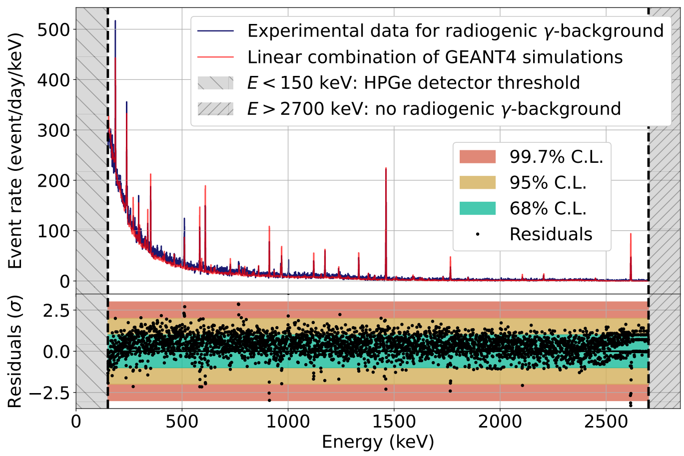

Figure 3: Reconstruction of the radiogenic background spectrum measured with the HPGe detector, based on Monte Carlo simulations performed with the GEANT4 framework. The experimental spectrum is shown in blue, the linear combination of simulated spectra in red, and the excluded energy regions in gray (top). Normalized residuals, (Data – Model)$/\sigma$, lie mostly within $\pm 3\sigma$, confirming the validity of the fit (bottom).

3.2 Reactogenic gamma background

The reactor-induced gamma background was characterized during the commissioning RUN014 of RICOCHET, using the bolometers named RED167 and RED237. The event rate of this component dominates over the radiogenic contribution during ON reactor cycles. Data collected between April and October 2024 covered both ON and OFF reactor cycles, allowing reactor-induced spectra to be extracted by subtraction. The study highlights the dominant ^{41}Ar contribution, produced by neutron capture on ambient argon and decaying with the emission of an intense 1293.64 keV gamma, which strongly impacts the RICOCHET ionization signal. A methodology similar to that used for the radiogenic case was adopted to reconstruct the experimental spectra, this time by contaminating the air around the cryostat and the polyethylene with ^{41}Ar, in order to reproduce leakage and scattering within the shielding. The objective is to predict the event rates of Electronic Recoils (ER) in the 2 to 7 keV energy range measured during RUN014, using these Monte Carlo simulations to validate the experimental data. The GEANT4 simulations successfully reproduce the measured spectra for both bolometers (Fig. 4). The photopeak of ^{41}Ar is well fitted, although a marked asymmetry on its low-energy side suggests that the model requires further improvements. In addition, both the Compton edge and the continuum show good agreement with the experimental data, despite a slight deficit that may originate from other reactor-induced radioisotopes (neutron capture on $^{54/56}$Fe or ^{1}H), which are not yet included in the simulations.

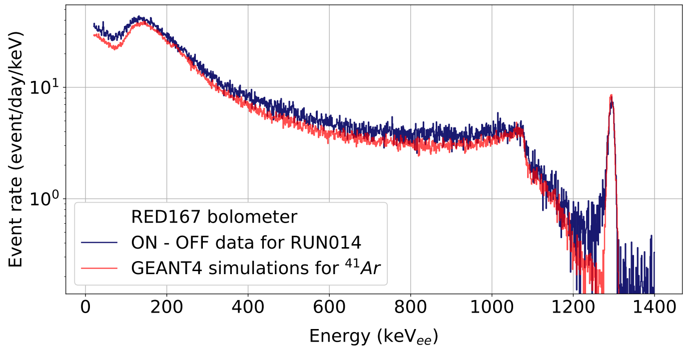

Figure 4: Reconstruction of the reactogenic background spectrum measured with the RED167 bolometer of RICOCHET, based on Monte Carlo simulations of ^{41}Ar contamination performed with the GEANT4 framework. The experimental spectrum is shown in blue and the simulated spectra in red.

The event rates derived from the reconstructed spectra are consistent with the measurements obtained with both bolometers, confirming that the ^{41}Ar contamination is the dominant contribution to the reactor-induced gamma background. Its simulation alone reproduces nearly all of the observed rates (Tab. 1), indicating that other potential sources play only a subdominant role. This result provides a solid basis for future improvements of the background model in RICOCHET analyses.

Detector ID	**RED167**	**RED237**
ON reactor data	1115 ± 172	1200 ± 184
OFF reactor data	135 ± 21	123 ± 19
ON - OFF data	980 ± 174	1077 ± 185
^{41}Ar simulation	812 ± 83	854 ± 94

Table 1: Average event rates after correction for efficiency in events per kg, per day and per keV (DRU) in the energy range from 2 to 7 keV [11], and rates expected from the ^{41}Ar simulation (this work).

4. Conclusion and outlook

The RICOCHET experiment aims to measure CEνNS with reactor antineutrinos, which requires a sensitivity to very low energy signals. A precise understanding of the surrounding backgrounds is therefore essential to distinguish signals of interest from noise. The gamma component of the background has been studied in dedicated campaigns, characterizing both its radiogenic and reactogenic contributions and validating the experimental measurements. Nevertheless, further improvements are underway to minimize this background, in particular by enhancing the shielding tightness to mitigate argon contamination and by performing additional simulations to account for high-energy gammas produced by neutron capture.

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