Exploring coherent elastic neutrino-nucleus scattering with the NUCLEUS experiment

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Abstract

The NUCLEUS experiment aims to measure the neutrino-nucleus coherent elastic scattering cross section exploiting cryogenic detectors equipped with TES. In this paper, we report on the status of the project; we present the recent results achieved in the long background run performed in the shallow underground laboratory UGL located at TUM University in Munich. The successful operation of the neutrino target detectors in coincidence with the other subdetectors of the experiment (muon veto, germanium cryogenic outer veto) allowed us to move in 2025 to the final experimental site: the Very Near Site at the Chooz nuclear plant in France.

Keywords: neutrino, coherent elastic scattering, cryogenic detector
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1. INTRODUCTION

Neutrinos are the particles of the Standard Model that still hide many of their fundamental properties. The mass scale and their nature are still unknown more than 60 years after their first detection by Cowan and Reines [1]. In the very last year, a Standard Model process, measured for the first time by the COHERENT collaboration using a 14.6 kg CsI[Na] scintillation crystal at the Spallation Neutron Source [3], serves as an additional hand lens to unveil their intimate nature: the coherent elastic neutrino-nucleus scattering (CENS) [2]. Indeed, thanks to the higher cross section with respect to other neutrino processes, CENS offers a unique probe of the Standard Model validity and possible doors to new physics. To study the CENS properties at very low energy, nuclear reactors with a antineutrino flux of 10^{20} /(s GWth) are the best candidate sources. Indeed, the antineutrinos produced by the nuclear fissions in the reactor, with energies up to 10 MeV, are an ideal source to explore the coherent interaction mode. In fact, CENS from reactor neutrinos allows us to measure the weak neutral current and the Weinberg angle at low momentum transfer, while deviations could indicate new physics [4]. However, observing CENS from nuclear reactor is challenging because of the very low threshold needed to detect the low-energy nuclear recoil of the order of 100 eV and simultaneously control the background in a shallow deep environment as the one available at a nuclear plant. Recent results from CONUS+ [5] demonstrate that this could be done. The NUCLEUS experiment addresses both challenges by combining gram-scale cryogenic calorimeters with energy thresholds of around 20 eV with a target back- ground rate of 100 counts/(kg · day · keV) [6].

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2. THE NUCLEUS EXPERIMENT

WHAT IS The NUCLEUS experimental site is the so-called "Very Near Site" (VNS) at the Chooz B Nuclear Power Plant in France, a $25m^2$ room in the basement of an administrative building, positioned 102 m and 72 m from the two 4.25 GWth reactor cores. This proximity ensures a high average electron antineutrino flux of approximately $1.7 \times 10^{12} \bar{v}_e$ /s cm2 [6]. However, the low overburden of 3 m of water equivalent (m.w.e.) calls for a robust environmental background mitigation strategy. To achieve the desired background level of 100 counts/(kg day keV), multiple layers of passive and active shielding are required [6]. Within the region of interest (ROI), spanning the range from 20 eV to 100 eV, the NUCLEUS experiment [6] anticipates a total counting rate of $30\bar{v}_e$ /kg day above the background [7]. The shielding strategy was studied and optimized by Monte Carlo simulations based on gamma and neutron measurements at the VNS [8]. These studies led to the development of the experimental setup shown in Figure 1, where active and passive shield layers combined together should allow us to effectively suppress background signals and ensure the high sensitivity required for CENS detection. The outermost layer active shield comprises 28 panels 5 cm thick plastic scintillator plates equipped with wavelength shifting fibers and silicon photomultipliers (SiPMs). This system [9] combined with the cryogenic muon veto placed below the mixing chamber inside the dilution refrigerator [10]† will be able to achieve, with a detection threshold of 5 MeV, an efficiency for muon identification greater than 99% [9]. Inside the muon veto, a 5 cm thick layer of lead and a 20 cm thick layer of borated polyethylene form the passive shield that attenuate, respectively, γ and n backgrounds. As the muon veto, the lead and polyethylene shielding are deployed both outside and inside the cryostat to ensure complete coverage around the cryogenic detectors. The structure inside the cryostat located below the cryogenic muon veto disk is composed of a lead disk and several polyethylene disks, coping the external shielding structure. Despite these layers of active and passive shields, a significant amount of low energy γ and neutrons still survive, originating a significant background in the ROI for CENS observation. For these reasons, two additional shields were designed to fully cover the CENS detectors. The first one is a neutron absorber made of B4C (boron carbide) with a total thickness of about 4 cm. Inside the B4C, six high-purity germanium detectors with a total

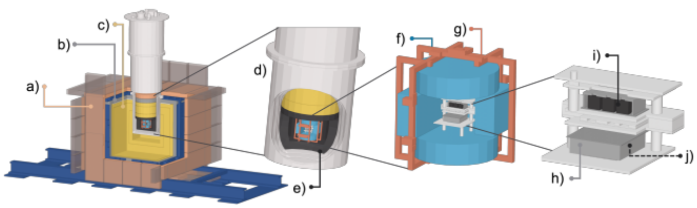

FIGURE 1: CAD rendering of the NUCLEUS experiment setup. (left–right) The full apparatus shows the mechanical shielding structure (dark blue). (a) The muon veto system (orange), composed of 28 individual 5 cm thick scintillator panels and an additional cryogenic extensions inside the cryostat, mitigates cosmic-ray muons. (b) 5 cm thick lead layer (grey) inside and outside the cryostat provides attenuation for gamma radiation. (c) 20 cm thick borated polyethylene layer (yellow) inside and outside the cryostat reduces neutron backgrounds. (d) The cryostat houses the dry dilution refrigerator, including (e) a 4 cm boron carbide layer (black) and (f) the cryogenic outer veto (COV) (light blue), made of six high-purity germanium detectors, arranged in (g) a copper holding structure (brown). The two inner detector modules of nine cubes of (i) CaWO4 and (j) Al2O3, held by (h) the silicon inner veto structure, are placed at the center to maximize thev4π-shielding coverage, ensuring a low background rate of below 100 counts/(kg · day · keV).

mass of 4 kg and a thickness of 2.5 cm, operated as ionized semiconductor A 5 cm thick disk of diameter 297 mm plastic scintillator equipped with wave- length shifting fibers and SiPMs detectors at around 10 mK, constitute the so-called cryogenic outer veto (COV) that attenuates and tags the residual $\frac{\beta}{\gamma}$ background. Within the COV, two arrays of nine CaWO4 (total mass 6 g) and nine Al2O3 (total mass 4 g),$5 \times 5 \times 5$ mm3 crystals equipped with W-TES (tungsten-based transition edge sensor) constitute the CENS detector. The CaWO4 detectors are expected to capture the CENS signal above the background; in contrast, the Al2O3 detectors will have a suppressed neutrino scattering rate, providing an in situ measurement of the background. As depicted in Figure 1, these nine target detector crystals are secured by two TES-instrumented silicon plates that serve as an inner veto system for background rejection, targeting events related to surface interactions on the one hand and mechanical stress-relaxation on the other hand. The latter is a potential candidate for the low-energy excess (LEE), a phenomenon observed across low-threshold experiments, characterized by a steep rise in event rate below a few hundred eV [11]. Simultaneous readouts from both the target detector and the holder can identify events originating from their interface. Nevertheless, this design is not yet ready to be implemented in the first phase of the NUCLEUS experiment and will be replaced with a non-instrumented copper holder. Anyhow to mitigate the contribution of the LEE, a double-TES read-out approach will be pursued. Indeed, in this configuration, particle recoils originating from the crystal volume are expected to distribute their energy among the two sensors, while signals from TES-related events occurring near a specific TES would predominantly or entirely be measured by the closest TES. This approach was validated by CRESST [12] and further advanced by the NUCLEUS collaboration [13], with double-TES detectors achieving low-energy thresholds, enabling precise LEE measurements and event identification.

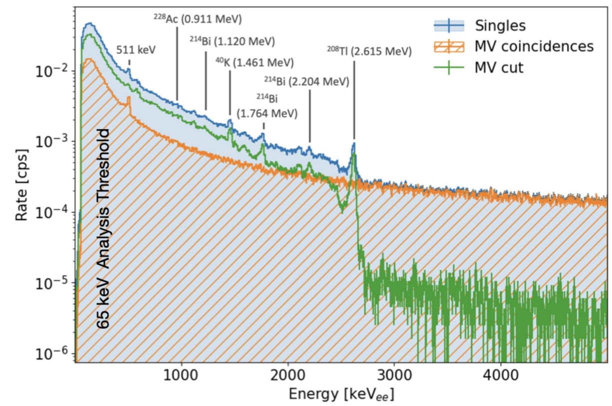

FIGURE 2: Energy spectra measured by the germanium detector. In blue the single counts, in orange the one in coincidence with the muon veto and in green the one in anticoincidence with the muon veto detector. The muon veto rejection power is at the level of 99%.

3. RESULT FROM LONG BACKGROUND RUN AT UGL

During the summer of 2024, the NUCLEUS collaboration successfully completed the commissioning of the cryogenic setup and all the subsystems described in the previous section: the full muon veto, the passive shields (without the B4C), one of the COV germanium detectors, and two CENS target crystals, one CaWO4 and one Al2O3; the Al2O3 crystal was equipped with the double-TES readout. The run was called long background run (LBR) and was performed at the shallow deep underground laboratory (UGL) at the TUM University in Munich for approximately 40 days. The LBR was intended to test the global performances of the experimental setup before the relocation into the VNS of the Chooz nuclear plant. The measured performance of the muon veto was in agreement with the expected one (¿99% tagging efficiency) as described in the caption of Figure 2. That figure shows the energy spectrum measured by the single germanium disk of the COV detector. The energy calibration was done by means of the γpeaks visible in the energy spectrum and coming from the natural environmental radioactivity (Th and U chain). The two CENS target crystals are held in a copper structure by means of bronze clamps. Al2O3 spheres are used for thermal and electrical isolation between the copper holder, the clamps, and the detector itself. The CaWO4 detector with single-TES readout is a cube with a 5 mm side length and a mass of 0.75 g; the Al2O3 detector with double-TES readout is a parallelepiped measuring $5 \times 5 \times 7.5$ mm3 with the same mass. The detectors are both cal- ibrated using the absolute calibration system exploiting LED at room temperature and a system of optical fibers that drive the LED signal up to the crystal face [14]. The working principle of the absolute calibration system is the following. Several LED signals with different durations, i.e., energy, can be sent to the detector, and for each of them, the energy deposited can be written as follows:

$$\mu = N_{ph} \cdot \epsilon \cdot r \quad (1)$$

where μ is the average amplitude in mV for each LED signal, N_{ph} the average number of absorbed photons, ϵ the energy of the photons emitted by the LED, and r the calibration coefficient. The standard deviation of such several energy deposi-

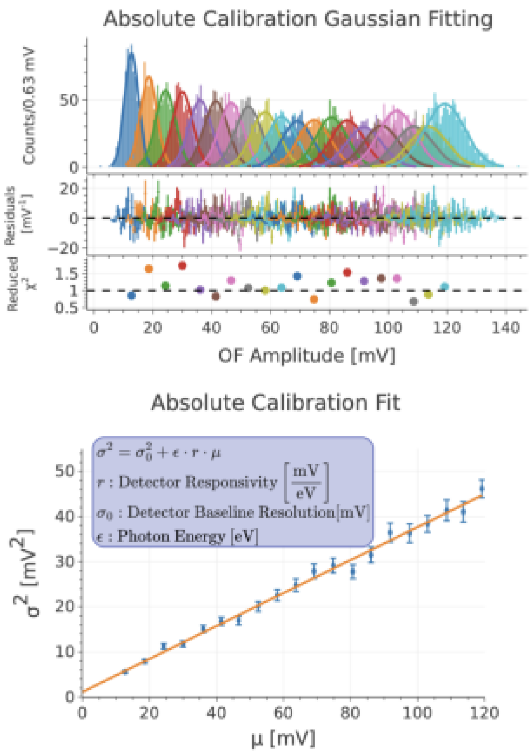

FIGURE 3: Top: Different energy depositions on the detector produced with the LED changing the time duration of the light signal, and then fitted with a Gaussian function to evaluate σ and μ. Bottom: fit of the σ_2 as a function of μaccording Eq. 3 to evaluate the calibration coefficient r.

tions σ will be given by (according to Poisson statistics $\sigma = \sqrt{N}$

$$\sigma^2 = N_{ph} \cdot \epsilon^2 \cdot r^2 + \sigma_0^2 \tag{2}$$

where σ_0 is the baseline noise RMS in mV. Combining the two equations is possible to obtain the following relation :

$$\sigma = \sqrt{\mu \cdot \epsilon \cdot r^+ \sigma_0^2} \tag{3}$$

Equation 3 has just one free parameter, the calibration coefficient r. Figure 3 shows the calibration procedure for the Al2O3 detector. The data analysis confirmed the stable oper- ation of both detectors over nearly 500 h each with approximately 80% of usable physics data with stable baseline resolutions of 6 eV RMS for Al2O3 and 7.5 eV RMS for CaWO4 achieving the targeted performances. Detailed analyses of the low-energy excess (LEE) and the comparison of the measured to simulated background level are currently ongoing.

4. CONCLUSIONS AND PROSPECTIVES

The NUCLEUS experiment aims to observe CENS from reactor neutrinos at the Chooz Nuclear Power Plant using gram-scale cryogenic calorimeters with a threshold of 20 eV. Operating at a shallow overburden of 3 m.w.e., the experimental site requires a robust shielding strategy combining active vetoes and passive layers to achieve the low background rate of approximately 100 counts/(kg day keV) necessary for successful CENS detection. The long background run to commission the NUCLEUS experiment at the underground laboratory of the Technical University of Munich demonstrates the stable operation of all systems over one month, confirming the integration of the cryogenic target detectors and their radiopure holding systems. Following this milestone, the installation at the Chooz Nuclear Power Plant is planned for 2025, enabling the NUCLEUS experiment to investigate neutrino interactions. Efforts to address the LEE through innovative detector designs are ongoing. For the first physics run, a detector module with 10 g of cryogenic detectors is under development to achieve an initial CENS measurement. A second phase, featuring a larger detector with a target mass of approximately 1 kg, is planned to enable precision measurements of the CENS cross section with several-percent accuracy [6].

5. FUNDING

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CONFLICTS OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this paper.

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