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Article

Development of the NUCLEUS Detector to Explore Coherent Elastic Neutrino-Nucleus Scattering †

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Abstract: The NUCLEUS experiment, currently being commissioned at the Technical University of Munich, is designed to observe coherent elastic neutrino-nucleus scattering (CEνNS) from reactor neutrinos and measure its cross-section with a percent-level precision at recoil energies below 100 eV. As a Standard Model process, CEνNS provides a unique probe into neutrino properties, potential new physics, and background suppression techniques relevant to dark matter experiments. The experiment utilizes gram-scale cryogenic calorimeters operating at 10 mK with an energy threshold of 20 eV. Situated at a shallow overburden of 3 m of water equivalent, the experimental site necessitates an advanced shielding strategy combining active vetoes and passive layers to reduce background rates to approximately 100 counts/(kg · day · keV), as confirmed by full setup simulations. The commissioning phase has successfully demonstrated the stable operation of the cryogenic target detectors, achieving baseline resolutions below 10 eV, and the integration of the various shielding systems. Following this milestone, the experiment is set to transition to the EdF Chooz B nuclear reactor in France in 2025, where it will enable precise measurements of CEνNS, contributing to the understanding of neutrino interactions and advancing the field of astroparticle physics.

Keywords: astroparticle physics; sub-Kelvin temperatures; cryogenic detector; particle detector; coherent elastic neutrino-nucleus scattering; CEνNS

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1. CEνNS from Reactor Antineutrinos

Coherent elastic neutrino-nucleus scattering (CEνNS) is a Standard Model process that offers a valuable probe of the Standard Model validity and new physics. The first observation of CEνNS was conducted in 2017 by the COHERENT collaboration using a 14.6 kg CsI[Na] scintillation crystal at the Spallation Neutron Source [1] which provides a pulsed neutrino beam with a flux of $4.3 \cdot 10^7\ \nu/(\mathrm{s} \cdot \mathrm{cm}^2)$ at 20 m from the source, with neutrino energies up to 53 MeV. A subsequent COHERENT measurement using argon [2] and germanium [3] probed the N^2-dependence of the CEνNS cross-section.

Nuclear reactors, with a neutrino flux of $\mathcal{O}(10^{20})\ \nu/(\mathrm{s} \cdot \mathrm{GW_{th}})$, are promising for CE$\nu$NS studies at lower energies. Reactor antineutrinos are produced in fission beta-decays and have energies up to 10 MeV, which place them fully within the coherent mode. CEνNS from reactor neutrinos allows researchers to measure the weak neutral current and the Weinberg angle at low momentum transfer, while deviations could indicate new physics [4].

Despite ongoing efforts in various collaborations, detecting CEνNS at nuclear reactors remains challenging [5]. As of December 2024, the only detection of CEνNS at a reactor was reported at the Dresden-II facility [6]; however, this finding conflicts with more sensitive searches conducted by the CONUS experiment [7]. The main challenges in observing CEνNS from nuclear reactors are achieving sub-keV detection thresholds of nuclear recoils and managing background levels in shallow-depth reactor environments [5]. The NUCLEUS experiment addresses both challenges by combining gram-scale cryogenic calorimeters with energy thresholds of around 20 eV with a target background rate of 100 counts/(kg · day · keV) [8,9].

2. The NUCLEUS Experiment

The NUCLEUS experimental site, referred to as the "Very Near Site" (VNS) at the Chooz B Nuclear Power Plant in France, occupies a 25 m^2 room in the basement of an administrative building, positioned 102 m and 72 m from the two 4.25 GW_{th} reactor cores. This proximity ensures a high average electron antineutrino flux of approximately $1.7 \cdot 10^{12}\ \bar{\nu}_e/(s \cdot cm^2)$ [9]. However, the low overburden of 3 m of water equivalent (m.w.e.) necessitates a robust cosmic-ray-induced background mitigation strategy. To achieve the desired background level of 100 counts/(kg · day · keV), multiple layers of passive and active shielding are required [9]. Within the region of interest (ROI), spanning the range from 20 eV to 100 eV, the NUCLEUS experiment anticipates a total counting rate of 30 $\bar{\nu}_e$/(kg · day) above the background [10]. The shielding strategy was studied and optimized by Monte Carlo simulations based on measurements at the VNS [11].

2.1. The NUCLEUS Target Detectors: Gram-Scale Cryogenic Calorimeters

The NUCLEUS experiment uses gram-scale cryogenic calorimeters of Calcium Tungstate ($CaWO_4$) and Sapphire (Al_2O_3), with a total target mass of 10 g. When a particle induces a nuclear recoil in the target crystal, the generated lattice vibrations propagate through the crystal via phonons. These phonons are detected by a tungsten-based transition edge sensor (W-TES) operating at the transition temperature of the tungsten film at around 10 mK [9]. The slight increase in temperature from the particle interaction results in a significant change in the TES resistance, which is read out by Superconducting QUantum Interference Devices (SQUIDs) [12]. This technology was developed within the CRESST experiment, which focuses on dark matter searches [13] and was further advanced by the NUCLEUS experiment for CEνNS detection. A prototype utilizing 0.5 g of Al_2O_3 demonstrated the proof of principle for this detection method [8,12]. To take advantage of the N^2-dependence of the CEνNS cross-section, the experiment employs a multi-target approach, featuring an array of nine $CaWO_4$ crystals (6 g) for CEνNS measurements and nine Al_2O_3 crystals (4 g) for in situ background assessment [9]. The $CaWO_4$ detectors are expected to capture the CEνNS signal above the background; in contrast, the Al_2O_3 detectors will have a suppressed neutrino scattering rate, providing an in situ measurement of the background. This background measurement with Al_2O_3 allows us to constrain the background model more precisely, thereby enhancing our sensitivity to CEνNS [9].

2.2. The NUCLEUS Inner Detector Module for the First Physics Run at Chooz

An inner detector module consisting of nine target detectors and a dedicated holding structure is currently being developed for NUCLEUS' first physics run at the nuclear power plant in Chooz. The first version of the module was built with detectors equipped with a single TES, while ongoing research investigates detectors with two TESs as an additional background-mitigation tool [14] which might be implemented in future versions.

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 to 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 [15]. Simultaneous readouts from both the target detector and the holder can identify events originating from their interface. The inner veto consists of a rigid 0.45 mm thick and a flexible 0.25 mm thin silicon plate. To minimize the contact area between the target crystals and the support structure and thereby prevent signal phonons from escaping detection in the TES of the target crystals, the contact points are implemented by silicon pyramids. These pyramids with a height of 0.2 mm are machined by the wet chemical etching of the inner veto plates and can be seen in the right insert of Figure 1. The detectors and inner veto plates are secured by two 1 mm thick silicon holding plates that provide all necessary electrical and thermal connections for the operation of the detectors and the inner veto system. Furthermore, the contact between the non-instrumented holding plates and the inner veto parts is facilitated by 1 mm thick Al_2O_3 spheres, ensuring electrical and thermal isolation. The height of the brass separation shells defines the force bending the thin inner veto silicon wafer, securing the target detectors. For the first physics run at Chooz, we target to deploy one inner detector module from $CaWO_4$ detectors (6 g) and one from Al_2O_3 detectors (4 g), representing the NUCLEUS-10 g target detector module.

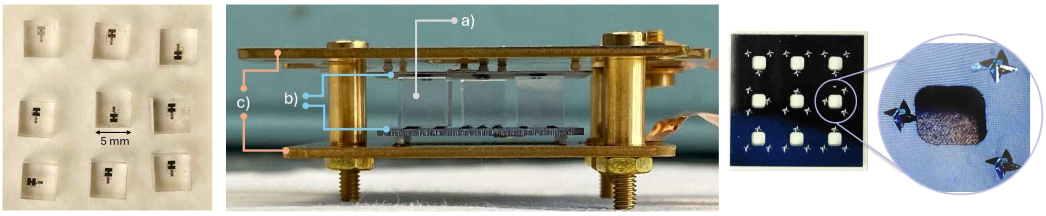

Figure 1. Photographs of a NUCLEUS inner detector module: (**Left**) Nine detector cubes equipped with a transition edge sensor (TES). (**Middle**) The first version of the detector module consisting of (a) nine Al_2O_3 cubes, each equipped with a TES, which are secured by (b) two TES-instrumented thin silicon plates that serve as the inner veto for the background rejection of events originating from both mechanical stress and surface events in the target detectors. This system is secured by (c) two non-instrumented thicker silicon plates equipped with electrical connections. (**Right**) A silicon inner veto plate with a zoom on the etched pyramids which allow contact between the holding structures and the target detectors to be minimized, reducing phonon escape and preserving detection efficiency.

2.3. *Active and Passive Shielding Layers for Background Mitigation*

The NUCLEUS experiment employs a multi-layered shielding strategy, which is shown in Figure 2, combining active and passive components to effectively suppress background signals and ensure the high sensitivity required for CEνNS detection.

The cryogenic outer veto (COV) combines six high-purity germanium detectors with a total mass of 4 kg and a thickness of 2.5 cm, operated as ionized semiconductor detectors at around 10 mK. The six COV crystals are held in place by a copper structure arranged to supply a 4π coverage around the two inner detector modules to significantly reduce ambient gamma-ray backgrounds. In addition, three layers of passive shielding are arranged inside and outside the cryostat for 4π coverage to suppress remaining critical background components. The first layer represents the boron carbide (B_4C) shield enclosed within the cryostat and surrounding the COV, which serves as the primary barrier against low-energy neutron backgrounds. The second layer, consisting of borated polyethylene, provides a barrier against neutrons. The final third layer consists of lead and offers an additional attenuation of gamma and neutron backgrounds. To address cosmic-ray muons, the outermost veto comprises 5 cm thick plastic scintillator plates equipped with silicon photomultipliers (SiPMs) and Wavelength Shifting fibers, achieving a detection threshold of 5 MeV and a simulated efficiency for muon identification of >99 % [16]. This muon veto system detects high-energy muons, which generate spallation neutrons in the lead shielding, a significant background mimicking CEνNS-like nuclear recoils. The muon veto system and the lead and polyethylene shieldings are deployed both outside and inside the cryostat to ensure complete coverage around the cryogenic detectors. The structure inside the cryostat includes a cryogenic muon veto disk, a lead disk, and several polyethylene disks, mimicking the external shielding structure. The cryogenic muon veto disk has been developed [17] to be deployed inside the cryostat above the boron carbide shield and thermalized to 800 mK. Monte Carlo simulations showed the ability of the nearly 4π-covering active and passive shielding layers to mitigate the cosmic and radiogenic background components to meet the goal of 100 counts/(kg · day · keV) in the ROI [10,11,18].

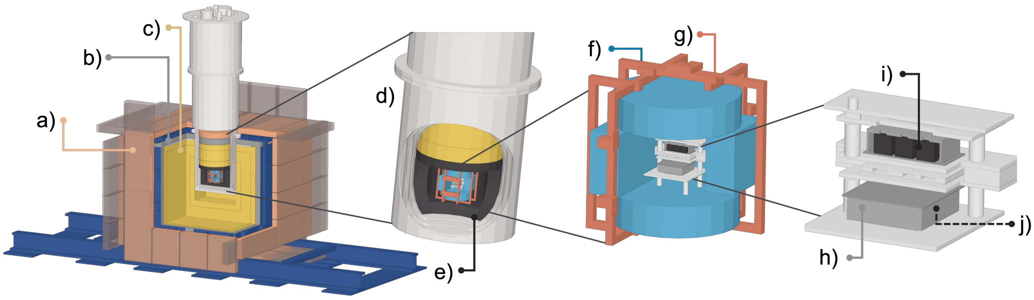

Figure 2. CAD rendering of the NUCLEUS experiment setup. (**left–right**) The full apparatus showing the mechanical shielding structure (dark blue). (a) The muon veto system (orange), composed of 28 individual 5 cm thick scintillator panels and an additional cryogenic extensions inside the croystat, mitigates cosmic-ray muons. (b) A 5-cm thick lead layer (gray) inside and outside the cryostat provides attenuation for gamma radiation. (c) A 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) $CaWO_4$ and (j) Al_2O_3, held by (h) the silicon inner veto structure, are placed at the center to maximize the 4π-shielding coverage, ensuring a low background rate of below 100 counts/(kg · day · keV).

3. Development of the Cryogenic Target Detectors for the Long Background Run to Commission the NUCLEUS Experiment at TUM

Over the course of 2023 and 2024, the various detector and shielding components were installed in the underground laboratory (UGL) at the Technical University of Munich (TUM) to commission the experiment. The commission phase involved several runs over the course of these two years to commission the sub-systems and concluded in a long background run (LBR) to demonstrate the stable operation of the full system. The major goal is to demonstrate the performance of the cryogenic target detectors in anti-coincidence with the COV and the muon veto systems and to validate our shielding strategy by comparing the measured to the simulated background data for the UGL site [19].

3.1. Cryogenic Target Detectors

While developing the cryogenic target detectors, we evaluated the performance of $CaWO_4$ and Al_2O_3 as target materials. As of December 2024, we demonstrated the reliable performance of both materials in a series of measurements conducted in the customized NUCLEUS dry dilution refrigerator. These detectors consistently achieved baseline resolutions of less than 10 eV over several weeks of operation across multiple runs. Two Al_2O_3 target detectors were simultaneously operated in the NUCLEUS inner detector module, achieving similar baseline resolutions and no cross-talk [19]. Meanwhile, other $CaWO_4$ and Al_2O_3 detectors were operated in simplified copper holders, as efforts are ongoing to develop the TES-instrumented silicon holding structures for anti-coincidence operation with the target detectors.

Multiple $CaWO_4$ detectors demonstrated excellent energy resolution of less than 10 eV over several weeks in various runs, enabling the development and validation of calibration techniques for cryogenic particle detectors. Specifically, a $CaWO_4$ detector was calibrated using nuclear recoils with the CRAB method [20] to investigate differences between nuclear and electron recoils. Another $CaWO_4$ detector was calibrated with sub-keV X-ray fluorescence lines and LED pulses [21], allowing us to explore detector non-linearities.

In addition to a detector cube with a single TES, we investigated detectors with two TESs (=the double-TES approach), developed to test a plausible source of the LEE in TES-based detectors: events arising from stress at the interface between the TES and the crystal or within the TES structure itself. Detectors with two TESs were tested to enable simultaneous and independent signal readout. In this configuration, particle recoils originating from the crystal volume are expected to distribute their energy among the 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 [22,23] and SPICE [24] and further advanced by the NUCLEUS collaboration [14,25], with double-TES detectors achieving sub-100 eV-thresholds, enabling precise LEE measurements and event differentiation.

Finally, for the LBR, we deployed a $CaWO_4$ single-TES detector cube with a 5 mm side length and a mass of 0.75 g, as is shown in the left photograph of Figure 3, as well as a Al_2O_3 double-TES detector measuring $[5 \times 5 \times 7.5]$ mm^3 with the same mass, shown in the photograph in the middle of Figure 3. Both detectors were operated at their transition temperature of approximately 14 mK. The goal of using these two target detectors was to characterize the particle background in the different target materials and further evaluate the background mitigation potential of the double-TES approach.

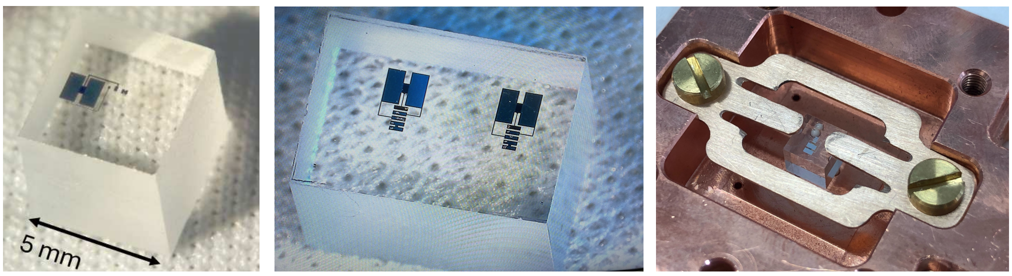

Figure 3. Photographs of the target detectors used in the LBR. (**Left**) A $CaWO_4$ detector cube equipped with a single TES. (**Middle**) An Al_2O_3 double-TES detector, featuring two independent TES sensors to investigate the LEE by differentiating crystal-originated signals from TES-related events. (**Right**) A detector cube mounted in a copper holder, secured by bronze clamps and thermally isolated using Al_2O_3 spheres between the detector and the clamp and the copper housing.

3.2. Development of the Target Detector Holders

Figure 4 shows the components of the detector holders of our cryogenic target detectors used for preparing the LBR. Each detector is completely encapsulated by a copper housing to block thermal radiation from the outside and secured with bronze clamps, as seen in the right picture of Figure 3. Al_2O_3 spheres are used for thermal and electrical isolation between the copper holder, the clamps, and the detector itself. The signal readout is facilitated by printed circuit board (PCB) traces that connect the TES wire bonds to external pin connections, where cables for the TES readout are attached. During the development phase, commercial PCBs with FR_4-cores, as shown in the left picture of Figure 4, were initially used. However, they were deemed unsuitable for the LBR due to radioactive impurities that would dominate the signal observed in our detectors [11,18]. In contrast, the customized PCB, seen in the right picture of Figure 4, is made from copper and features copper-kapton-copper traces glued to the copper plate. To further reduce background from impurities, all copper parts were fabricated from electrolytic tough pitch (NOSV) copper [26] due to its high purity and low oxygen content, enhancing the intrinsic thermal conductivity. Additionally, all components of the holders undergo a rigorous cleaning procedure involving isopropyl alcohol and acetone, followed by etching with citric acid in a hydrogen peroxide solution to effectively remove any oxidation layers and improve thermal conductivity.

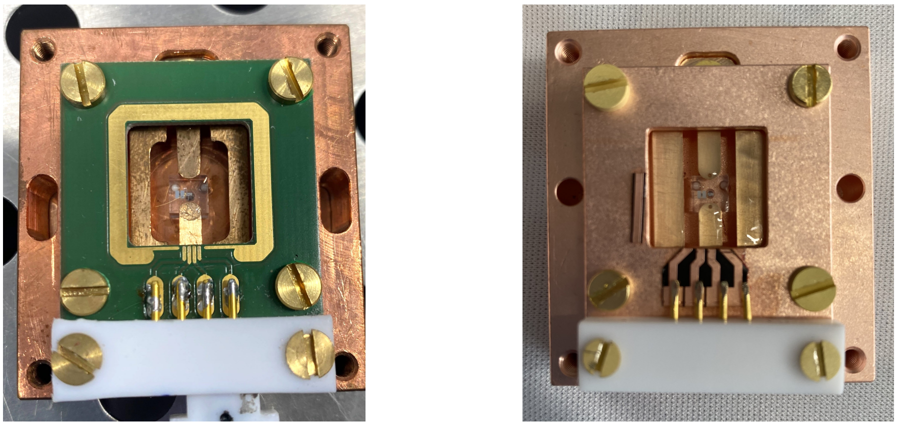

Figure 4. Photographs of the $CaWO_4$ detector cube mounted in different copper holders for the Long Background Run (LBR). (**Left**) A copper holder with a commercial PCB featuring an FR_4-core, which was later replaced due to radioactive impurities affecting the particle background. (**Right**) A refined copper holder equipped with a customized PCB made from copper-kapton-copper traces, ensuring minimal radioactive background. Both holders are made of NOSV copper and all components underwent rigorous cleaning and etching processes to improve thermal conductivity.

3.3. Status of the Commissioning

The LBR to commission the full NUCLEUS experiment at TUM concluded in September 2024, demonstrating the stable performance of the cryogenic target detectors with most of the active and passive shielding systems over more than a month. During the LBR, the full muon veto system, comprising 28 Si-PM panels and an additional cold muon veto disk, was successfully operated for approximately 40 days. The outer and inner shielding, consisting of lead and polyethylene layers, were deployed, while the B_4C layer was dispensable due to the higher overburden at the UGL site compared to the Chooz site [11].

We implemented one $CaWO_4$ detector with single-TES readout and one Al_2O_3 detector with double-TES readout, both calibrated using a customized LED calibration system [27]. Initial analyses confirmed the stable operation of both detectors over nearly 500 h each with approximately 80 % of usable physics data with stable baseline resolutions below 20 eV, achieving the targeted performance metrics. Additionally, one of the six COV Ge crystals was deployed above the target detectors and successfully operated at the same time. Detailed analyses of the cryogenic detectors in anti-coincidence with the COV and muon veto systems, as well as investigations of the low-energy excess (LEE) and the comparison of the measured to simulated background level, are currently ongoing.

4. Conclusions and Outlook

The NUCLEUS experiment aims to observe CEνNS 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 $100\,\mathrm{counts}/(\mathrm{kg}\cdot\mathrm{day}\cdot\mathrm{keV})$ necessary for successful

CEνNS 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 a one-month period, confirming the integration of the cryogenic target detectors and their radio-pure 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 CEνNS measurement. A second phase, featuring a larger detector with a target mass of approximately 1 kg, is planned to enable precision measurements of the CEνNS cross-section with several-percent accuracy [9].

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Data Availability Statement: The datasets presented in this article are not readily available because the data are part of an ongoing study that will be published in a separate detailed paper about the long background run and about the simulations performed for the NUCLEUS experiment. Requests to access the datasets should be directed to nicole.schermer@tum.de.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CEνNS	Coherent elastic neutrino-nucleus scattering
m.w.e.	Meters of water equivalent
ROI	Region of interest
TES	Transition edge sensor
LEE	Low energy excess
COV	Cryogenic outer veto
SiPMs	Silicon photomultipliers
UGL	Underground laboratory
TUM	Technical University of Munich
LBR	Long background run
PCB	Printed circuit board

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