Exploring coherent elastic neutrino-nucleus scattering of reactor neutrinos with the NUCLEUS experiment

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Abstract

The NUCLEUS experiment aims to perform a high-precision measurement of Coherent Elastic Neutrino–Nucleus Scattering (CEvNS) at the EdF Chooz B nuclear power plant in France. CEvNS is a unique process to study neutrino properties and to search for physics beyond the Standard Model. The study of CEvNS is also important for light Dark-Matter searches. It could be a possible irreducible background for high-sensitivity Dark-Matter experiments. NUCLEUS is based on ultra-low threshold (∼20 eV$_{nr}$) cryogenic

calorimeters, operated at tens-of-mK temperatures. At present, the experiment is under construction at the Technical University Munich, and will be followed by a commissioning phase before being relocated to the reactor site.

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1 Introduction

The NUCLEUS experiment aims to detect Coherent Elastic Neutrino-Nucleus Scattering from reactor neutrinos. Reactor electronic anti-neutrinos, created by β-decays of the fission products, have energies up to 10MeV. With such a low energy, they necessarily interact by neutral current with the nucleus as a whole, it is the so-called "fully coherent regime" of Neutrino-Nucleus Elastic Scattering. Moreover nuclear reactors, with $\mathcal{O}(10^{20})$ neutrinos produced per GW_{th} and per second, are copious sources of neutrinos, making them promising sources to observe CEvNS. They offer a way which is complementary to experiments running at stopped-pion sources (e.g. COHERENT [1]) and which study CEvNS in a higher energy regime.

CEvNS is a new probe to test the Standard Model and to search for new physics. CEvNS can be used to look for the sterile neutrino, study electromagnetic properties of the neutrino [2], measure the Weinberg angle at low momentum transfer [3] or look for non standard interactions [4]. The measurement of CEvNS is closely connected to Dark Matter searches. Both are sharing the same experimental signature: a sub-keV nuclear recoil and a similar detection technique based on cryogenic bolometers. The synergy between DM searches and CEvNS expands to the characterisation of "the neutrino floor", which will ultimately limit the sensitivity of the current and next generation of experiments in the low mass regime.

By being a neutral current interaction, CEvNS is flavor independent. In addition, as opposed to the Inverse Beta decay (IBD) detection channel, CEvNS has no energy threshold. Also, it exhibits up to a two orders of magnitude boost in the cross-section when compared to the IBD cross-section. This boost depends on the squared number of neutrons in the target nucleus. As a consequence, the heavier the target, the higher the cross-section, but the lower the recoil energy. Therefore, the choice of the target material should find a good compromise between high counting rate and detectable nuclear recoils. The challenges to observe CEvNS from reactor neutrinos are similar to the ones tackled by rare event Dark Matter search experiments in the low WIMP mass regime. First, the need to reach a low nuclear recoil threshold and second, a good background mitigation to achieve a low background level. The shallow overburden often imposed by the location of nuclear reactors is an additional challenge for reactor neutrino experiments and requires a good shielding strategy to discriminate cosmic-rays induced backgrounds that become dominant above ground.

The NUCLEUS experiment will use gram-scaled cryogenic calorimeters to detect CEvNS from reactor neutrinos at the Chooz B Nuclear Power Plant in France. The detection principle and the experimental apparatus are described in the following section.

2 The NUCLEUS experiment

The NUCLEUS experimental site, called the "Very Near Site", is a $25m^2$ room in the basement of an administrative building located at 102m and 72m from the two 4.25 GW_{th} reactor cores of the Chooz B nuclear Power Plant in France. This location guarantees a high neutrino average flux of about 1.7×10^{12} $\nu/(s\,cm^2)$. Nevertheless, its low overburden (3 meter water equivalent) implies the need of a relevant cosmic-ray induced background mitigation strategy [5]. Several layers of passive and active shielding are necessary in order to reach a background level of 100 counts/(kg day keV). In the region of interest, between 20 eV and 100 eV, a total counting rate of 30 ν/(kg day) above background is expected in the NUCLEUS experiment.

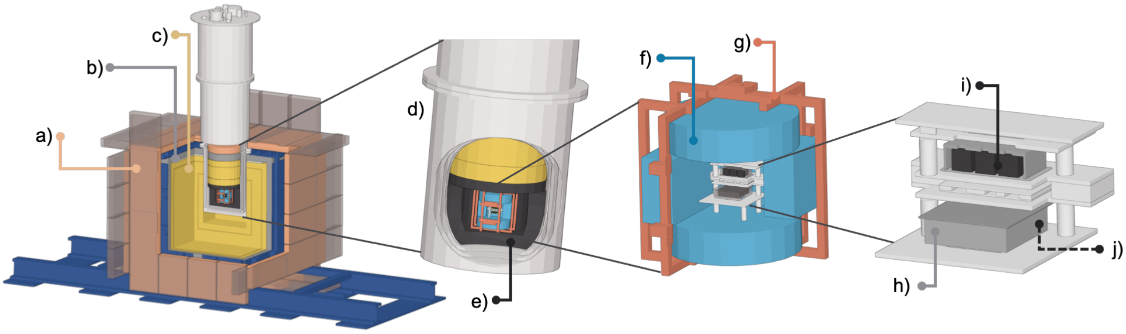

Figure 1: CAD drawing of the NUCLEUS experiment. **From left to right**, the full NUCLEUS apparatus with the shielding mechanical structure (dark blue), **a)** 28 5-cm thick Muon Veto panels, **b)** a 5-cm thick lead layer, and **c)** a 20-cm thick borated polyethylene. **d)** A dilution refrigerator is inserted inside the shielding and contains **e)** a 4-cm thick boron carbide layer and **f)** a Cryogenic Outer Veto made of six high purity germanium crystals held by **g)** a copper cage. Finally the cryogenic detectors are organised in two arrays of nine cubes of **i)** $CaWO_4$ and **j)** Al_2O_3, held by **h)** the silicon inner veto.

2.1 The NUCLEUS target detectors: gram-scaled cryogenic calorimeters

Gram-scaled cryogenic calorimeters made of Sapphire (Al_2O_3) and Calcium Tungstate ($CaWO_4$), will be used, totaling 10g of detectors. They are based on the technology developed by CRESST for Dark Matter searches [6]. When a particle induces a nuclear recoil in the target crystal ($(5mm)^3$ cubes of Al_2O_3 and CaO_4 for NUCLEUS) it creates a lattice vibration which is travelling along the crystal through phonons. This lattice vibration is read out by a Transition Edge Sensor made of Tungsten (W-TES). The detector is operated at the transition temperature of the Tungsten film, so the slight rise of temperature induced by phonons means a significant rise of the TES resistance which can be read-out by a SQUID (Superconducting QUantum Interference Device) [7]. A prototype made of 0.5g of Al_2O_3 showed the first proof of principle by reaching a threshold of $E_{th} = (19.7 \pm 0.9)$ eV_{nr} [8].

The NUCLEUS experiment is taking advantage of the N^2-dependency of CEvNS cross section by using a multi-target approach (see figure 2a) with an array of 9 $CaWO_4$ cubes (6g) to measure CEvNS and an array of 9 Al_2O_3 (4g) to perform an in-situ background measurement [5]. In July 2022, 18 $CaWO_4$ individual cubes have already been equipped with W-TES and have been successfully tested. Comparable performances have been achieved in the NUCLEUS dry refrigerator with respect to the early prototype operated in a wet fridge. The Al_2O_3 crystals are currently under tests.

2.2 The NUCLEUS active and passive shielding layers

The crystals will be held by an TES-instrumented silicon structure. In addition to the support function, this holder, called Inner Veto (IV), will be operated in anti-coincidence in order to reject surface and mechanical-stress relaxation related events. A first mock-up has been mechanically and thermally tested with Si detector dummies. New tests will soon be performed with the $CaWO_4$ crystals. The Inner Veto prototype geometry is shown in figure 2 b). In the near future, the Si bottom wafer will be replaced by a Si beaker to maximise the coverage of the veto.

The next veto system is called Cryogenic Outer Veto (COV) and is made of six 2.5-cm thick high purity germanium crystals read out in ionisation mode with a threshold of $\mathcal{O}(10\text{ keV})$. They form a 4π-covering active shielding against external backgrounds (mainly against ambient radioactivity and atmospheric muons). Tests with a prototype proved the possibility to use it in anti-coincidence mode with a bolometric detector [9]. The two final cylindrical crystals have already been prepared, tested and validated. The four rectangular ones are under production and will soon be tested as well. The COV and the cryogenic detectors will be held by a copper cage suspended to a spring system to decouple the detectors from the cryostat vibrations [10].

a) b) c)

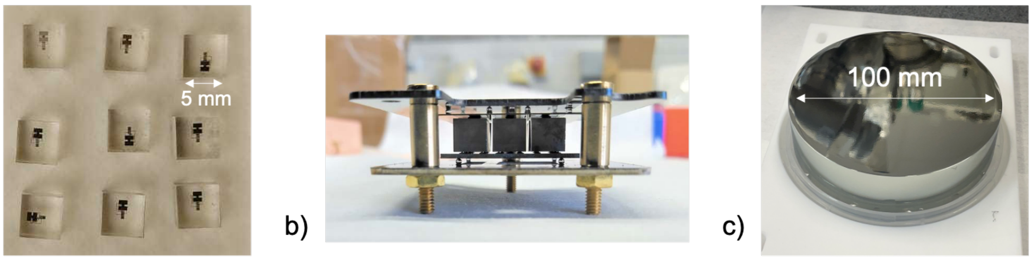

Figure 2: Photographs of NUCLEUS detector crystals and IV prototype. **a)** Nine $CaWO_4$ cubes cut and equipped with W-TES. **b)** Inner Veto mock-up with nine Si detector dummies. **c)** High Purity Ge crystal of the future NUCLEUS Cryogenic Outer Veto.

The most external shielding system is located at room temperature. It is made of 28 5-cm thick scintillating plastics read out with optical fibers and Silicon PhotoMultipliers (SiPMs) and acts as a muon veto. A module prototype of the Muon Veto (MV) has been completely validated and characterised [11]. The final modules are under production and will soon be integrated to the structure. In order to reach a geometrical efficiency $> 99\%$, the coverage of the MV is increased to 4π by adding a Cryogenic Muon Veto at the 800mK stage inside the cryostat. First measurements proved its efficiency without loss of scintillation in cold conditions [12].

In addition to the three active vetos, passive shields are covering the detector in both cryogenic and external stages. First, a 5-cm thick lead layer is used to shield the gammas from ambient radioactivity. The 20-cm thick 5% borated polyethylene layer reduces the impact of secondary neutrons and moderates and attenuates atmospheric neutrons. Finally, an up-to-4-cm thick boron carbide (B_4C) layer will be added inside the cryostat, the closest to the detectors. Its role is to capture slow and thermal neutrons reaching the vicinity of the detectors provoked by the interaction of fast neutrons with the several shielding layers of the experiment. Those neutrons produce recoils in the region of interest by elastic scattering and then mimic exactly the neutrino signal. The importance of such a layer has been demonstrated by Monte Carlo simulations [13].

3 First estimate of NUCLEUS background

In order to estimate the background level in the target crystals, extensive Geant 4 [14] Monte Carlo simulations are run. The full NUCLEUS apparatus geometry has been implemented as well as the vetoes anti-coincidence cuts with their respective thresholds (30eV for the IV, 1keV for the COV, 5MeV for the MV). In addition, an anti-coincidence between the crystals is applied with a 10eV threshold. Atmospheric muons, atmospheric neutrons and ambient gammas have been identified as the main contributors of background for NUCLEUS. A first set of simulations permitted to optimise the shielding geometry. Preliminary results demonstrated a good mitigation of the expected background from the NUCLEUS shielding geometry and the possibility to reach the goal level of <100 counts/(kg day keV) [13].

Many rare event search experiments observe an exponentially rising background at sub-keV energies close to their respective threshold. This rise still has an unknown origin and currently overwhelms our knowledge about external backgrounds in this energy regime [15]. Even if this excess represents a challenge for the NUCLEUS targeted background level, the previously described background mitigation strategy will allow investigating its origin and nature.

4 Conclusion and outlook

The NUCLEUS experiment aims at observing to observe CEvNS from reactor neutrinos at the Chooz B Nuclear Power Plant using gram-scaled cryogenic calorimeters with a 20eV_{nr} threshold. MC 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.

The blank assembly phase is now proceeding at the underground laboratory of the Technical University of Munich, with a commissioning phase likely to start at the beginning of next year. The goal of this phase is first, to test the mechanical integration but also to perform calibrations at keV energies and below with LED systems, XRF and neutron source (with the CRAB project [16,17]). The installation at the Chooz complex is then expected to happen at the end of 2023 to be ready to start the physics run beginning of 2024. This first phase of NUCLEUS with 10g of detectors aims to perform a first measurement of CEvNS. A second phase with a larger detector (1kg) is expected to come later in order to achieve a precision measurement of CEvNS cross-section at the several percent level.

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