PROCEEDINGS OF SCIENCE

NUCLEUS: cryogenic calorimeters to detect coherent nuclear scattering of reactor anti-neutrino

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NUCLEUS is an experiment conceived for the detection of the coherent elastic neutrino nucleus scattering. The experiment will be carried out in the nuclear power plant of Chooz-B in France that provides an intense flux of anti-neutrinos. The aim of NUCLEUS is to perform a very precise measurement of the coherent elastic scattering below 100 eV by employing extremely sensitive cryogenic detectors based on $CaWO_4$ and Al_2O_3 target crystals. At present, the NUCLEUS apparatus is in commissioning phase at the Underground Laboratory of the Technical University Munich, where - after its installation and the first measurement phase - the experiment will be fully tested. Thereafter the entire apparatus will be moved to the reactor site at Chooz.

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1. Introduction

Coherent elastic neutrino nucleus scattering (CEνNS) is a Standard Model process predicted in 1973 [1] but observed for the first time only in 2017 [2]. Its study can reveal non-standard neutrino properties and can allow to search for new physics beyond the Standard Model [3, 4].

The CEνNS cross section scales quadratically with the number of neutrons in the nucleus and, in medium size nuclei, it can be up to two orders of magnitude larger than in other neutrino interactions [3]. Its detection is, anyhow, challenging because of the very low recoiling energy of the nucleus that is of order of tens or hundreds of eV for MeV neutrinos. The study of CEνNS requires a very intense neutrino or anti-neutrino source in MeV range, a very low threshold detector at the order of 10 eV and well controlled and low background level in the sub-keV range. The detector features can be satisfied by the cryogenic bolometers developed in the last decades for direct Dark Matter investigation. The NUCLEUS experiment has been proposed with the aim to perform a high precision measurement of the CEνNS by using the very intense flux of anti-neutrinos produced in the β decays of the fission products at the two reactors of the Chooz nuclear power plant in France. NUCLEUS is based on the detector technology of the CRESST Dark Matter experiment [5]. As targets it will employ $CaWO_4$ and Al_2O_3 gram-scale crystals which are operated as calorimeters at mK temperature with ultra-low energy threshold and placed inside active and passive shields to reduce the background level.

2. The NUCLEUS experiment

The NUCLEUS experiment will be carried out at Chooz B nuclear power plant located in the Ardennes department in France and operated by the EDF [6, 7]. The NUCLEUS experimental site, called “Very Near Site” (VNS), is a 24 m^2 room in the basement of an administrative building of the nuclear plant. The room has 3 m.w.e. overburden and is located at a distance of 102 m and 72 m from the two 4.25 GWth reactor cores. At the VNS the anti-neutrino flux is 1.7×10^{12} $\nu/(s \cdot cm^2)$ with energy in the 0-8 MeV range and mean value of 1.5 MeV. Anti-neutrino from the cores are produced via the β decays of the fission products of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu. The expected counting rate for CEνNS in $CaWO_4$ and Al_2O_3 between 20 eV and 100 eV is about 30 $\nu/(kg \cdot day)$. In order to identify the presence of such a signal in the NUCLEUS experiment the required background level is 100 cpd/kg/keV in the region of interest.

Since the overburden of the VNS is small, the background of cosmic origin (i.e. mainly muons, neutrons and their secondaries) has to be suppressed by using passive and active techniques. No effect due to the neutron background from the reactor cores is expected. Measurements of neutron and muon flux at the site have been carried out by the Collaboration [7]. In order to characterize the VNS room, a campaign of environmental gamma measurements have been also performed. These measurements allow to have an estimation of the background and to optimize the set-up to achieve the background level goal.

The main part of the NUCLEUS set-up are: i) $CaWO_4$ and Al_2O_3 target crystals; ii) Silicon Inner Veto enclosing the target crystals; iii) a Cryogenic Outer Veto made of high purity Germanium detectors; iv) a cryostat hosting the target detectors and the so called Inner Cold Shield; v) passive

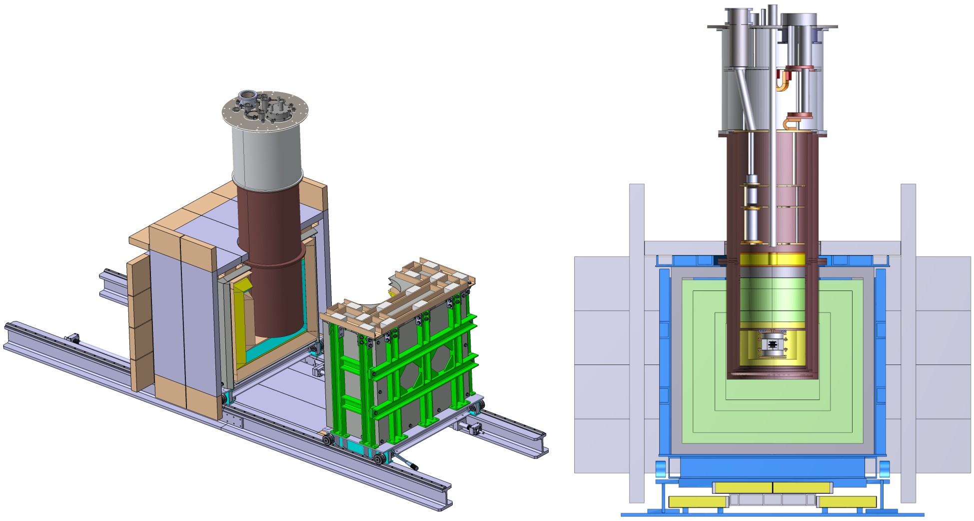

Figure 1: The two figures show the NUCLEUS set-up. In the picture on the left the design of the complete set-up is depicted. The Muon Veto, the passive shield surrounding the cryostat and the mechanical structure supporting the Muon Veto plate are shown. The shield is composed by two identical parts that can be opened and translated along a railway to ease the access to the cryostat. In the picture on the right a section of the set-up is reported; the different layers of the passive/active shield, the Cold Outer Veto and the inner detectors are shown.

shield made of several layers of different materials; vi) external muon detectors supported by a mechanical structure. The set-up is shown in Figure 1.

2.1 The target crytals and the inner veto

The target detector is composed by two array of 3×3 crystals, each of volume $0.5 \times 0.5 \times 0.5$ cm^3, composed respectively by $CaWO_4$ (total mass $\simeq$ 6 g) and Al_2O_3 (total mass $\simeq$ 4 g) cryogenic calorimeters. They will operate at mK, i.e. at the transition temperature of the Tungsten film, and the phonons readout is assured by Transition Edge Sensor made of Tungsten (W-TES). These allow to measure with high accuracy the slight rise of temperature subsequent to the interaction of a particle with the target nuclei. The use of a multi target detector is crucial in NUCLEUS to exploit the N^2-dependence of the CEνNS cross section in order to identify the signal above the background. A prototype based on a 0.5 g Al_2O_3 crystal reached an energy threshold of (19.7 ± 0.9) eV [8]. In Summer 2022, an array of 18 $CaWO_4$ crystals has been produced and the single crystals have been successfully characterized and tested. An array of 3×3 $CaWO_4$ crystals is shown in Figure 2-left. Tests on Al_2O_3 crystals are in progress.

The target crystals are held in a Silicon beaker support structure where two wafers press the crystal arrays (see Figure 2-right). This structure is also instrumented with TESs and acts as an active Inner Veto able to reject surface backgrounds and holder-related events such as mechanical stress relaxation events. A mock-up has been realized and mechanical and thermal test have been successfully carried out.

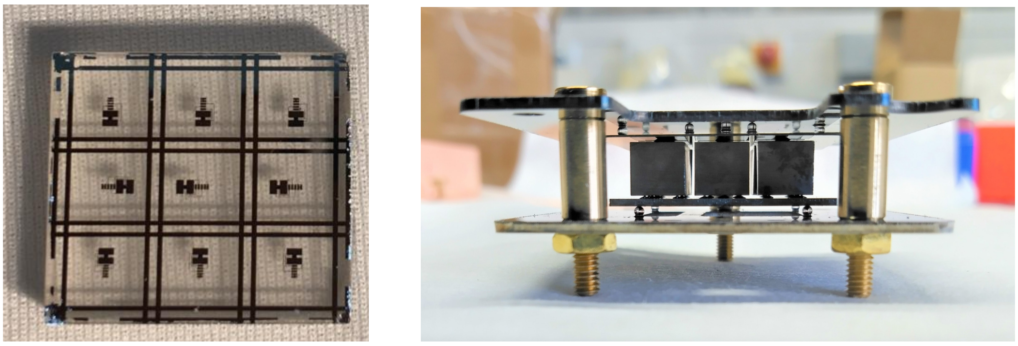

Figure 2: The picture on the left shows an array of 9 $CaWO_4$ crystals instrumented with TESs before the cut into individual crystals. The size of each crystal is $0.5 \times 0.5 \times 0.5$ cm^3. In the picture on the right the mock-up of the Inner Veto with dummy detectors is shown; the Si wafer, that pushes the crystal together, is visible with the holding plate where electrical and thermal contacts are connected. Between the holding plates and the wafer layers, sapphire balls are also present to assure mechanical stability.

2.2 The active and passive shield

The most internal active shield, placed inside the cryostat, is represented by the so-called Cold Outer Veto (COV). It is a high purity Germanium detector composed of 6 crystals (two of cylindrical and four of rectangular shape) fully enclosing the inner detectors. The COV will be about 10 cm in height, 10 cm in diameter and 2.5 cm thick. It will operate at few keV energy threshold. Its main purpose is to allow an effective rejection of muons, environmental and muon-induced gammas and neutrons entering the inner detectors. The two final cylindrical crystals have already been prepared and validated [9]. The four rectangular ones are in production and will be instrumented and tested soon. The COV will be supported by a copper cage suspended to a spring system to decouple the detectors from the cryostat vibrations [10].

A multi layer passive shield encloses the cryogenic detectors and the cryostat. It is of cubic geometry with an outer edge length of about 1 m. This shield, from outside to inside, is composed by: i) 5 cm of low radioactive lead to strongly reduce the environmental gammas; ii) 20 cm of 5% Boron loaded Polyethylene (PE) to mainly moderate and adsorb neutrons; iii) 4 cm of B_4C placed inside the cryostat to capture the neutrons surviving the PE shield and reaching the inner detectors. A Monte Carlo simulation, in fact, showed that this neutron component, if not reduced, would produce a relevant nuclear recoil signal in the region of interest for the CEνNS.

An Inner Cold Shield is placed inside the cryostat to fill the space not covered by the external passive shield. Disks of lead and borated PE, of the same thicknesses as the external shield layers, are accommodated over the COV and aligned with the external shield. Copper disks and slices keep in contact the different cold shield parts to facilitate thermalization. An active Cold Muon Veto composed by plastic scintillator is also placed over the Inner Cold Shield. Inner Cold Shield and Cold Muon Veto are at the 800 mK stage [11].

Finally the external passive shield is totally surrounded by a Muon Veto made of 28 plastic scintillators of 5 cm thickness. They have optical fibers as light collector and Silicon PhotoMultipliers as light readout. A module prototype of the Muon Veto has been completely validated and characterized [12]. The other modules are under production. A mechanical structure supports the

Muon Veto panels and keeps them close to the external passive shield. The shield is composed of two symmetrical parts that can be opened by sliding them on a railway to easily access the cryostat (see Figure 1).

3. The NUCLEUS potentiality for CEνNS detection

Simulation studies based on Geant4 have been extensively performed to optimize the design of the NUCLEUS set-up and to obtain an estimation of the background counting rate expected in the different detectors and, in particular, in the target crystals.

The full NUCLEUS apparatus geometry has been implemented in a dedicated code. The preliminary results demonstrate that, in the present NUCLEUS configuration, the target level of <100 counts/(kg day keV) for the background can be reached [13]. In particular, as mentioned, the reactor correlated background component is negligible while the main background contributions are: atmospheric muons and neutrons and the secondary particles produced in the interaction of these particles with the set-up, environmental gammas and radiation from radioactive contamination in the material surrounding the detectors. Passive shield, active veto and the capability of the multi target detectors to reject coincidence events in the crystals are able to reduce the background to the design level.

To give an estimation of the reachable sensitivity of NUCLEUS some examples can be considered. In the simplest hypothesis of a flat background < 100 cpd/kg/keV in the region 10-1000 eV, a 20 eV energy threshold for the calorimeters and an average reactor power of 80%, the CEνNS signal can be pointed out at 5σ in about 40 days of measurement. In the hypothesis of an exponential and a flat background, rising exponentially below about 300 eV, by profiting from the presence of $CaWO_4$ and Al_2O_3 target crystals, an observation of the CEνNS at about 5σ in 1 year could be achieved [14].

It is worth to note that in the last years low threshold experiments have observed an exponentially rising background at sub-keV energy range. The origin of this excess is still not clear [15]. Even if this excess represents a challenge for the NUCLEUS targeted background level, the veto system of NUCLEUS can help investigate its origin and its nature.

4. Conclusion and outlook

The NUCLEUS experiment is now in its blank assembly phase. The experimental design was finalized in May 2022 and the set-up assembly is in progress at the UGL underground laboratory of the Technical University of Munich. The assembly is expected to be concluded at the beginning of 2023 when the commissioning phase will start. The goal of this phase is to optimize the mechanical integration and to test the operations of all parts of the set-up. Calibrations at keV energies and below with LED systems, X-ray fluorescence and neutron source (with the CRAB project [16]) are foreseen. The deployment of the NUCLEUS set-up at the Chooz nuclear power plant is expected for the end of 2023 and the start of the physics run for the beginning of 2024. This first phase of NUCLEUS with 10 g target crystals aims to point out the presence of the CEνNS signal. A second phase with a 1 kg scale detector is then expected for the future with the aim of measuring the CEνNS cross-section with an uncertainty at a few % level.

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