PROCEEDINGS OF SCIENCE

The NUCLEUS experiment: a search for coherent elastic neutrino-nucleus scattering with reactor antineutrinos

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Coherent elastic neutrino-nucleus scattering (CEνNS) offers a unique way to study neutrino properties and to search for new physics beyond the Standard Model. The NUCLEUS experiment aims at measuring the CEνNS signal from reactor antineutrinos using newly developed cryogenic detectors with ultra-low recoil energy threshold. The experiment is currently under construction for a blank assembly and later planned to be installed in between the two 4.25 GW$_{\text{th}}$ nuclear reactors of the Chooz B power plant in the French Ardennes. This proceeding presents an overview of the first phase of the NUCLEUS experiment. A general description of the experimental apparatus and its expected sensitivity to the CEνNS is provided.

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1. Introduction

NUCLEUS [1] is designed to measure precisely the CEνNS cross-section using low energy reactor antineutrinos. CEνNS is a neutral current interaction originally suggested in 1974 by D. Freedman [2]. At low energies, typically below 50 MeV, neutrinos see any target nucleus as whole rather than a set of individual nucleons, thus leading to a significant boost of the elastic scattering cross-section. CEνNS is a thresholdless process insensitive to the neutrino flavor with a cross-section that scales with the squared number of neutrons ($\sigma_{CE\nu NS} \sim N^2$). The CE$\nu$NS signal consists in a standalone nucleus recoil whose energy typically lies below the keV regime. The CEνNS process was observed for the first time in 2017 by the COHERENT collaboration at 6.7σ C.L. using neutrinos emitted by the Spallation Neutron Source (SNS) at the ORNL and a 14.6 kg CsI[Na] scintillator detector [3]. Despite a high cross-section, measurement of CEνNS at reactors still represents an experimental challenge, requiring detections setup with both ultra low energy thresholds and high background discrimination capabilities. As of today, no measurement of the CEνNS process has been achieved using reactor antineutrinos. The CEνNS process is a unique low-energy probe of the Standard Model that holds the potential of a broad field of research such as measuring the Weinberg angle at low momentum transfer, investigating a possible neutrino magnetic dipole moment or testing the sterile neutrino hypothesis. Taking advantage of the intense antineutrino flux emitted by nuclear reactors, CEνNS could potentially allow to perform precision physics with drastically smaller detectors than those commonly used by inverse beta decay experiments.

2. The NUCLEUS experiment

NUCLEUS is a two-phase experiment aiming to scale a 10-g multi target (1st phase) detection setup up to a 1-kg Ge and Si payload (2nd phase). The NUCLEUS detector technology relies on developments achieved within the CRESST direct dark matter search experiment [4]. The NUCLEUS-10g detector will be composed of $CaWO_4$ and Al_2O_3 cryogenic calorimeters with demonstrated ultralow thresholds of 20 eV [5]. The use of two different materials with different cross-section aims at improving the characterization of backgrounds in the direct vicinity of the target detectors. Because of the high tungsten nucleus mass, the $CaWO_4$ target detectors will be sensitive both to the backgrounds and the CEνNS signal, while the Al_2O_3 target detectors will essentially perform a background only measurement. The experiment will be installed at the so-called Very Near Site (VNS). The VNS consists in a 24 m^3 basement room of an administrative building located at respectively 72 m and 102 m of the two 4.25 GWth pressurized water reactors of the Chooz B nuclear power plant. The ~3 mwe overburden offers a modest reduction factor of ~1.4 of the atmospheric muon flux, as well as a ~8 reduction factor in the neutron flux with respect to surface conditions. The source consists in a pure $\bar{\nu}_e$ flux originating from the beta decay of unstable radio-isotopes produced either by the fission or the neutron activation of the uranium and plutonium content of the nuclear fuel. With ~6 $\bar{\nu}_e$ emitted per fission and ~200 MeV released per fission, an intense average flux of $\sim 1.7 \times 10^{12}$ cm$^{-2}\cdot$s^{-1} is expected at the VNS assuming a reactor power loading factor of 80 %. The CEνNS signal expected at the VNS can be observed in figure 1 for multiple materials. A ~5 times higher signal rate is expected in the $CaWO_4$ detectors than in the Al_2O_3 ones. The CEνNS cross-section can be inferred by comparing the rates and shape of the recoil spectrum measured in each array with a prediction of the expected recoil spectrum assuming the Standard Model CEνNS cross-section.

3. The NUCLEUS-10g experimental setup

The target detectors consist of two 3x3 arrays of $CaWO_4$ (6 g) and Al_2O_3 (4 g) equipped with thin-film tungsten Transisition Edge Sensors (TES). A 19.7 eV recoil energy threshold was demonstrated on a first Al_2O_3 cubic prototype with 5 mm edge in 2017 [5]. The target detectors are embedded into instrumented inner veto detectors, both protecting against alpha and beta surface backgrounds, as well as low energy events potentially induced by mechanical stress relaxation in the detector surroundings. An inner veto detector consists of a silicon rectangular beaker, hosting the target detectors, and closed by a 200 μm thick flexible silicon wafer. The inner vetoes are equipped with a TES readout system of <1 keV trigger threshold and an optical light calibration system. The target detectors along with the inner veto detectors are encapsulated in a cryogenic outer veto, which is a 4π assembly of 6 2.5-cm thick HPGe crystals operated in ionisation mode to actively shield against external neutron and gamma radiations. The outer veto is installed inside a Bluefors cryostat equipped with a pulse tube dilution refrigerator reaching a base temperature of $\sim$10 mK. The cryostat is surrounded by an external passive shield consisting of graded layers of lead and borated PE to reduce the ambient gamma and neutron backgrounds. The passive shielding is covered by a muon veto consisting of 5-cm thick plastic scintillators read out by WLS fibers connected to SiPMs, and ensuring a >99% geometric coverage. The experimental setup is presented in figure 2. The commissioning of the full detector apparatus will begin at the TUM underground laboratory in early 2022. The experimental setup will be relocated at Chooz in 2023 to start it first physics run.

4. Sensitivity of NUCLEUS-10g

The sensitivity of the NUCLEUS-10g experimental setup was investigated for different background scenarios [1]. With the hypothesis of a simple and optimistic flat background signal of 100 counts/(kg·keV·day) with a recoil energy threshold of 20 eV, a 5σ observation of a CEνNS is achievable in ~40 days of data taking as shown in figure 1. Because NUCLEUS is aiming at measuring a signal in a poorly explored energy range with unknown background shape and rate, a conservative background model adding an exponential rise towards low energy to a flat component was also investigated. While background scenarios mimicking the CEνNS signal were found to be detrimental to the sensitivity, the multi-target approach of NUCLEUS-10g has the potential to strongly mitigate the impact of an unknown background shape. In the case of a signal-like background, a 4σ observation can still be reached after about one year of data taking.

5. Conclusion

Gram-scale cryogenic calorimeters are a very promising technology to measure CEνNS with reactor neutrinos. Thanks to an unprecedented and demonstrated low energy threshold of 20 eV, NUCLEUS-10g aims to measure CEνNS at a 10% level precision within a year of data taking.

A measurement with a precision of 1% is expected to be in reach of the second phase with the deployment of a kg-scale detector.

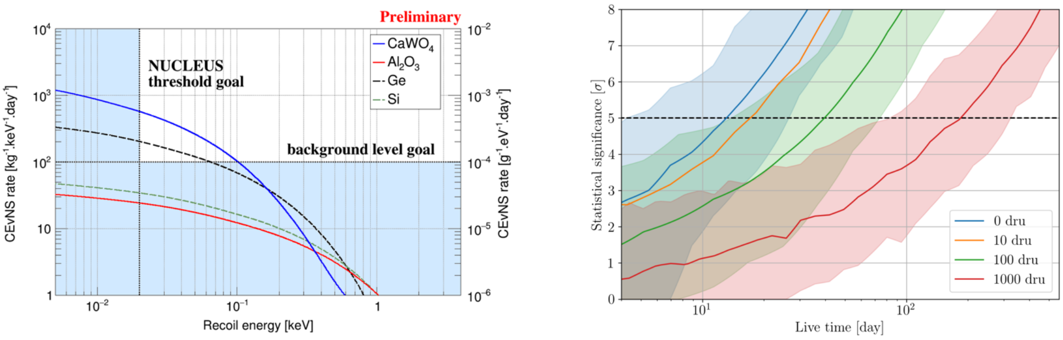

Figure 1: Left: differential CEνNS rate expected at the VNS for different target materials assuming an average loading factor of 80% of the reactors. Right: statistical significance of CEνNS observation as a function of live time for NUCLEUS-10g, for different background indices, using an energy threshold of 20 eV. 1 differential rate unit (dru) corresponds to 1 event per keV per kg per day. For each background index, the median line and 90% probability bands are shown [1].

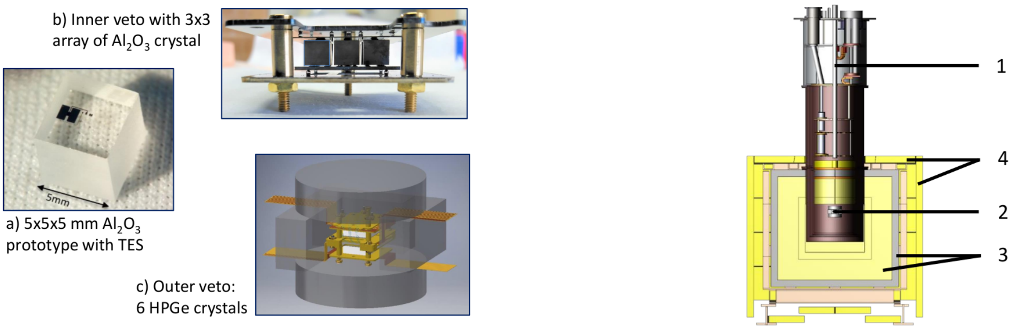

Figure 2: Left: pictures and sketch of the Al$_2$O$_3$ single crystal prototype (a), Al$_2$O$_3$ crystal array embedded in an inner veto prototype (b) and of the outer veto (c). Right: sketch of the NUCLEUS experiment. The setup consists of a cryostat (1) which hosts the NUCLEUS-10g detection setup (2) and is surrounded by a passive shielding (3). The outermost layer is the active muon-veto (4) made from plastic scintillator panels. The full setup with a footprint of approximately 1 m^2 is placed on a weight support platform.

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