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CEνNS at the low-energy frontier in NU-CLEUS

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NU-CLEUS is a proposed cryogenic experiment to make precision measurements of coherent elastic neutrino-nucleus scattering at moderate distance from a nuclear power reactor. The use of ultra-low threshold gram-scale cryogenic calorimeters promises high-statistics measurements with miniaturized targets. Initially, NU-CLEUS will deploy a target array of 10 g while preparing for a scaling-up to 1 kg of total target mass. We discuss the physics potential resulting from such a setup in terms of precise cross-section measurements in a previously unaccessible energy range. Results from a prototype target detector operated above ground are presented.

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1. Coherent Elastic Neutrino-Nucleus Scattering

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS), first proposed in 1974 [1] has become the focus of much experimental effort in recent years. It is a unique interaction channel of the neutrino, with a cross-section enhanced by orders of magnitude beyond other reactions in the same energy range. When the exchanged momentum between neutrino and nucleus becomes smaller (in natural units) than the inverse radius of the nucleus, the neutrino becomes insensitive to nuclear structure, and the scattering contributions from all nucleons start overlapping in phase. This leads to an enhancement of the cross-section of N^2, neglecting the small weak charge of the proton. This makes CEνNS the dominant interaction channel for neutrinos below an energy of few tens of MeV. As an elastic process, CEνNS does not distinguish between neutrino flavors and has no fundamental energy threshold. This property makes CEνNS an interesting portal to precise study of low-energy neutrinos, allowing the test of physics scenarios beyond the standard model. For many decades, CEνNS has been out of reach of experimental observation, with its combined requirement of a (weakly interacting) low-energy projectile and a heavy nuclear target. Kinematics restrict the resulting nuclear recoil energies (the only signature of the process) to below at most a few keV. Thus the study of CEνNS shares important characteristics with direct dark matter searches, which has been a strong driver of low-energy detector technology in recent decades. It is therefore not surprising that many applied and proposed detector technologies (including the one described here) build upon experiences from dark matter search.

The first observation of CEνNS was reported in 2017 by the COHERENT collaboration [2], making use of the pulsed neutrino emission of the Spallation Neutron Source at Oak Ridge National Laboratory. The COHERENT collaboration continues to expand their physics program for example by deploying new detectors with different target materials [3]. A large number of new experiments globally (such as CONNIE [4], CONUS [5], MINER [6], ν-gen [7], RED-100 [8], RICOCHET [9], TEXONO [10]) are planned, starting or already taking data to contribute to the study of CEνNS . Among these, the NU-CLEUS experiment is unique in applying ultra-low threshold cryogenic detectors, which for the first time allow being sensitive to the majority of CEνNS -induced nuclear recoils in the target material.

2. The NU-CLEUS experiment

The NU-CLEUS experiment plans to study CEνNS at a moderate distance of few tens of m from a nuclear power reactor. This strong artificial neutrino source provides a high flux of low-energy neutrinos. The proposed detector technology, gram-scale cryogenic detectors, promise an ultra-low energy threshold of order 10 eV along with a thermal measurement, which obviates the problematic determination of quenching factors at these energies. With this combination of source and detector, NU-CLEUS aims at a precision measurement of low-energy neutrinos. This goal will be pursued in a staged approach: NU-CLEUS -10g (deploying ten grams of target detectors) allows a first measurement of CEνNS at a nuclear reactor with $\sim$ 10% precision. The later phase NU-CLEUS -1kg can reach percent-level precision and allows the study of various physics scenarios beyond the standard model.

The key feature of NU-CLEUS is the unprecedentedly low energy threshold of its target detectors. The mean nuclear recoil energy deposited through CEνNS by reactor neutrinos in $CaWO_4$ is about 63 eV. The demonstrated threshold of a nucleus prototype detector [11] of 19.7 eV is thus well matched to observe a large number of CEνNS events.

Part of the NU-CLEUS strategy in all stages is the deployment of multiple target materials (Al_2O_3 and $CaWO_4$ in NU-CLEUS -10g, Si and Ge in NU-CLEUS -1kg). The heavy tungsten and germanium nuclei profit strongly from the enhancement of the cross-section by neutron number N^2, while Al_2O_3 and Si contain only light nuclei. With the precisely predicted ratios of CEνNS cross-section between the different target materials, this approach can be used as an in-situ background characterisation. As opposed to event-by-event particle identification (which establishes nuclear-recoil vs. electron-recoil nature), this statistical approach, together with detailed modeling efforts, can also be used to constrain the particularly dangerous neutron background.

3. The NU-CLEUS detector concept

The NU-CLEUS detector technology builds upon cryogenic calorimeters developed for dark matter search. The detectors comprise a single-crystal target, possible target materials include $CaWO_4$, Al_2O_3, Ge and Si. The sensor is a transition-edge-sensor (TES), formed by a thin tungsten film stabilized within its superconducting transition around 15 mK. The main technological change between the leading technology in low-mass dark matter search, the CRESST-III detectors [12], and the NU-CLEUS gram-scale cryogenic calorimeters, is a down-scaling of the target mass. A basic argument built from a signal model predicts a scaling of the energy threshold $\propto M^{2/3}$ as a function of target mass M [13]. Comparing with CRESST detectors, an energy threshold below 10 eV appears feasible for a fully optimized NU-CLEUS target detector.

The small detector size comes with a number of advantages: most important is the aforementioned ultra-low energy threshold. The first demonstrator gram-scale cryogenic calorimeter described in [13] achieved an energy threshold of 19.7 eV using a 0.5 g Al_2O_3 target. As the measured phonon signal is largely independent of particle type, a cryogenic calorimeter can precisely measure these small deposited energies without relying on challenging external determinations of quenching factors at low energy.

Another advantage for small targets is the reduced total rate, which limits the stability of larger detectors operated above ground. As the response of a TES becomes non-linear at higher pulse amplitudes, pile-up can strongly degrade the energy resolution of such devices. With a rate around 0.1 Hz (operated without significant shielding), the demonstrator showed that gram-scale cryogenic calorimeters can be operated stably in challenging environments. While the target mass ensures a lower particle rate, the smaller size of gram-scale cryogenic calorimeters also speeds up the phonon collection, leading to faster pulses. This feature will become important when operating these detectors in anticoincidence with a muon veto of $O(1m)$ side length with expected count rates in the kHz regime.

The small size of the target detectors also opens up new possibilities in the holding scheme. The NU-CLEUS target will be encapsulated into other cryogenic detector systems, forming a fiducial-volume cryogenic detector. The cryogenic assembly will comprise, apart from the target detector array, an inner veto, which provides the holding force as well as a 4 π surface veto with sub-keV threshold, and a massive outer veto operated in anti-coincidence against external gamma and neutron backgrounds. Monte Carlo studies of such an arrangement indicate background rejection over several orders of magnitude are possible at lowest energies [11].

4. Candidate site at a nuclear reactor

In the search for a possible location of the NU-CLEUS experiment, contact has been established with EDF, the operator of the Chooz Nuclear Power Plant (CNPP) in north-eastern France. A candidate site, dubbed the Very Near Site, was identified in the basement of an office building at a distance of 102 m and 72 m to the two 4.25 GW_{th} cores of CNPP. First background measurements of muons and fast neutrons have been performed. First results were presented at NEUTRINO 2018 [14], a more complete publication is in preparation.

5. Physics reach of NU-CLEUS

In its first phase, NU-CLEUS -10g, the experiment aims for a O(10%) measurement of the CEνNS cross-section within about one year of data-taking, limited by statistics. In the future phase NU-CLEUS -1kg, a percent-level measurement is in reach driven by the control of systematics.

With its high-statistics dataset of low-energy neutrino interactions, NU-CLEUS will become sensitive to a host of new-physics scenarios. Already with the dataset of the first observation in 2017, COHERENT significantly constrained the parameter space for neutrino non-standard interactions (NSI) with up- and down-quarks [2]. With a more precise measurement of the CEνNS cross-section, NU-CLEUS can contribute to reducing the allowed parameter space for NSI, thus constraining physics beyond the standard model, such as models with new light mediator particles.

An important property of the neutrino that becomes experimentally accessible at very low energies is its magnetic dipole moment (MDM). A neutrino MDM manifests itself as an additive component to the scattering cross-section sharply rising towards zero momentum transfer. While the value predicted by the extended standard model (related to the neutrino mass term) is out of reach experimentally, an MDM just below current bounds (from neutrino-electron scattering) is viable in extensions of the standard model. With its uniquely low energy-threshold, NU-CLEUS is well situated to improve the current limit and possibly observe indications of new physics.

Within the framework of the standard model, precise knowledge of the CEνNS cross-section can be viewed as a measurement of the weak mixing angle at low momentum transfers. With its ultra-low threshold, NU-CLEUS can extend this measurement to momentum transfers as low as 1 MeV/c. With increasing precision, the CEνNS -based constraint has the potential to become the most important neutrino-based measurement of the weak mixing angle.

6. Conclusions and Outlook

The NU-CLEUS experiment proposes to measure CEνNS with high precision at a nuclear reactor. This is made possible with the technology of gram-scale cryogenic calorimeters, which have demonstrated energy thresholds below 20 eV. Already in the first phase, with a total target mass of 10 g, NU-CLEUS has the potential to explore new physics at the low-energy neutrino frontier.

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