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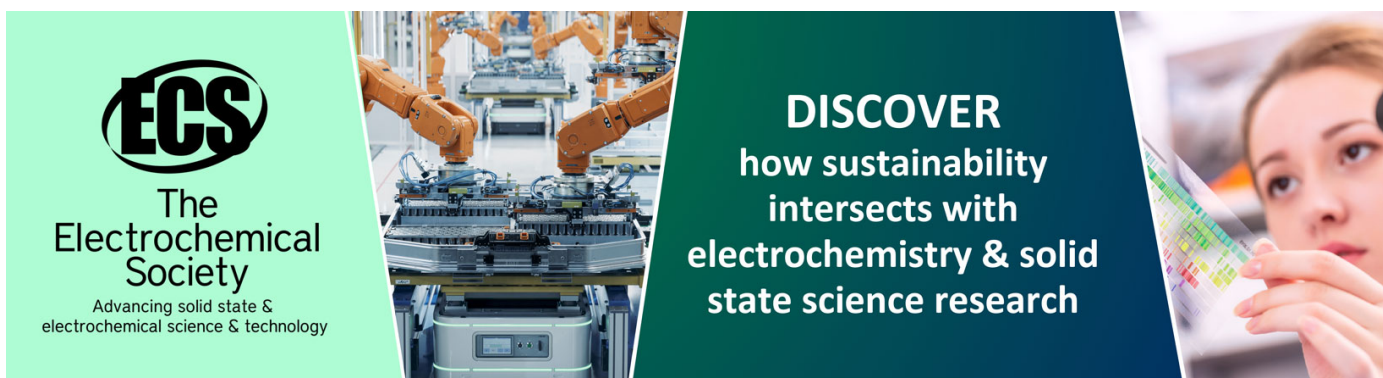
The ν -cleus experiment: Gram-scale cryogenic calorimeters for a discovery of coherent neutrino scattering

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The ν -cleus experiment: Gram-scale cryogenic calorimeters for a discovery of coherent neutrino scattering

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Abstract. We investigate new gram-scale cryogenic detectors, 1-2 orders of magnitude smaller in size than previous devices. These are expected to reach unprecedentedly low energy thresholds, in the 10 eV-regime and below. This technology allows new approaches in rare-event searches, including the search for MeV-scale dark matter, detection of solar neutrinos and a rapid discovery of coherent neutrino-nucleus scattering (CNNS) at a nuclear reactor. We show a simple scaling law for the performance of cryogenic calorimeters, allowing the extrapolation of existing device performances to smaller sizes. Measurement results with a 0.5 g sapphire detector are presented. This prototype reached a threshold of 20 eV, which is one order of magnitude lower than previous results with massive calorimeters. We discuss an experiment, called ν -cleus, which enables a 5- σ discovery of CNNS within about 2 weeks of measuring time at 40 m distance from a power reactor. In a second stage, this experiment enables precision measurements of the CNNS cross-section and spectral shape for new physics within and beyond the Standard Model.

1. Introduction

Coherent neutrino-nucleus scattering (CNNS) is a neutral current process firmly predicted by the Standard Model of Particle Physics, first proposed in 1974 [1] and only recently observed by the COHERENT experiment [2] at a stopped-pion source. Although the cross-section is about 4 orders of magnitude higher than for neutrino-electron scattering, the process remained unobserved until recently due to enormous requirements on the detector technology. The typical recoil energies E_R induced by CNNS can be approximated as

$$E_R \approx \frac{2}{3A} \left(\frac{E_\nu}{1\text{MeV}} \right)^2 \text{ keV} \quad (1)$$

where A is the mass number and E_ν is the neutrino energy. In case of an oxygen target and $E_\nu = 1\text{ MeV}$ (typical energy regime of neutrinos from a nuclear reactor), a recoil energy of $E_R \approx 40\text{ eV}$ is expected, well below the threshold of previous devices [3]. Due to the coherent enhancement of the scattering cross-section (with the neutron number squared), the expected recoil spectrum is boosted significantly for heavy targets. This is illustrated in Fig. 1 (full red line) for a CaWO_4 target. The heavy tungsten nucleus “boosts” the rate to $\sim 10^3$ counts/[kg



keV day] below ~ 100 eV, well above expected background levels (grey band). Additionally, the expected spectra of light-mass dark matter and from CNNS of solar neutrinos are shown in Fig. 1. We aim for the first discovery of CNNS at a nuclear reactor which will, in a second stage, enable precision measurements of the cross section with a high potential to observe new physics. We recently demonstrated the detector technology required to access nuclear recoils in the 10 eV regime (see section 2). Further, we describe the planned experimental site (section 3) and sensitivity studies for ν -cleus (section 4).

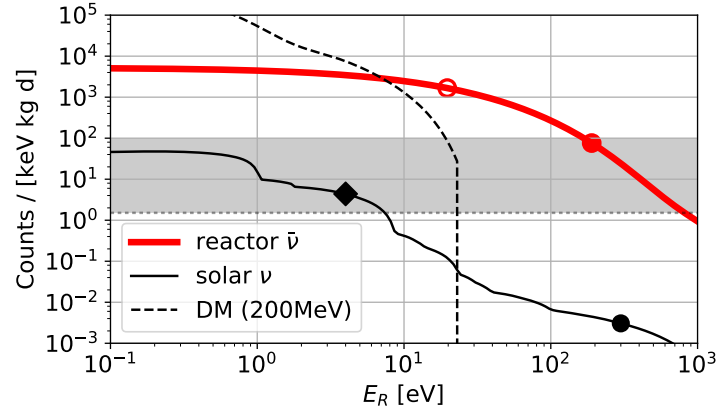


Figure 1. Recoil spectra for CaWO_4 as target material: CNNS of anti-neutrinos from a 4 GW nuclear reactor at a distance of 40 m, for 200 MeV mass DM ($\sigma = 1$ pb), and for CNNS of solar neutrinos. The range of measured background levels for state-of-the-art surface sites and at an underground location (dotted line) [4] are indicated as grey bands. Previous cryogenic detector technology [5, 3] is shown as filled dots, the performance of the detector presented here is depicted as a circle (surface operation) and a diamond (projected underground operation). Figure from [6].

2. The ν -cleus detector

We have demonstrated the new detector technology of gram-scale cryogenic calorimeters (gramCCs) which allows to access unprecedentedly low nuclear-recoil energies. A prototype detector, a 0.5 g Al_2O_3 crystal with a dedicated transition-edge-sensor (TES) [6] (see Fig. 2 left), has been operated in a dilution refrigerator at ~ 20 mK in a setup above ground. It has reached a threshold for nuclear recoils of $E_{th} = (19.7 \pm 0.9)$ eV, one order of magnitude lower than previous devices. Details on the measurement can be found in [6].

The results of this prototype measurement has been used to set the first limit on the spin-independent DM particle-nucleon cross section below 500 MeV/ c^2 [7] and constrains sub-GeV SIMPs (Strongly Interacting Massive Particles) [8].

For the ν -cleus experiment we plan to build an array of gramCCs made of CaWO_4 and Al_2O_3 (9 each) with a total mass of 10 g. It will be mounted in a holder made of Si wafers (see Fig. 2 right). In addition, the gramCCs will be embedded in two cryogenic veto detectors: 1) an inner veto completely surrounding the target detectors which reject surface-related backgrounds and 2) a outer veto, a massive Ge or Si crystal which acts as anti-coincidence veto against external radiation. Both veto detectors are equipped with TESs and in this arrangement act as a fiducial-volume cryogenic detector - a new cryogenic-detector concept which will significantly reduce backgrounds to levels well below what is required for a detection of CNNS [9].

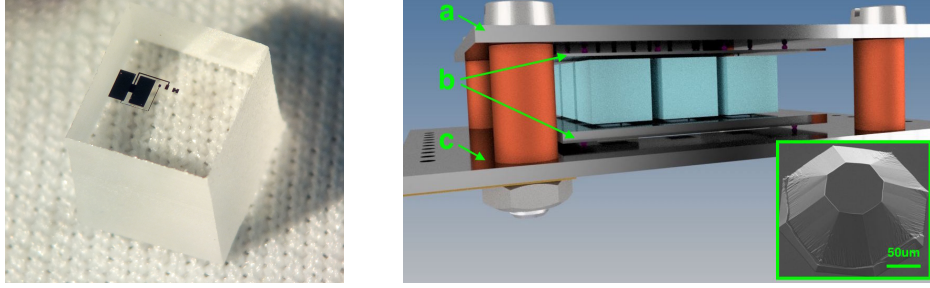


Figure 2. Left: Prototype gram-scale calorimeter consisting of a 0.5 g Al_2O_3 crystal and a dedicated TES sensor [6]. Right: Technical drawing of the inner detector part of ν -cleus10g. An array of 9 gram-scale calorimeters (blue cubes) are held by a support structure made of Si wafers (a+c) and a dedicated active veto component (b). For details see [9]. Pictures from [9] and [7].

3. Experimental setup at the reactor

Nuclear reactors are among the most luminous sources for anti-neutrinos on Earth, with a benchmark 4 GW power reactor isotropically emitting circa $7.5 \cdot 10^{20}$ particles per second. We study sites with a small overburden at different distances from the reactor core: a **near site** at 15 m within the reactor containment provides the highest signal rates but also challenges from reactor-correlated backgrounds and strong logistical constraints. An **intermediate site** at 40 m can be located outside the reactor building, e.g. in an adjoining basement, with correspondingly better access and infrastructure, along with a relaxed background environment. A **far site** 100 m from the reactor core frequently lies outside the reactor compound, so that a dedicated experimental facility with free access is feasible. Fig. 3 illustrates these options.

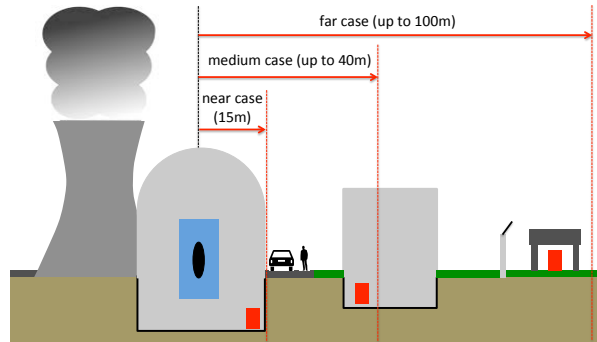


Figure 3. Schematic view of the studied sites at a nuclear power plant. Picture from [9].

4. Sensitivity studies

For each of the possible sites introduced in section 4, a likelihood study (described in greater detail in [9]) is used to quantify the discovery potential achievable with ν -cleus10g. A likelihood-ratio test (background-only model vs. a model including the expected CNNS signal) is applied to an ensemble of simulated event spectra. The background model used is flat with a rate of 200 counts/[kg keV day], the assumed energy threshold is 20 eV. Fig. 4 shows the results of the

study, displayed as the median detection significance of the CNNS signal versus measurement time for the three distances, along with 90% bands. Even at the far site, a $5\text{-}\sigma$ detection of CNNS is possible within a year of measurement time. At the intermediate site, it is expected in less than two weeks. The high neutrino rate at the near site allows a $5\text{-}\sigma$ detection within a day, which permits high-significance reactor power monitoring via neutrinos (provided the backgrounds can be controlled as assumed). These results are robust against changes of the assumed threshold and background levels, even realistic non-flat backgrounds can be tolerated to some extent [9].

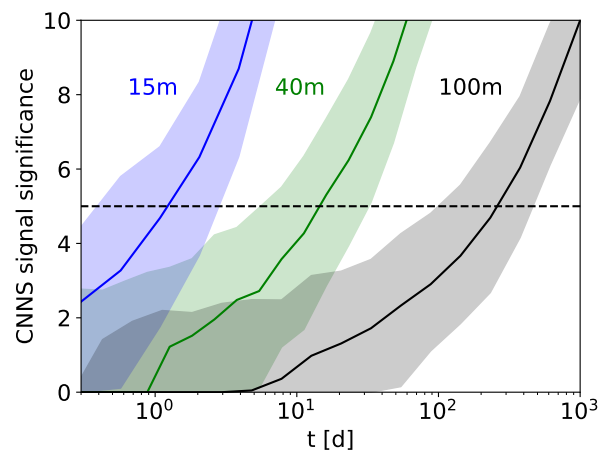


Figure 4. Statistical significance for a detection of CNNS at the three different experimental sites investigated vs. measuring time with ν -cleus 10g (full lines). The bands indicate the 90% confidence intervals. Figure taken from [9].

5. Conclusion

The ν -cleus experiment is a promising approach to discover CNNS at a nuclear reactor within 1-2 weeks of measuring time with a detector of 10g in target mass. The unprecedentedly low energy threshold and the smallness of the devices provide the possibility to gather high-statistics neutrino samples for precision measurements on reasonable time-scales. The experiment at a nuclear power reactor will be sensitive to sterile neutrinos, the Weinberg angle at low momentum transfers, the electron neutrino magnetic moment, exotic neutral currents and non-standard interactions (see [9, 10] and references therein). ν -cleus sets the stage for a future small-scale solar neutrino experiment: GramCCs with a total target mass of 10-100kg will be able to measure pp-chain neutrinos with unprecedented sensitivity and measure CNO neutrinos for the first time (work to be published). Furthermore, the technology is applicable for reactor safeguard measures such as accident monitoring and non-proliferation with a high gain for global security.

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