PROCEEDINGS OF SCIENCE

Search for coherent neutrino-nucleus scattering in the NEON experiment

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The NEON (Neutrino Elastic-scattering Observation with NaI) experiment aims to observe Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) using a NaI(Tl) detector located at 23.7 m from a nuclear reactor core with a thermal power of 2.8 GW. CEνNS is a process predicted by the Standard Model in which low-energy neutrinos elastically scatter off nuclei, resulting in a coherent enhancement of the cross-section. This process was first observed by the COHERENT experiment using CsI(Na) and later confirmed with liquid argon and germanium detectors. NEON seeks to extend these observations to reactor neutrinos, which provide a much higher flux but produce lower-energy nuclear recoils. The primary goal of the experiment is to achieve a statistically significant CEνNS detection while maintaining precise background control. These findings pave the way for future high-precision CEνNS studies using reactor neutrinos and provide strong constraints on new physics scenarios. In addition to CEνNS, NEON explores light dark matter interactions, inelastic neutrino-nucleus scattering, and searches for dark sector particles. This proceeding provides an overview of the experiment, its current status, and future prospects.

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1. Introduction

Coherent elastic neutrino-nucleus scattering (CEνNS) is a low-energy neutrino interaction process that was theoretically predicted over 40 years ago. The process was first proposed by Freedman in 1974 [1] but remained unobserved until the COHERENT experiment successfully detected it in 2017 using a CsI(Na) scintillator [2]. The small recoil energy of the nucleus, which is typically below 1 keV, made its detection extremely difficult for decades.

CEνNS is unique because its cross-section scales quadratically with the number of neutrons, significantly enhancing the interaction cross-section for heavy nuclei. This feature makes it an important tool for probing neutrino properties, understanding weak interactions, and testing new physics beyond the Standard Model. Furthermore, CEνNS has important applications in reactor monitoring, nuclear non-proliferation, and astrophysical neutrino detection.

Most previous CEνNS detections have been conductedat spallation sources, such as the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory [2–4]. Spallation sources provide higher-energy neutrinos ($\sim$ 30 MeV) compared to reactors ($\sim$ 3 MeV), allowing larger nuclear recoils. However, reactors provide a much higher neutrino flux, making them ideal for precision CEνNS measurements, provided that sufficiently low energy thresholds can be achieved.

NEON is designed to take advantage of the high flux of reactor neutrinos, aiming to achieve the lowest energy threshold ever reached with NaI(Tl) detectors [5]. The experiment has been operational since April 2022 and continues to collect data, focusing on reducing background levels and improving signal extraction techniques.

2. Experimental Setup

The NEON experiment employs six NaI(Tl) scintillation crystals with a total mass of 16.7 kg, located 23.7 meters from a 2.8 GW thermal power nuclear reactor as shown in Fig. 1. The NaI(Tl) crystals are encapsulated in a low-background housing and coupled to high-efficiency photomultiplier tubes (PMTs) to maximize light collection [6, 7].

To mitigate external radiation and cosmic ray backgrounds, the detector is placed inside a multi-layer passive shielding system. This shielding consists of lead, polyethylene, and copper layers, designed to suppress gamma-ray and neutron backgrounds. Additionally, an active muon veto system is employed to tag cosmic-ray-induced events.

A key challenge in the experiment is achieving a sufficiently low energy threshold to detect the expected CEνNS recoil signals. The NaI(Tl) crystals in NEON achieve a high light yield of approximately 24 photoelectrons per keV [7], significantly improving sensitivity over previous NaI(Tl) detectors. The achieved trigger threshold is approximately 0.1 keVee, which is among the lowest thresholds ever reported for NaI(Tl) detectors.

Calibration of the detector is performed using internal background peaks and external gamma-ray sources. The stability of the detector response has been continuously monitored since the start of data collection in April 2022. The long-term performance of the detector indicates that a stable and well-characterized operation is maintained.

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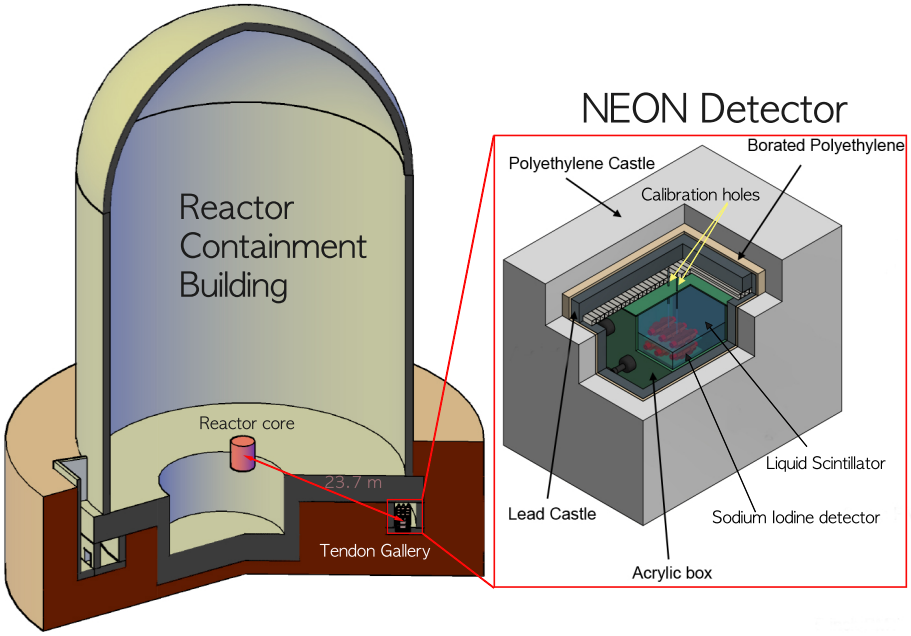

Figure 1: Schematic view of the NEON detector. The NEON detector is located 23.7m from the reactor core of unit-6 at the Hanbit nuclear power complex, which operates at a thermal power of 2.8GW. The detector consists of six NaI(Tl) modules enclosed within 800 L of liquid scintillator, surrounded by a 10 cm-thick lead layer, a 3 cm-thick borated polyethylene layer, and a 20 cm-thick high-density polyethylene shield.

3. Background Reduction and Data Analysis

To achieve the required sensitivity, NEON implements a comprehensive background reduction strategy. The primary challenge in detecting CEνNS is achieving a sufficiently low background rate while maintaining a low energy threshold. The detector's background is mainly influenced by ambient radioactivity, cosmic muons, and PMT noise. NEON applies multiple techniques to mitigate these effects.

One of the most effective approaches involves the use of waveform analysis and machine learning-based noise rejection. A Boosted Decision Tree (BDT) algorithm has been implemented to distinguish genuine nuclear recoil signals from noise events as described in Ref. [8]. The current background level is approximately 7 counts/kg/keV/day at 0.6 keV. Further efforts are being made to lower this background to below 3 counts/kg/keV/day, which is essential for a high-significance observation. Additionally, deep learning techniques are being explored to further refine event selection by analyzing raw waveforms directly. To obtain a clean and sufficent number of signal samples, we have developed waveform simulation packages for scintillating NaI(Tl) crystals [9].

Reactor-on and reactor-off data comparisons play a crucial role in identifying neutrino-induced signals as shown in Fig. 2. Seasonal variations in background rates due to changes in radon levels have been observed and accounted for in the analysis. These effects are used to model reactor-on minus reactor-off data shown in Fig. 2 (C).

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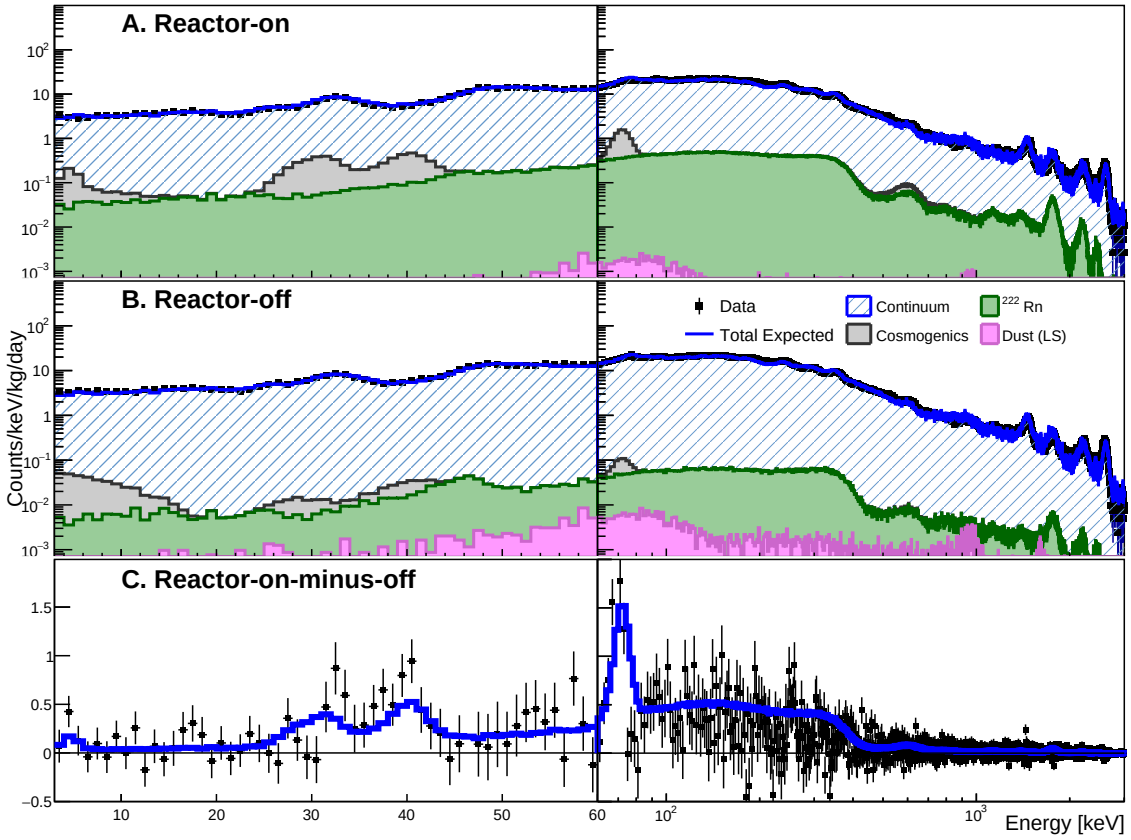

Figure 2: Single-hit energy spectra of the detector-6 module. The figure shows the normalized energy spectra of single-hit events (black points) in the detector-6 module, compared with the expected background contributions (blue solid lines) for reactor-on data (A), reactor-off data (B), and the reactor-on-minus-off spectrum (C). The expected background includes time-independent continuum components and time dependent contributions such as cosmogenic activation, ^{222}Rn in the calibration holes, and ^{238}U and ^{232}Th from dust contamination in the liquid scintillator. For the reactor-on-minus-off spectrum (C), only time-dependent components contribute to the background.

4. CEνNS Search Status

Preliminary studies with NEON data indicate a possible CEνNS observation with a significance greater than 3σ assuming 0.2 keVee energy threshold. Due to significant phosphorus noise events below 0.6 keVee, we have focused on identifying scintillation events in the low-energy signal region. Ongoing efforts aim to further reduce this background through improved event selection techniques.

The use of machine learning for background rejection has demonstrated promising results. Initial applications of a Boosted Decision Tree have already improved the signal-to-background ratio. A more advanced deep learning approach, utilizing raw waveform analysis, is expected to enhance this further. If successful, NEON will achieve an unprecedented sensitivity to reactor neutrino-induced CEνNS.

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5. Additional Physics Goals

Beyond CEνNS, NEON is pursuing several complementary physics goals. One of the most exciting areas is the search for light dark matter (LDM). If dark matter particles interact with electrons or nuclei via a light mediator, reactor-produced dark photons could serve as a powerful probe. The current analysis [10] has placed new constraints on dark photon-mediated LDM interactions, improving upon previous results from TEXONO and DAMIC, as shown in Fig. 3.

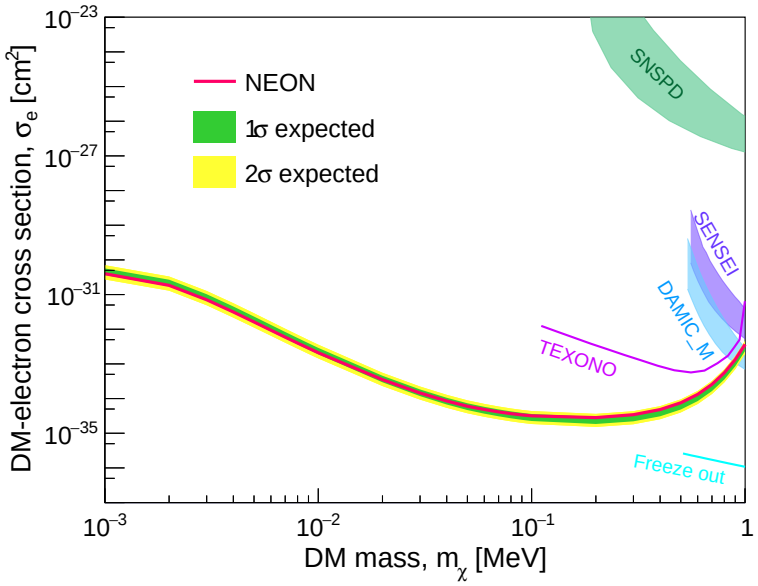

Figure 3: The 90% confidence level exclusion limit on the LDM-electron scattering cross-section from NEON data, along with the $\pm1\sigma$ and $\pm2\sigma$ ranges of the expected sensitivities. The plot is taken from Ref. [10].

Additionally, NEON is investigating potential signals from axion-like particles (ALPs). For both axion-electron and axion-photon couplings, our observed limits probe previously unveiled parameter spaces [11]. The proximity to a high-power nuclear reactor provides an ideal environment to search for new physics signatures in the MeV mass range.

Another key objective is the study of inelastic neutrino-nucleus scattering (IνNS) [12]. This process has a much smaller cross-section than CEνNS, but the emitted 57.6 keV x-ray provides relatively higher-energy signals, making its detectin valuable for understanding neutrino interactions. The NEON experiment is expected to achieve above 2σ level measurement of IνNS, making it one of the first reactor-based studies of this process.

6. Conclusion and Future Plans

The NEON experiment is successfully operating with stable performance, demonstrating the capability to detect CEνNS from reactor neutrinos. The ongoing analysis is expected to yield a significant result in the near future. Beyond CEνNS, NEON has set world-leading constraints on light dark matter interactions and is exploring additional neutrino processes such as IνNS. Future

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plans include scaling the detector mass to 100 kg, further enhancing background suppression techniques, and broadening the experiment's reach to sterile neutrinos and other beyond-Standard-Model scenarios. As data collection continues, NEON is poised to make significant contributions to neutrino physics and dark matter searches.

Acknowledgments

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