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RECODE program for reactor neutrino CEvNS detection with PPC Germanium detector

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The measurement of coherent elastic neutrino–nucleus scattering (CEνNS) can test the standard model and explore new physics. REactor neutrino COherent scattering Detection Experiment (RECODE) is a CEνNS detection experiment aiming at realizing the accurate measurement of reactor CEνNS using HPGe detectors. This experiment has two HPGe arrays, each consisting of five 1-kg HPGe detectors. It is designed to have a low background (< 2 counts/kg/keV/day), low energy threshold (~ 1 keVnr), and long-term stability (≥ 3 years). The experimental system will be placed on the ground surface, 25 m away from the reactor core of the Sanmen Nuclear Power Plant, where the neutrino flux is on the order of 10^{13} /cm^2/s. Herein, the conceptual design, prestudies, and experimental schedule of RECODE are outlined.

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1. Introduction

Coherent elastic neutrino–nucleus scattering (CEνNS) [1] is a fundamental neutrino-nucleus interaction in the standard model (SM). This is the dominant interaction between the neutrinos and nuclei at low neutrino energies ($E_\nu \lesssim 100$ MeV). In this process, the nucleus scatters with the neutrino as a whole and recoils elastically. CEνNS has the largest predicted cross-section of all low-energy neutrino couplings.

CEνNS detection experiments can test SM and explore new physics. Additionally, CEνNS detection provides a new method for real-time reactor monitoring and detection of solar and supernova neutrinos. Thus, the detection of CEνNS has recently become a crucial frontier topic in the field of neutrino physics. Several CEνNS detection experiments, such as COHERENT [2, 3], CONUS [4], νGeN [5], and TEXONO [6], are currently running or under construction. In 2017, COHERENT collaboration observed CEνNS with high energy neutrino beam from spallation neutron source using a 14.6-kg CsI[Na] scintillator [2]. In 2020, COHERENT collaboration reported the first measurement of CEνNS in Ar using a liquid argon detector [3]. However, no experiment has observed the CEνNS of reactor neutrinos until now, and CEνNS has not been observed through a germanium detector.

2. Experimental design

RECODE is a reactor CEνNS detection experiment based on high-purity germanium (HPGe) detectors. In this experiment, we employed two same HPGe arrays, each with five HPGe units. Each HPGe unit consists of a 1-kg HPGe detector, a support structure, and front-end electronics. Each five HPGe units will be placed in a vacuum cryostat and cooled using a liquid-nitrogen cold finger. The total mass of the two HPGe arrays is approximately 10 kg. The two identical detector arrays will be performed joint measurements with same or different distance to the reactor core, to reduce the uncertainty. The designated location of RECODE is the Sanmen Nuclear Power Plant in Zhejiang, China. The experimental system will be placed on the ground surface, 25 m from the reactor core. The neutrino flux at this location is of the order of 10^{13} /cm^2/s.

Reactor neutrino CEνNS detection experiments require a low background, low energy threshold, and long-term stability because the cross section of CEνNS is extremely low, and the energies of most reactor neutrinos are low. These requirements have been achieved in the China Dark matter EXperiment (CDEX), which is also based on HPGe detectors [7, 8]. Thus, RECODE is expected to have a background of < 2 counts/kg/keV/day and an energy threshold of ~ 1 keVnr (160 eVee, "eVee" represents electron equivalent energy derived from a charge calibration). The detectors used in RECODE are expected to operate stably for at least three years.

3. Background control and systematic uncertainty reduction

The background of RECODE primarily arises from cosmic rays, reactor neutrons, and radioactive isotopes in the HPGe crystals and surrounding materials. To reduce the background produced by cosmic rays and reactor neutrons, we designed a shielding system consisting of the oxygen-free copper, boron doped polyethylene, lead, polyethylene, and a plastic scintillator muon veto system.

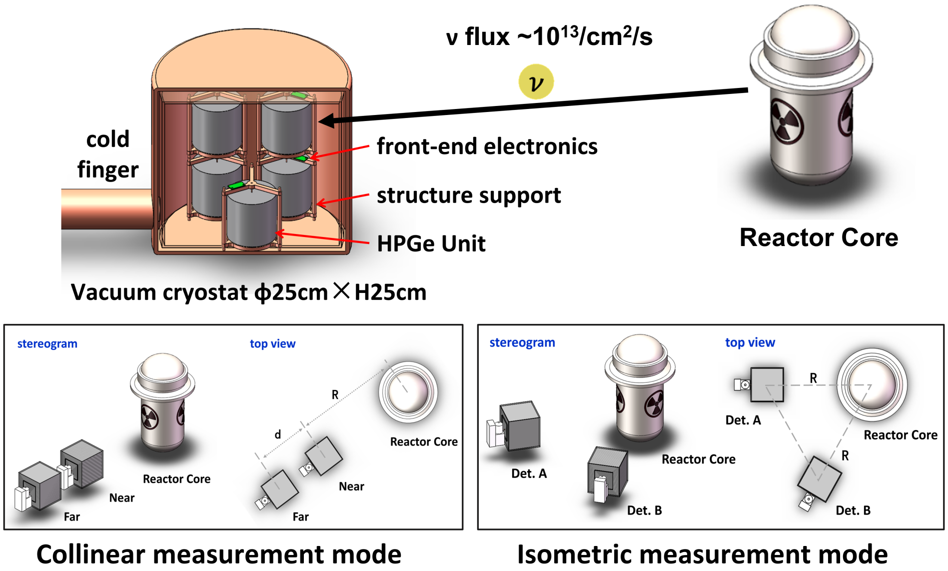

Figure 1: The conceptual design of RECODE

This shielding system is estimated to achieve an anticoincidence efficiency of cosmic rays over 99%. The gamma and neutron fluxes will be reduced by 5 and 3 orders of magnitude, respectively. To further reduce the background produced by radioactive isotopes in the surrounding materials, we plan to minimize structural materials near the crystals and strict material screening.

The quenching factor of germanium nuclei at low energies has not been accurately measured. Its systematic uncertainty can reach 10%–20%, which is the main source of the total systematic uncertainty in RECODE. Therefore, we plan to perform more accurate measurements to reduce the uncertainty of the quenching factor.

Furthermore, the systematic uncertainty associated with neutrino flux is estimated to be ~3%. To reduce this uncertainty, we plan to perform joint measurements by using two identical detector arrays. In the first phase of the experiment, we will use the two arrays to perform collinear measurements. Subsequently, during the second phase, we will exchange the placements of the two arrays and perform another collinear measurement. In the third phase, an isometric measurement will be performed. These joint measurements can help reduce the systematic uncertainties related to the neutrino flux and background.

4. Schedule and prospects

Testing of the RECODE subsystems commenced in 2023 at the China Jinping Underground Laboratory (CJPL) and the ground laboratory in Xichang, including background measurement, subsystem design, individual detector testing, joint testing, and proposal development. In 2025, the physics run is scheduled to commence following the installation testing. The physics run will have three phases and be completed in 2027. Data analysis and physics analysis will be performed throughout the physics run.

During the physics run, the expected CEνNS event rate for RECODE is ~ 500 /kg/year. The signal-to-noise ratio around the energy threshold is projected to be ~ 5:1. Thus, RECODE can obtain a significance of 3σ for CEνNS signals in one day. After 3 years of physics run, we can realize the accurate measurement of reactor CEνNS, improve the measurement accuracy of the weak mixing angle for low momentum transfer, and improve the constraints on non-standard neutrino interactions.

5. Summary

RECODE is a reactor CEνNS detection experiment based on HPGe detectors. Its designated location is the Sanmen Nuclear Power Plant in Zhejiang, China. The primary objective of this experiment is to achieve an accurate measurement of the reactor CEνNS, enhance the measurement accuracy of the low-energy value of the weak mixing angle, and improve the constraints on non-standard neutrino interactions. Herein, we outline the conceptual design, prestudies, and experimental schedule of RECODE. Subsystem testing for RECODE is currently underway, and the physics run of RECODE is scheduled to commence in 2025.

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