PROCEEDINGS OF SCIENCE

Coherent neutrino-nucleus elastic scattering at reactor with TEXONO experiment

S. Karmakar,[a,b] **M. K. Singh,**[a,*] **H. T. Wong,**[a] **and V. Sharma**[c] **on behalf of the TEXONO collaboration**

[a] *Institute of Physics,*
Academia Sinica, Taipei 115201, Taiwan
[b] *Department of Physics, Institute of Applied Sciences and Humanities, GLA University,*
Mathura, Uttar Pradesh 281406, India
[c] *Department of Physics, H.N.B.Garhwal University,*
Pauri Garhwal, Uttarakhand 246174, India
E-mail: `man.bhu9@gmail.com; manu@gate.sinica.edu.tw`, `htwong@gate.sinica.edu.tw`

The low energy coherent neutrino-nucleus elastic scattering is being studied in a number of experimental programs around the world. As part of TEXONO's neutrino research program at Kuo-Sheng nuclear power plant, state-of-art high purity point-contact Germanium detectors with $O(100\ \text{eV})$ threshold are utilized to study such low energy neutrino interactions at the complete coherency regime. This work will provide an overview of current coherent neutrino-nucleus elastic scattering activities and recent results at the TEXONO experiment. We will also discuss the quantitative studies of quantum-mechanical coherency effects in coherent neutrino-nucleus elastic scattering.

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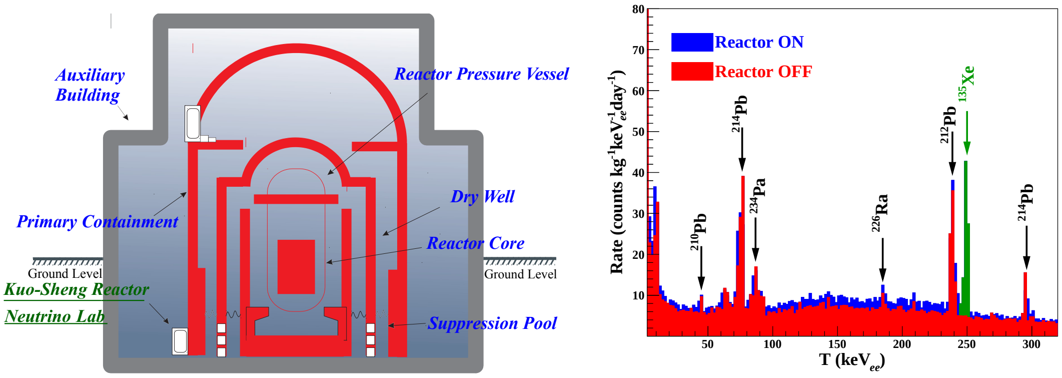
PoS(TAUP2023)226

1. Introduction

The detection of the weak neutral current opens the door to the potential occurrence of coherent neutrino-nucleus elastic scattering (CνA_{el}), a Standard Model (SM) process in which neutrinos can coherently interact with an entire atomic nucleus. Its cross section in SM can be given by [1]

$$\frac{d_{\mathrm{C}\nu\mathrm{A_{el}}}}{dq^2}(q^2,E_\nu) = \frac{1}{2}\left[\frac{G_F^2}{4\pi}\right]\left[1-\frac{q^2}{4E_\nu{}^2}\right]\left[\varepsilon Z F_Z(q^2) - N F_N(q^2)\right]^2 , \tag{1}$$

where G_F is the Fermi coupling constant, $F_{Z(N)}(q^2)$ are the proton(neutron) nuclear form factors for $A(Z,N)$, while $\varepsilon \equiv(1-4\ \sin^2\theta_\mathrm{W})$=0.045, indicating the dominant contributions are from the neutrons [2, 3]. In order for this process to occur, the momentum exchange must be smaller than the inverse of the nuclear size, limiting the feasibility of the process to neutrinos with energies up to a few tens of MeV (E_ν <50 MeV). As a result, despite having the largest possible cross section for CνA_{el}, it took nearly 43 years for it to be experimentally detected in 2017 by the COHERENT collaboration using the CsI[Na] scintillator detector [4] at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory and later confirmed with the liquid Argon (LAr) scintillator detector [5]. Recently, the DRESDEN-II collaboration has provided indications of a potential CνA_{el} signature with reactor neutrinos ($\bar{\nu}_e$) [6].



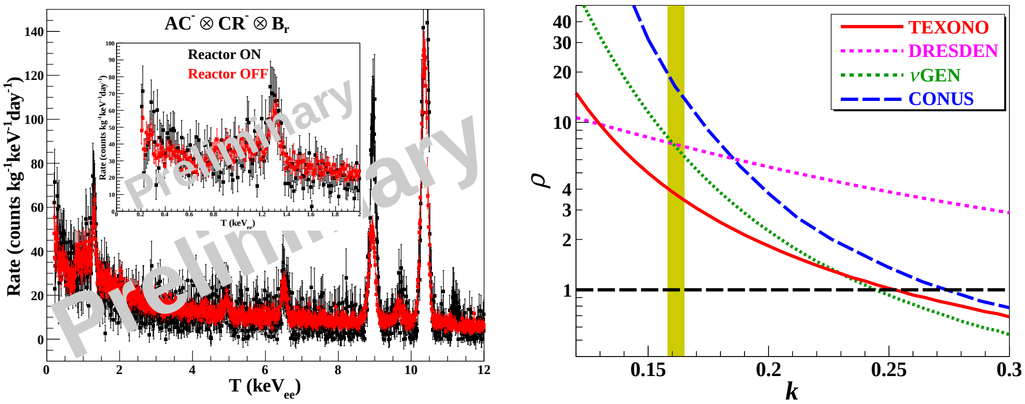
(a) (b)

Figure 1: (a) Schematic representation (not to scale) of the Kuo-Sheng nuclear reactor building, highlighting the location of the Kuo Sheng Reactor Neutrino Laboratory (KSNL). (b) Appearance of 249.8 keV γ-line in reactor ON data leads to enhancement in background of high energy as well as low energy region.

The observation of CνA_{el} is of significant importance in enhancing our understanding of the SM and unraveling the mysteries of physics beyond the SM. Quantitative analysis has revealed that coherency is predominantly complete (about >95%) involving reactor and solar neutrinos, while it is only partial for neutrinos from π-DAR (pions decay-at-rest by SNS) and weak for atmospheric neutrinos [2]. Thus, investigations of νA_{el} using neutrino sources (Reactor, Accelerator, Solar, etc.) offer complementary insights and encompass the transitions from fully coherent to decoherent states. As a result, a multitude of experiments (such as TEXONO [7], DRESDEN−II [6], CONUS [8], νGEN [9], etc.) are being conducted worldwide using reactor neutrinos to observe CνA_{el} in the fully coherent regime.

2. Measurements from TEXONO data

The **T**aiwan **EX**periment **O**n **N**eutrin**O** (TEXONO) Collaboration has undertaken multiple generations of experiments and is presently focused on detecting the signature of CνA_{el} using reactor neutrinos from Kuo-Sheng Nuclear Power Station (KSNPS) located on the northern shore of Taiwan. The KSNL is situated at an overburden of approximately 30 meter-water-equivalent and is positioned 28 m away from the core No. 1 of the KSNPS, which has a nominal thermal power output of 2.9 GW, consequently, the laboratory is exposed to a $\bar{\nu}_e$-flux of 6.35×10^{12} cm^{-2}s^{-1} [7, 10]. A schematic diagram (not drawn to scale) of the Kuo-Sheng nuclear reactor building indicating KSNL site is shown in Fig. 1(a). Ref. [10] and references therein explain facility details.



(a) (b)

Figure 2: (a) An uncorrelated and bulk event-corrected AC$^-$⊗CR$^-$⊗B$_r$ spectrum of Reactor ON and OFF data, with an inset of low energy region. (b) Upper exclusion plot for CνA_{el} cross section measurement at 90% C.L. From measurements of quenching factor, the yellow shading represents the 3σ bound on k.

In this study, data was taken at KSNL with a p-type point-contact Germanium detector (pPCGe) enclosed by a NaI(Tl) Anti-Compton (AC) detector. Approximately 70 mm in diameter and height both, with a mass of 1.47 kg, the target sensor is a Germanium crystal. A critical factor in the studies of reactor CνA_{el} is the physics signal threshold. The Pulser FWHM achieved is ~70 eV, and the electronic noise threshold is 200 eV. The analysis procedures are based on several generations of experiments, as described in Refs. [7, 10]. Events that are originated within the bulk of the detector are retained as potential signal candidates [11]. In accordance with the standard definitions [10], candidate events induced by neutrinos are labeled as AC$^-$⊗CR$^-$⊗B$_r$ (Anti-Compton veto⊗Cosmic Ray veto⊗Bulk Events Corrected), as shown in Fig. 2(a). An anomalous background feature is observed in the reactor ON data due to ^{135}Xe contamination. The isotope ^{135}Xe [12] is a fission product and undergoes β^- decay at a half-life of 9.14 hours to ^{135}Cs*, which then de-excites by γ-rays to the long-lived ground state ^{135}Cs. The dominant γ-line at 249.8 keV observed in Reactor ON spectra is shown in Fig. 1(b). In the low (< 10 keV) energy region, ambient γ-rays like this one produce flat Compton backgrounds to the AC$^-$⊗CR$^-$⊗B$_r$ samples.

The observable of CνA_{el} is nuclear recoil, which further quenched [13]. To translate it into measurable electronic energy deposition we need to understand the "Quenching Function" (QF). In this analysis, we adopt the Lindhard Model [13] characterized by one parameter k. A minimum χ^2 analysis is performed as a function of parameter k within the signal region spanning 200 to 400 eV of the residual spectrum (reactor ON−OFF data with exposures of 65 kg·day ON and 438 kg·day OFF), while considering the contribution of Compton background originating from ^{135}Xe, via measurement as well as simulation. The present work investigated the ratio (ρ) of the measured cross section to the SM CνA_{el} cross section. The upper exclusion plot (see Fig. 2(b)) is estimated

PoS(TAUP2023)226

in the ρ versus k parameter space at 90% C.L. for TEXONO as well as νGEN [9], DRESDEN [6] from their published reactor ON−OFF data under identical analysis, and overlaid the upper limit of CONUS [8]. The yellow band represents the best estimate of the k-parameter in the Lindhard model. With $\rho > 4.2$ for k=0.157 at 90% C.L., TEXONO excludes the other Germanium focused reactor-based experiments in the most sensitive 3σ allowed values of k.

3. Future prospects

The data taking for reactor ON was stopped from 01/07/2021, due to the reactor's decommissioning phase. Until 2025, we are allowed to collect reactor OFF data, which will surely improve OFF data statistics. Additionally, we are working on the development of robust bulk surface events reconstruction technique, which can potentially reduce the noise threshold to $\sim$ 150 eV$_{ee}$.

4. Acknowledgment

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