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Probing physics within and beyond the Standard Model with coherent neutrino nucleus elastic scattering at the Kuo-Sheng reactor neutrino laboratory with the TEXONO experiment

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Nuclear power reactors offer an intense source of anti-electron neutrinos ($\bar{\nu}_e$) for investigating coherent neutrino nucleus elastic scattering (CνA_{el} – a Standard Model process) at low-energy in the complete coherency regime. Furthermore, they offer avenues for probing the beyond Standard Model (BSM) aspects of CνA_{el}, including various low mass light mediators and non-standard interactions. The TEXONO experiment employs state-of-the-art point-contact high purity Germanium detectors at $O(100\ \mathrm{eV}_{ee})$ threshold to study neutrino physics at the Kuo-Sheng nuclear power plant. In this presentation, we will give an overview of our research activities and present latest results in probing SM and BSM physics with CνA_{el}.

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1. Introduction

Coherent neutrino-nucleus elastic scattering (CνA_{el}), a neutral current Standard Model (SM) process theoretically proposed over four decades ago, involves the interaction of a low-energy neutrino with a nucleus as a whole, resulting in a measurable kinetic recoil energy [1]. The *coherence* in CνA_{el} is due to the fact that, for neutrino energies under some tens of MeV (E_ν <50 MeV), the neutrons in the nucleus contribute coherently to the cross section, resulting in a quadratic dependence ($\propto N^2$) on the number of neutrons in the target material and has the largest value among the other low-energy interaction channels of neutrino [2]. Due to its low-energy signal, the experimental observation of CνA_{el}, despite its largest cross-section, remained elusive for over four decades. In 2017, the COHERENT collaboration made a breakthrough by detecting CνA_{el} using the CsI[Na] scintillator detector [2] at the Spallation Neutron Source (SNS), followed by subsequent confirmation with liquid Argon scintillator detector [3] and recent claim with Germanium detector [4].

The groundbreaking observation of CνA_{el}, serving as experimental validation of the SM, has triggered a wide range of intriguing investigations, from conventional SM to studies of exotic neutrino physics beyond the Standard Model (BSM) (see Refs. [5, 6] for additional details). As part of BSM investigations, CνA_{el} experiments have the potential to explore non-standard neutrino-quark interactions (NSIs), studying electromagnetic properties of neutrinos (such as finite magnetic moments and millicharges), investigations of light mediators (for example scalars and/or axion-like particles, and light vectors such as dark photons), as well as sterile neutrinos, neutrino generalized interactions (NGI), dark large mixing angle (DLMA), and a multitude of others [7]. Furthermore, CνA_{el} observation is crucial for understanding the neutrino floor [8], which represents an irreducible background for DM direct detection experiments, driven by coherent neutrino scattering from atmospheric, solar, and supernova neutrinos [9].

Multiple experimental campaigns by the **T**aiwan **EX**periment **O**n **N**eutrin**O** (TEXONO) Collaboration have been conducted, with the current focus on detecting CνA_{el} via reactor neutrinos sourced from the Kuo-Sheng Nuclear Power Station (KSNPS) located on Taiwan's northern coast. At a depth of around 30 meter-water-equivalent (m.w.e.) and 28 meters from the core No. 1 of the KSNPS, with a thermal power output of 2.9 GW, the Kuo Sheng Reactor Neutrino Laboratory (KSNL) is exposed to an anti-electron neutrino ($\bar{\nu}_e$) flux of 6.35×10^{12} cm^{-2}s^{-1}. For an in-depth understanding of the TEXONO experiment's facility, please refer to Ref. [10] and the associated references provided therein. The current work is dedicated to probing the CνA_{el} signal within the SM and searching for light mediators (scalar and vector) in reactor neutrino data, aiming to identify potential new physics BSM. In this research, measurements were performed at KSNL utilizing an electrocooled p-type point-contact Germanium detector (pPCGe) shielded by a NaI(Tl) Anti-Compton (AC) detector. The Germanium crystal, with a diameter and height of approximately 70 mm and a mass of 1.47 kg, achieved a Pulser FWHM of about ~70 eV$_{ee}$ and an electronic noise threshold of 200 eV$_{ee}$, which are vital for reactor CνA_{el} analysis.

2. Cross section of CνA_{el} in the SM and extended frameworks

In CνA_{el}, a neutrino of any flavor scatters with a nucleus at low momentum transfer, resulting in coherent addition of scattering amplitudes as the nucleon wave functions align in phase. The cross section of CνA_{el} in the SM can be expressed as:

$$\frac{d\sigma_{\rm SM}}{dT}(T, E_\nu) = \frac{G_F^2 M_N}{4\pi}\left(1 - \frac{M_N T}{2E_\nu^2}\right) Q_{\rm SM}^2 F^2(q^2) \, , \tag{1}$$

where T is the nuclear recoil energy, G_F is the Fermi coupling constant, M_N is the mass of the target nuclei (e.g. Germanium as in our analysis), E_ν is the incident neutrino energy, and $Q_{\rm SM}$ represents the SM weak nuclear charge [11, 12]. The nuclear form factor $F(q^2)$ corresponds to the physical dimensions of the nucleus and the distribution of nuclear density. The presence of novel mediators interacting with SM neutrinos and quarks modifies the CνA_{el} cross section Eq. 1 within the SM, thereby extending the SM framework. We consider two simplified extensions of the SM within the framework of CνA_{el}, incorporating light vector and scalar mediators.

In BSM frameworks, new Z'-like *vector bosons* emerge naturally in simple $U(1)'$ extensions of the SM. In this framework, the relevant components of the extension that could contribute to CνA_{el} are presented as a scaling transformation of the SM CνA_{el} cross section, leading to a resultant modification within BSM

$$\frac{d\sigma_{\rm SM+Z'}}{dT} = Q_{Z'}^2(T)\frac{d\sigma_{\rm SM}}{dT}, \tag{2}$$

where the prefactor $Q_{Z'}$ is defined as

$$Q_{Z'}(T) = 1 - \frac{\sqrt{2}}{G_F}\frac{Q_{Z'}}{Q_{\rm SM}}\frac{g_{Z'}^{\nu V}}{2M_N T + M_{Z'}^2}. \tag{3}$$

The corresponding modified nuclear charge $Q_{Z'}$ associated to the $Z^{'}$ can be further realized as related to the quark coupling

$$Q_{Z'} = \left(2g_{Z'}^{uV} + g_{Z'}^{dV}\right)Z + \left(g_{Z'}^{uV} + 2g_{Z'}^{dV}\right)N. \tag{4}$$

Taking into account the universal coupling of leptons and quarks, it becomes

$$Q_{Z'} = 3g_{Z'}(N+Z). \tag{5}$$

As part of the BSM framework, the modification of CνA_{el} is achieved through a possible scalar propagator, leading to an extension of the SM in this study by incorporating a real *light scalar boson* ϕ of mass M_ϕ. The CνA_{el} cross section is modified by the ϕ interaction, which adds incoherently to the SM contribution

$$\frac{d\sigma_{\rm SM+\phi}}{dT} = \frac{d\sigma_{\rm SM}}{dT} + \frac{d\sigma_\phi}{dT}, \tag{6}$$

with

$$\frac{d\sigma_\phi}{dT} = \frac{M_N}{4\pi} g_\phi^{\nu S^2} Q_\phi^2 \left(\frac{M_N T}{E_\nu^2 (M_\phi^2 + 2M_N T)^2}\right) F^2(q^2), \tag{7}$$

where $g_\phi^{\nu S}$ represents the scalar-neutrino coupling. The nuclear charge associated with the exchange of the ϕ can be given by [13]

$$Q_\phi = Z \sum_{q=u,d} g_\phi^{qs}\frac{m_p}{m_q} f_q^p + N \sum_{q=u,d} g_\phi^{qs}\frac{m_n}{m_q} f_q^n, \tag{8}$$

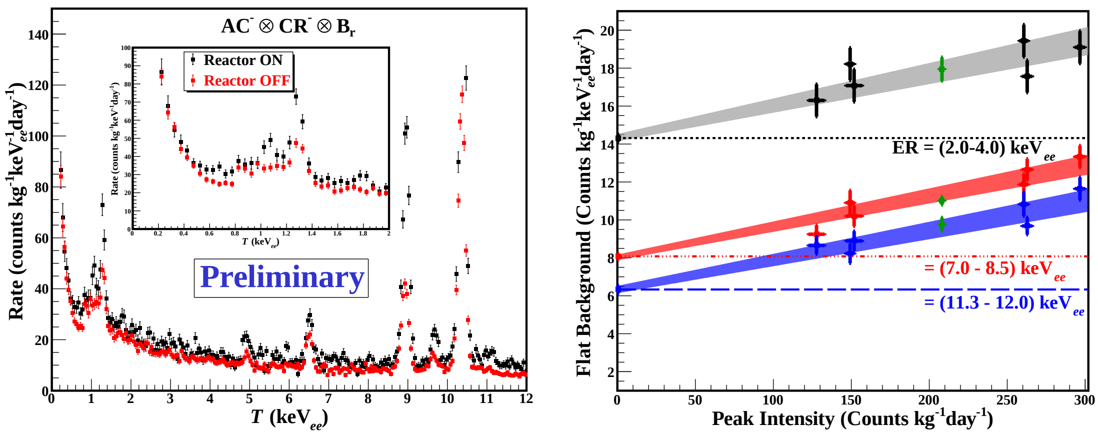
where $m_{p,n}$ and m_q represents the mass of nucleon [proton (p), neutron (n)] and quarks (u, d). The effective low-energy coupling between a ϕ mediator and the nucleon (p, n) for the quark q is determined by the hadronic form factors $f_{u,d}^{p,n}$. For simplicity, we assume a universal coupling to leptons and quarks, resulting in

$$Q_\phi = g_\phi \; 17.3 \; (N+Z). \tag{9}$$

This allows us to explore within the parameter space characterized by M_ϕ and g_ϕ. To gain further insight into above equations, readers may refer to Ref. [7] and the relevant references cited therein.

3. Measurements from TEXONO data

The data analysis methodologies employed by the TEXONO are grounded in multiple generations of experiments, as thoroughly detailed in Refs. [10, 14]. Potential signal candidates are identified as events originating from within the bulk of the detector [15]. Candidate events induced by neutrinos, dark matter, and other exotic events are classified as $AC^{-}\otimes CR^{-}\otimes B_r$, following the standard definitions outlined in Ref. [10]. This notation signifies the uncorrelated Anti-Compton veto⊗Cosmic Ray veto⊗Bulk Events Corrected, as depicted in Fig. 1(a) during both the reactor ON and OFF phases. Current analysis incorporates 245/560 kg-days of data collected during reactor ON and OFF periods. We are currently conducting a comprehensive cross-check of various event sample correlations. Given this ongoing analysis, the limits presented here are preliminary and may evolve as we further refine our data handling procedures.



(a) (b)

Figure 1: (a) The spectrum of reactor ON and OFF data, corrected for uncorrelated and bulk events $AC^{-}\otimes CR^{-}\otimes B_r$, with an inset focusing on the low-energy region. (b) The correlation between the flat background (between 2-4 keV$_{ee}$, 7-8.5 keV$_{ee}$, and 11.3-12 keV$_{ee}$ energy regions) and the intensity of the ^{135}Xe 249.8 keV γ-line. To calibrate the contamination of the $AC^{-}\otimes CR^{-}\otimes B_r$ background in the residual spectrum, this variation is utilized. The shaded region depicts the $\pm 1\sigma$ uncertainty band around the best linear fit.

The observed fluctuations in the low-energy background level during different phases of reactor ON data have led the TEXONO to explore potential unknown structures in the high-energy region. The reactor ON data exhibit an unusual background feature, which is attributed to contamination by ^{135}Xe isotope. The isotope ^{135}Xe, a fission product, undergoes β^{-}-decay with a half-life of 9.14 hours, resulting in the formation of the excited state ^{135}Cs*. This excited nucleus subsequently de-excites via γ-ray emission, transitioning to the long-lived ground state of ^{135}Cs [16]. The resulting γ-ray emission, primarily at 249.8 keV, is prominently observed in the Reactor ON spectra. Ambient γ-rays, such as this one, in the low-energy region (< 10 keV$_{ee}$) produce a flat Compton background, affecting uncorrelated $AC^{-}\otimes CR^{-}\otimes B_r$ samples. We employ a correlation analysis between the 249.8 keV γ-ray intensity of ^{135}Xe and the flat background level in three energy regions (ER) to effectively reduce the Compton background contribution, as demonstrated in Fig. 1(b) and supported by simulations.

4. Results and discussion

The estimated upper limit at 90% C.L. on the excess over the SM predicted cross section $\left(\rho = \frac{\sigma_{\text{Measured}}}{\sigma_{\text{SM}}}\right)$ is displayed in Fig. 2 for the residual spectrum (reactor ON minus OFF) of the aforementioned data set. This analysis utilizes the Lindhard model for characterizing low-energy nuclear recoils through quenching factor $Q(T)$. At the standard Lindhard parameter for Germanium, k=0.157, the achieved limit is ρ<3.8. Here, k is a dimensionless parameter that represents the electronic energy loss in the standard Lindhard model for $Q(T)$. Moreover, k>0.145 is excluded when considering the SM predicted $C\nu A_{el}$, which is competitive with other ongoing experiments.

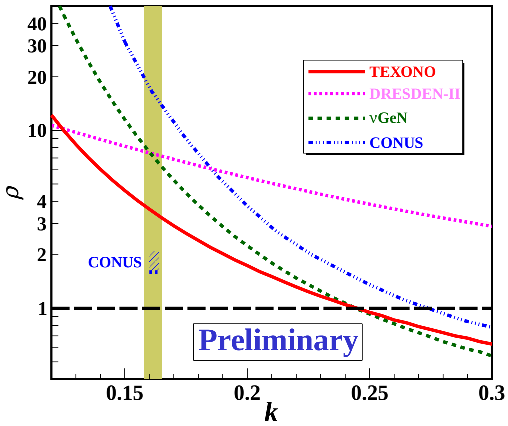
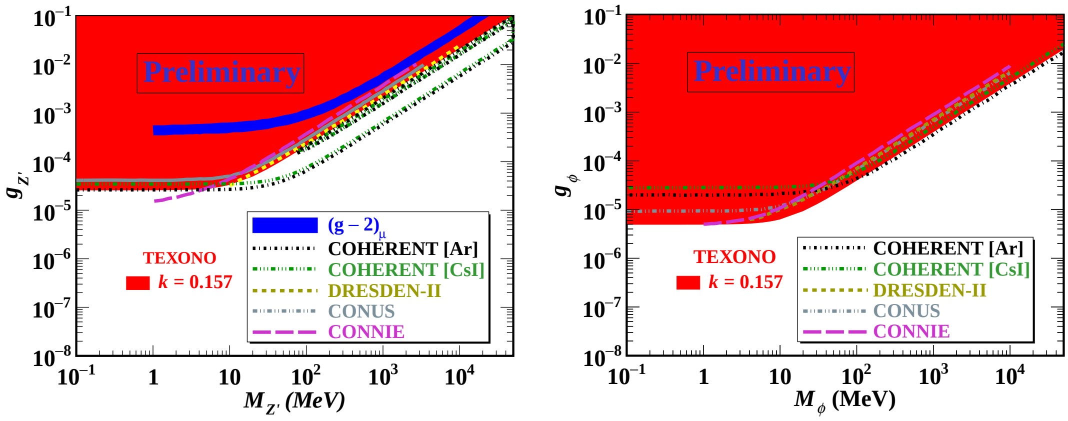


Figure 2: An upper exclusion plot for SM $C\nu A_{el}$ cross section measurement at 90% C.L. The 3σ bound on k, as determined from quenching factor measurements, is represented by the yellow shading. To provide a comprehensive comparison, we have superimposed the results of our analysis with those from contemporary experiments, such as DRESDEN-II [17], CONUS (dotted line) [6], recent CONUS result (blue hatched shade) [18], and νGeN [19].



(a) (b)

Figure 3: Limits for low-mass vector (a) and scalar (b) mediators, estimated at the 90% C.L. The results from multiple experiments, including CONNIE at 95% C.L. [20], DRESDEN-II at 2σ C.L. [21], COHERENT at 90% C.L. [22], and CONUS at 90% C.L. [6], are superimposed to provide a comprehensive view of the current status, though direct comparisons are avoided due to varying C.L. across the experiments.

In addition to setting limits on SM $C\nu A_{el}$, we have also estimated the 90% C.L. upper limits on the masses ($M_{\phi,Z'}$) and couplings ($g_{\phi,Z'}$) of light scalar and vector mediators within extended SM frameworks. It is noteworthy to mention that in the investigation of neutrino-nucleus scattering, both models are intriguing because these mediators may affect the recorded recoil spectra, particularly when their masses are below the maximum momentum transfer. As a result, experiments employing reactor neutrinos can exhibit even greater sensitivity, particularly in the mediator mass region below ~10 MeV, as evident in Fig. 3(a), outperforming those that employ π-DAR sources. The steeper profile of the scalar interaction enabled us to achieve a competitive bound of $g_\phi < O(10^{-5})$ in the low mass (10 MeV) region.

The KSNPS is in the decommissioning phase, however, we are still allowed to gather reactor OFF data until 2025, which will certainly bolster our statistics. We are actively working to expand our data set and conduct a thorough cross-check of various event sample correlations. This will enable us to impose more stringent constraints on the parameters of interest. In the next phase, the experimental setup will be relocated under the CDEX collaboration to the Sanmen Nuclear Power Station in Zhejiang, China [23], which has a thermal power output of 3.4 GW. The detector will be positioned approximately 25 meters from the center of the core, facing $\bar{\nu}_e$ flux $O(10^{13})\text{cm}^{-2}\text{s}^{-1}$ to further investigate CνA_{el} and other aspects extending into BSM.

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