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Measurement of $\bar{\nu}_e - e^-$ Scattering Cross-Section and Constraints on New Physics with a CsI(Tl) Crystal Array at the Kuo-Sheng Reactor Laboratory

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The $\bar{\nu}_e - e^-$ elastic scattering cross-section was measured with a CsI(Tl) scintillating crystal detector array with a total mass of 187 kg at the Kuo-Sheng Nuclear Power Station. The detectors were exposed to a reactor $\bar{\nu}_e$ flux of 6.4×10^{12} cm^{-2}s^{-1} originated from a core with 2.9 GW thermal power. The physics motivations, conceptual design, detector hardware, data analysis and background understanding of the experiment are presented. Using 29882/7369 kg-days of Reactor ON/OFF data, the Standard Model (SM) of electroweak interaction was probed at the 4-momentum transfer range of $\sim 3 \times 10^{-6}$ GeV^2. A cross-section ratio of $R_{expt} = [1.08 \pm 0.21 \text{ (stat)} \pm 0.16 \text{ (sys)}] \times R_{SM}$ was measured. Constraints on the electroweak parameters (g_V, g_A) were placed, corresponding to a weak mixing angle measurement of $\sin^2\theta_W = 0.251 \pm 0.031 \text{ (stat)} \pm 0.024 \text{ (sys)}$. The destructive interference in the SM $\bar{\nu}_e$-e processes was verified with the value of $R^{INT}_{expt} = -0.92 \pm 0.30\ (stat) \pm 0.24\ (sys)$. Bounds on neutrino anomalous electromagnetic properties were placed: neutrino magnetic moment at $\mu_{\bar{\nu}_e} < 2.2 \times 10^{-10} \mu_B$ at 90% confidence level, and the neutrino charge radius at $\langle r^2_{\bar{\nu}_e} \rangle = [0.61 \pm 1.30 \text{ (stat)} \pm 1.01 \text{ (sys)}] \times 10^{-32}$ cm^2.

Since Neutrino-electron scattering are purely leptonic processes with robust Standard Model (SM) predictions, their measurements can provide constraints to physics beyond SM. The $\bar{\nu}_e - e^-$ data taken at the Kuo-Sheng Reactor Neutrino Laboratory were used to probe two scenarios: Non-Standard Neutrino Interactions (NSI) and Unparticle Physics. New constraints were placed to the NSI parameters $(\varepsilon^{eL}_{ee}, \varepsilon^{eR}_{ee})$, $(\varepsilon^{eL}_{e\mu}, \varepsilon^{eR}_{e\mu})$ and $(\varepsilon^{eL}_{e\tau}, \varepsilon^{eR}_{e\tau})$ for the Non-Universal and Flavor-Changing channels, respectively, as well as to the coupling constants for scalar (λ_0) and vector (λ_1) unparticles to the neutrinos and electrons.

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1. NEUTRINO-ELECTRON SCATTERING AND NEW PHYSICS

Neutrino electron scattering is pure leptonic process which is explained well with electroweak theory. Cross-section measurement of $\bar{\nu}_e - e^-$ scattering opens a new window to measure electroweak parameters of Standard Model (SM) as well as electromagnetic properties of neutrinos such as charge radius and magnetic moment. In addition, searching for excess number of events over SM prediction makes possible to search new physics beyond the SM such as Non-Standard Interaction of neutrinos (NSI) and Unparticle Physics (UP). The neutrino electron scattering cross-section is given by in the laboratory frame

$$\left[\frac{d\sigma}{dT}(\bar{\nu}_e e)\right]_{SM} = \frac{2G_F^2 m_e}{\pi} \cdot \left[g_R^2 + (g_L+1)^2(1-\frac{T}{E_\nu})^2 - g_R(g_L+1)\frac{m_e T}{E_\nu^2}\right] \quad , \tag{1.1}$$

where T is the kinetic energy of the recoil electron, E_ν is the incident neutrino energy, m_e is mass of the electron and chiral couplings g_L and g_R are defined in terms of coupling constants $g_V = -\frac{1}{2} + 2\sin^2\theta_W$ and $g_A = -\frac{1}{2}$ as $g_L = \frac{1}{2}(g_V + g_A) = -\frac{1}{2} + \sin^2\theta_W$ and $g_R = \frac{1}{2}(g_V - g_A) = \sin^2\theta_W$.

Atmospheric and Solar neutrino anomalies is explained via neutrino oscillations which mimics neutrinos being massive unlike Standard Model prediction. NSI of neutrinos arise in beyond the SM theories especially in neutrino gaining mass models. See-saw type models, low energy SUSY with R-parity breaking, unified SUSY models as a renormalization effect and models acquiring mass relatively due to presence of extra Higgs boson and existence of Heavy Gauge Boson Z' are some of the BSM which contain NSI of neutrinos. Short-baseline reactor neutrino experiments is a powerful channel to search for NSI effects due to high neutrino flux and being able to neglect oscillation effects. In a model independent approach, NSI of neutrinos is modification of four-Fermi interaction with some new couplings. NSI may cause lepton number violation which is called Flavor Changing (FC) NSI. If the flavor is conserved, it is called Nonuniversal (NU) NSI. The cross-section including both SM and NSI interactions for $\bar{\nu}_e + e \to \bar{\nu}_e + e$ is given by [1]

$$\begin{aligned}\left[\frac{d\sigma}{dT}\right]_{SM+NSI} = \frac{2G_F^2 m_e}{\pi} \cdot [& \left(\tilde{g}_R^2 + \sum_{\alpha\neq e}|\varepsilon_{\alpha e}^{eR}|^2\right) + \left((\tilde{g}_L+1)^2 + \sum_{\alpha\neq e}|\varepsilon_{\alpha e}^{eL}|^2\right)\left(1-\frac{T}{E_\nu}\right)^2 \\ & - \left(\tilde{g}_R(\tilde{g}_L+1) + \sum_{\alpha\neq e}|\varepsilon_{\alpha e}^{eR}||\varepsilon_{\alpha e}^{eL}|\right)\frac{m_e T}{E_\nu^2}] \quad , \end{aligned} \tag{1.2}$$

where $\tilde{g}_L = g_L + \varepsilon_{ee}^{eL}$ and $\tilde{g}_R = g_R + \varepsilon_{ee}^{eR}$.

The idea of unparticle physics depends on the possibility of existence of a scale invariant sector, (which is described by Banks-Zaks (BZ) fields) that decouples at large energy scale. BZ fields may coexist with SM fields at a higher energy scale. It has been proposed that below an energy scale Λ_U, BZ operators may turn into unparticle operators O_U with a non integer scaling dimension denoted by d_S and d_V for the scalar and vector cases respectively and this enables to search unparticle physics effects in SM sector [2] $\bar{\nu}_e - e^-$ scattering experiments can probe the virtual effects of Unparticles which act as mediators in the interactions. The interaction can proceed via scalar (U_S) or vector (U_V) unparticle exchange. Moreover this new kind of interaction can be flavor violating (FV) as in NSI or flavor conserving (FC) as SM dictates. For the $\bar{\nu}_e - e^-$ scattering with scalar unparticle exchange, the interference effects with SM is suppressed by a factor of m_ν/Λ and therefore negligible.

2. EXPERIMENTAL SET-UP AND DATA ANALYSIS

One of the most important project of the TEXONO research program is to study $\bar{\nu}_e - e^-$ elastic scattering at $Q^2 \sim (3\times10^{-6})$ GeV^2 reactor neutrino range. The CsI(Tl) crystals were arranged as a 12×9 array matrix inside an OFHC copper box. The detector consisted of 100 crystals giving a total mass of 187 kg. Each single crystal module has a hexagonal-shaped cross-section with 2 cm side, 40 cm length and modular mass of 1.87 kg. The properties, advantages and the performance of the prototype modules of CsI(Tl) scintillating crystal detector were documented elsewhere [3]

Neutrino-induced candidate events were selected through the suppression of: (a) cosmic-ray and anti-Compton background by CRV and multiplicity cuts (MHV), (b) accidental and α-events by PSD, and (c) external background by Z-position cut. A total of 29882/7369 kg-day of Reactor ON/OFF data was recorded and the combined $ON-BKG$ residual spectrum is displayed in Figure 1, from which various electroweak parameters were derived. There is an excess in the residual spectrum corresponding to $\sim$414 neutrino-induced events. The residual spectrum of Figure 1 corresponds to $R_{expt} = [1.08\pm0.21\pm0.16]\times R_{SM}$ with $\chi^2/dof = 8.7/9$, giving $\sin^2\theta_W = 0.251\pm0.031\pm0.024$. The allowed region in the $g_V - g_A$ plane is depicted in Figure 2. The accuracy is comparable to that achieved in accelerator-based $\nu_e - e$ scattering experiments [5]. The measured value of R^{INT}_{expt} is $-0.92\pm0.30\pm0.24$ which verifies the SM prediction of destructive

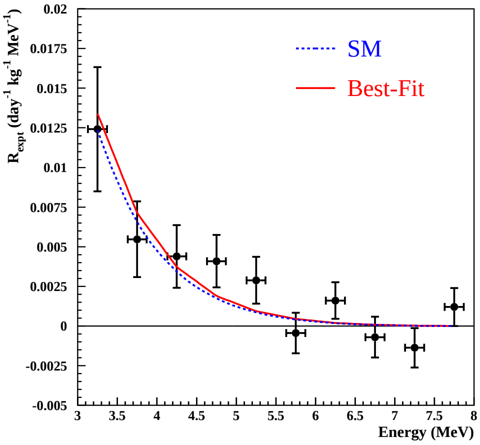

Figure 1: The combined ON-BKG residual spectrum together with SM.

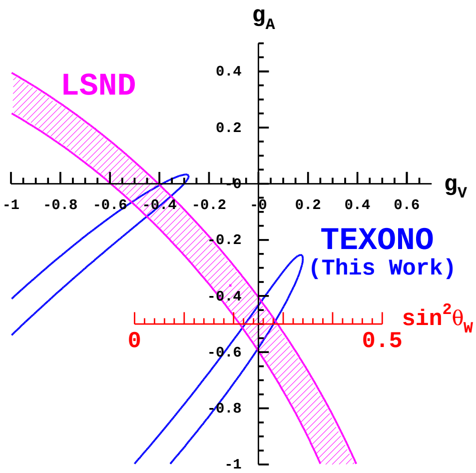

Figure 2: The 1-σ allowed region $g_V - g_A$ space defined by statistic uncertainty only, together with $\sin^2\theta_W$.

interference. Existence of neutrino magnetic moment ($\mu_{\bar{\nu}_e}$) would contribute an additional term to the cross-section of Eq. 1.1:

$$\left(\frac{d\sigma}{dT}\right)_{\mu_\nu} = \frac{\pi\alpha_{em}^2\mu_\nu^2}{m_e^2}\left[\frac{1-T_e/E_\nu}{T_e}\right] . \qquad (2.1)$$

From the best fit a limit of $\mu_{\bar{\nu}_e} < 2.2\times10^{-10}\times\mu_B$ at 90% C.L. was derived. A finite neutrino charge radius $\langle r^2_{\bar{\nu}_e}\rangle$ would lead to radiative corrections which modify the electroweak parameters by $g_V \to -\frac{1}{2} + 2\sin^2\theta_W + (2\sqrt{2}\pi\alpha_{em}/3G_F)\langle r^2_{\bar{\nu}_e}\rangle$; $\sin^2\theta_W \to \sin^2\theta_W + (\sqrt{2}\pi\alpha_{em}/3G_F)\langle r^2_{\bar{\nu}_e}\rangle$ where α_{em}

and G_F are the fine structure and Fermi constants, respectively. The results of -2.1×10^{-32} $cm^2 < \langle r^2_{\bar{\nu}_e} \rangle < 3.3 \times 10^{-32}$ cm^2 at 90% C.L were obtained. The complete version of this work can be found in Ref. [4]

Table 1: Constraints at 90% C.L. due to one-parameter fits on the NSI couplings. The results are presented as "best-fit ± statistical error ± systematic error".

NSI Parameters	Measurement Best-Fit	χ^2/dof	Bounds at 90% C.L.	Projected Sensitivities
NU {	$\varepsilon^{eL}_{ee} = 0.03 \pm 0.26 \pm 0.17$	8.9/9	$-1.53 < \varepsilon^{eL}_{ee} < 0.38$	± 0.015
	$\varepsilon^{eR}_{ee} = 0.02 \pm 0.04 \pm 0.02$	8.7/9	$-0.07 < \varepsilon^{eR}_{ee} < 0.08$	± 0.002
FC {	${\varepsilon^{eL}_{e\mu}}^2 ({\varepsilon^{eL}_{e\tau}}^2) = 0.05 \pm 0.27 \pm 0.24$	8.9/9	$\lvert\varepsilon^{eL}_{e\mu}\rvert(\lvert\varepsilon^{eL}_{e\tau}\rvert) < 0.84$	± 0.052
	${\varepsilon^{eR}_{e\mu}}^2 ({\varepsilon^{eR}_{e\tau}}^2) = 0.008 \pm 0.015 \pm 0.012$	8.7/9	$\lvert\varepsilon^{eR}_{e\mu}\rvert(\lvert\varepsilon^{eR}_{e\tau}\rvert) < 0.19$	± 0.007

Constraints for scalar and vector UP couplings were derived at $\Lambda_U = 1$ TeV as well as at different energy scale up to $\Lambda_U = 10$ TeV. Both Flavor Conserving and Flavor Violating couplings give similar bounds in this parameter space. CsI(Tl) gave rise to more stringent limits compared to other experiments. New constraints derived to the NSI parameters for both the Non-Universal and Flavor-Changing channels are summarized in Table [1]. The detailed of this analysis and derived bounds can be found in Ref. [6]

3. CONCLUSION

The sensitivities can be further enhanced in future experiments. Electromagnetic calorimeters using CsI(Tl) with tens of tons of mass have been constructed, such that the target mass is easily expandable. The dominant background above 3 MeV were all external to the target scintillator. Accordingly, they will be attenuated effectively through self-shielding in a target with bigger mass. A 30 times increase in data strength (for instance, with 1 ton fiducial mass and 1000 days data taking) and $\times 1/10$ suppression in background can improve the statistical accuracies to 0.8% and 0.12% for cross-section and $\sin^2\theta_W$, respectively. Systematic uncertainties originate mainly from the evaluation of the reactor neutrino spectra. This can be overcome by a simultaneous measurement of the $\bar{\nu}_e$ spectra via the matured inverse beta-decay process $\bar{\nu}_e + p \to n + e^+$ with, for instance, large liquid scintillator detectors.

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