Studies of Neutrino-Electron Scattering at the Kuo-Sheng Reactor Neutrino Laboratory

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Studies on $\bar{\nu}_e - e^-$ elastic scattering were performed using a 200-kg CsI(Tl) scintillating crystal detector array at the Kuo-Sheng Nuclear Power Plant in Taiwan. The measured cross section of $R_{\exp} = [1.00 \pm 0.32(\text{stat})]$; $R_{SM}$ is consistent with the Standard Model expectation and the corresponding weak mixing angle is derived as $\sin^2 \theta_W = 0.241 \pm 0.05(\text{stat})$. The results are consistent with a destructive interference effect between neutral and charged-currents in this process. Limits on neutrino magnetic moment of $\mu_\nu < 2.0 \times 10^{-10} \mu_B$ at 90% confidence level and on electron antineutrino charge radius of $\langle r_e^2 \rangle < (0.12 \pm 2.07) \times 10^{-32} \text{cm}^2$ were also derived.

1. NEUTRINO - ELECTRON SCATTERING

Neutrino-electron scatterings ($\nu_e(\bar{\nu}_e) - e^-$) are fundamental electroweak processes which play important roles in neutrino oscillation studies and in probing the electroweak parameters of the Standard Model (SM) and in the studies of neutrino properties such as the electromagnetic moments and charge radius [1]. The differential cross section for $\bar{\nu}_e - e^-$ scattering can be written as [1, 2]:

$$
\frac{d\sigma_{SM}}{dT}(\bar{\nu}_e e) = \frac{G_F^2 m_e}{2\pi} \left[(g_V - g_A)^2 + (g_V + g_A + 2)^2 \left(1 - \frac{T}{E_{\nu}}\right)^2 - (g_V - g_A)(g_V + g_A + 2)\frac{m_e T}{E_{\nu}}\right]
$$

(1)

where $T$ is the kinetic energy of the recoil electron, $E_{\nu}$ is the incident neutrino energy and $g_V$, $g_A$ are coupling constants which can be expressed as $g_V = -\frac{1}{2} + 2\sin^2 \theta_W$ and $g_A = -\frac{1}{2}$.

The total cross section for $\bar{\nu}_e - e^-$ scattering can be written as

$$
\sigma_{SM} = \int_T \int_{E_{\nu}} \frac{d\sigma_{SM}}{dT} \frac{d\phi}{dE_{\nu}} dE_{\nu} dT = \frac{G_F^2 m_e}{2\pi} \left\{ (g_V - g_A)^2 I_1 + (g_V + g_A + 2)^2 I_2 \right\} - (g_V - g_A)(g_V + g_A + 2)I_3
$$

(2)

where $I_1$, $I_2$, $I_3$ are integrals of the function of 1, $(1 - T/E_{\nu})^2$ and $m_e T/E_{\nu}^2$ over the antineutrino spectrum and the recoil energy of electron, respectively. In the low energy neutrino studies we must consider the electron mass dependent term $I_3$ in Eq. 2 because of its significant contribution to the cross section [2].

The value of weak mixing angle ($\sin^2 \theta_W$) was measured precisely at high energy (10-100 GeV) at the accelerators, and at lower energy with Moller scattering and atomic parity violation experiments [1]. The interactions $\nu_e(\bar{\nu}_e) - e^-$ have the additional unique features of being sensitive to the contributions of charged current (CC), neutral current (NC) and their interference (INT). The cross-sections of $\nu_e - e^-$ have been measured at accelerators [3]. For reactor $\bar{\nu}_e - e^-$, the existing data are either controversial [4, 5] or with large uncertainties [6]. There is much room for improvement and this work is an attempt to bridge this gap.

2. EXPERIMENTAL SET-UP

An important component of the TEXONO research program is to study $\bar{\nu}_e - e^-$ elastic scattering at the MeV reactor neutrino range. The neutrino laboratory is located at the Kuo-Sheng Nuclear Power Plant a distance of 28 m from the reactor core with 2.9 GW of thermal power, having a total flux of about $6.4 \times 10^{12} \text{ cm}^{-2}\text{s}^{-1}$. The details of neutrino source and neutrino spectrum were discussed in Ref. [2]. The CsI(Tl) scintillation detector array is enclosed by 4$\pi$ low-activity passive shielding materials with a total mass of 50 tons, as well as a layer of active cosmic-ray...
(CRV) plastic scintillator panels. The entire target space is covered by a plastic bag flushed with dry nitrogen to suppress background due to the diffusion of the radioactive radon gas.

The CsI(Tl) crystals were arranged as a $12 \times 9$ array matrix inside an OFHC copper box, as shown schematically in Figure 1. The detector consisted of 100 crystals giving a total mass of 200 kg. Each single crystal module has a hexagonal-shaped cross-section with 2 cm side, 40 cm length and 2 kg mass. The light output was read out at both ends of the crystal by PMTs with low-activity glass of 29 mm diameter. The properties, advantages and the performance of the prototype modules of CsI(Tl) scintillating crystal detector were documented elsewhere. These properties make crystal scintillators suitable for the study of low energy neutrino experiments. The PMT signals were recorded by 20 MHz Flash Analog-to-Digital-Converters (FADCs) running on a VME-based data acquisition system. The sum of the two PMT signals gives the energy of the event, while their difference provides information on the longitudinal “Z” position. An energy resolution of $<10\%$ FWHM and a Z-resolution of $\sim 2$ cm at 660 keV as well as excellent $\alpha/\gamma$ event identification by pulse shape discrimination (PSD) were demonstrated in prototype studies.

3. DATA ANALYSIS

Neutrino-induced candidate events were selected through the suppression of: (a) cosmic-ray and anti-Compton background by CRV and multiplicity cuts, (b) accidental and $\alpha$-events by PSD, and (c) external background by Z-position cut. The spectra at the various stages of the background rejection were displayed in Figure 2. In situ calibration was achieved using the measured $\gamma$-lines from $^{137}$Cs, $^{40}$K and $^{208}$Tl. A signal to background ratio of $\sim 1/15$ at 3 MeV was achieved. The spectra measured during the Reactor OFF periods constituted a background measurement.

The internal contaminations of the $^{238}$U and $^{238}$Th series were measured and found to be negligible compared to the observed background rates. Residual background at the relevant 3–6 MeV range are either cosmic-ray induced or due to coincidence of $\gamma$-emissions following $^{208}$Tl decays. Their intensities were evaluated from the in situ multi-hit samples, the $^{208}$Tl-2614 keV lines as well as from simulation studies, and the results provide the second background measurement. The background from both methods was subsequently combined (BKG) and subtracted from the candidate Reactor-ON samples.
4. PHYSICS RESULTS

A total of 31874.7/7860.1 kg-day of Reactor ON/OFF data was recorded and the combined ON−BKG residual spectrum is displayed in Figure 3 from which various electroweak parameters were derived. Only events with energy more than 3 MeV above the $^{208}\text{Tl}$ end-point were used for physics analysis. There is an excess in the residual spectrum corresponding to $\sim 400$ neutrino-induced events. The uncertainties cited in what follows are only statistical. Intense efforts on the studies of systematic effects are underway.

4.1. Cross Section and Electroweak Parameters

Denoting the measured event rate as

$$R_{\text{exp}} = \zeta \cdot R_{SM} \quad (3)$$

where $R_{SM}$ is the SM predicted values, the residual spectrum of Figure 3 corresponds to $\zeta = 1.00 \pm 0.32(\text{stat})$ with $\chi^2/\text{dof} = 9.78/9$, giving

$$\sin^2 \theta_W = 0.24 \pm 0.05(\text{stat}) \quad (4)$$

The allowed region in the $g_V - g_A$ plane is depicted in Fig. 4. The accuracy is comparable to that achieved in accelerator-based $\nu_e - e$ scattering experiments [3].

Residual spectra from OFF-BKG data were extracted and used for demonstrating the validity of background understanding and the analysis procedures. The fractional deviation (OFF-BKG)/OFF = 0.011 $\pm$ 0.018 at $\chi^2/\text{dof} = 8.23/9$ indicates excellent agreement with SM expectations and good systematic control.

To study the interference term, the event rate is parametrized as

$$R_{\text{exp}} = R_{CC} + R_{NC} + \eta \cdot R_{INT} \quad (5)$$

where $R_{CC/NC/INT}$ are the SM charged-, neutral currents and interference contributions, respectively. Table 1 shows the expectations on $\zeta$ for the possible cases. The measured value of $\zeta$ verifies the SM prediction of destructive interference.
Table I: The expected $\zeta$ ratios for the different interference scenario and how they are compared to the measured one.

| Interference         | $\zeta$ |
|----------------------|---------|
| Destructive ($\eta = 1$) | 1       |
| Constructive ($\eta = -1$) | 2.46    |
| No Interference ($\eta = 0$) | 1.73    |
| Measurement          | $1.00 \pm 0.32$ (stat) |

4.2. Magnetic Moment and Neutrino Charge Radius

Existence of neutrino magnetic moment ($\mu_{\bar{\nu}_e}$) would contribute an additional term\cite{5,13} to the cross-section of Eq. 1:

$$
\frac{d\sigma}{dT_{\mu_{\bar{\nu}}}} = \pi \alpha_{em} \mu_{\bar{\nu}}^2 \frac{m_{\bar{\nu}}^2}{T_{\bar{\nu}}} \left[ 1 - \frac{T_{\bar{\nu}}/E_{\nu}}{T_{\bar{\nu}}} \right].
$$

(6)

Parametrizing the measured event rates as

$$
R_{exp} = R_{SM} + \kappa^2 \cdot R(\mu_{\bar{\nu}} = 10^{-10} \mu_B),
$$

(7)

the best fit value of $\kappa^2 = -0.52 \pm 2.74$ at $\chi^2/dof = 9.79/9$ was obtained. A limit of

$$
\mu_{\bar{\nu}_e} < 2.0 \times 10^{-10} \times \mu_B
$$

(8)

at 90% CL was derived.

A finite neutrino charge radius $\langle r_{\bar{\nu}_e}^2 \rangle$ would lead to radiative corrections\cite{2,14} which modify the electroweak parameters by:

$$
g_{\bar{\nu}} \rightarrow \frac{1}{2} + 2\sin^2\theta_W \sqrt{2\pi\alpha_{em}/3G_F} \langle r_{\bar{\nu}_e}^2 \rangle; \quad \sin^2\theta_W \rightarrow \sin^2\theta_W + \sqrt{2\pi\alpha_{em}/3G_F} \langle r_{\bar{\nu}_e}^2 \rangle
$$

(9)

where $\alpha_{em}$ and $G_F$ are the fine structure and Fermi constants, respectively. Results of

$$
\langle r_{\bar{\nu}_e}^2 \rangle = (0.12 \pm 2.07) \times 10^{-32} \text{ cm}^2
$$

(10)

at $\chi^2/dof = 9.82/9$ were derived accordingly.

References

\[1\] W. M. Yao et al., *J. Phys.* G **33**, 321 (2006), for details and references.
\[2\] B. Kayser et al., *Phys. Rev.* D **20**, 87 (1979).
\[3\] R. C. Allen et al., *Phys. Rev.* D **47**, 11 (1993); L. B. Aurbach et al., *Phys. Rev.* D **63**, 112001 (2001).
\[4\] F. Reines, H.S. Gurr, and H.W. Sobel, *Phys. Rev. Lett.*, **37**, 315 (1976).
\[5\] P. Vogel and J. Engel, *Phys. Rev.* D **39**, 3378 (1989).
\[6\] G. S. Vidyakin et al., *JETP Lett.* **55**, 206 (1992); A. I. Derbin et al., *JETP Lett.* **57**, 796 (1993); Z. Daraktchieva et al., *Phys. Lett.* B **615**, 081601 (2005); A.G. Beda et al., arXiv:0705.4576v1 (2007).
\[7\] H. T. Wong et al., *Phys. Rev.* D **75**, 012001 (2007).
\[8\] H. B. Li et al., *Nucl. Instrum. Methods* A **459**, 93 (2001).
\[9\] H. T. Wong et al., *Astroparticle Phys.* **14**, 141 (2000).
\[10\] Y. Lin et al., *Nucl. Instrum. and Methods* A **482**, 125 (2002).
\[11\] W. P. Lai et al., *Nucl. Instrum. and Methods* A **465**, 550 (2001).
\[12\] Y.F. Zhu et al., *Nucl. Instrum. Methods* A **557**, 490 (2006)
\[13\] H.T. Wong and H.B. Li, *Mod. Phys. Lett.* A **20**, 1103 (2005).
\[14\] J. Barranco et al., *Phys. Lett.* B **662**, 431 (2008).