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Measurement of Charged Current anti-neutrino cross-section on water and hydrocarbon with limited acceptance at 1.5 deg off axis with the T2K beam

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The measurement of the flux-integrated cross-sections on H_2O and CH using the T2K anti-neutrino beam is reported. The signal is defined as the charged-current interaction with one induced muon and no detected charged-pion nor proton. The phase spaces of muons are restricted to $p_\mu > 0.4$ MeV$/c$ and $\theta_\mu < 30$ degrees, in the laboratory frame. In addition, detectable phase spaces of pions and protons are defined as $p_\pi > 0.2$ MeV$/c$ and $\theta_\pi < 70$ degrees, and $p_{\mathrm{p}} > 0.6$ MeV$/c$ and $\theta_{\mathrm{p}} < 70$ degrees, respectively. No pions nor protons are required in these regions. Both of the $\bar{\nu}_\mu$ cross-sections and $\bar{\nu}_\mu + \nu_\mu$ cross-sections on H_2O and CH targets, and their ratios are measured. The results of $\bar{\nu}_\mu$ cross-section measurements are $\sigma_{\mathrm{H_2O}} = (1.082 \pm 0.068(\mathrm{stat.})^{+0.145}_{-0.128}(\mathrm{syst.})) \times 10^{-39}$ cm^2/nucleon, $\sigma_{\mathrm{CH}} = (1.096 \pm 0.054(\mathrm{stat.})^{+0.132}_{-0.117}(\mathrm{syst.})) \times 10^{-39}$ cm^2/nucleon, and $\sigma_{\mathrm{H_2O}}/\sigma_{\mathrm{CH}} = 0.987 \pm 0.078(\mathrm{stat.})^{+0.093}_{-0.090}(\mathrm{syst.})$, and those of $\bar{\nu}_\mu + \nu_\mu$ cross-section measurements are $\sigma_{\mathrm{H_2O}} = (1.155 \pm 0.064(\mathrm{stat.})^{+0.148}_{-0.129}(\mathrm{syst.})) \times 10^{-39}$ cm^2/nucleon, $\sigma_{\mathrm{CH}} = (1.159 \pm 0.049(\mathrm{stat.})^{+0.129}_{-0.115}(\mathrm{syst.})) \times 10^{-39}$ cm^2/nucleon, and $\sigma_{\mathrm{H_2O}}/\sigma_{\mathrm{CH}} = 0.996 \pm 0.069(\mathrm{stat.})^{+0.083}_{-0.078}(\mathrm{syst.})$.

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1. Experimental Apparatus

T2K [1] is a long-baseline neutrino-oscillation experiment designed to measure the mixing of muon (anti-)neutrinos with the other flavors. The T2K neutrino oscillation analysis mainly relies on data from two detectors: Super-Kamiokande (H_2O target) as a far-detector and ND280 (H_2O and CH targets) as a near-detector. Uncertainties in the modeling of neutrino-nucleus interactions due to the difference in the target at the near and the far-detector constitute an additional source of systematic errors in the T2K oscillation analysis. Therefore, it is crucial to understand the difference in neutrino cross-sections between H_2O and CH targets. Considering this fact, we performed neutrino-nucleus cross-section measurements using detectors (Fig. 1) with H_2O and CH targets at J-PARC. The WAGASCI module[2] has 1280 scintillator bars aligned in a 3D grid structure, and each grid cell is filled with the H_2O target. The 0.6 tons H_2O target is included in the WAGASCI module, and its volume is four times larger than that of scintillator bars. The Proton Module[3] is a fully active tracking detector consisting of scintillator bars only, and it is used as a CH target detector. The INGRID module[4] contains iron plates and scintillator bars, and it is used as a muon range detector in this measurement. These detectors are located at an off-axis angle 1.5 degrees, and at this position, the neutrino flux is similar to that at the ND280 position (2.5 degrees), as shown in Fig. 2.

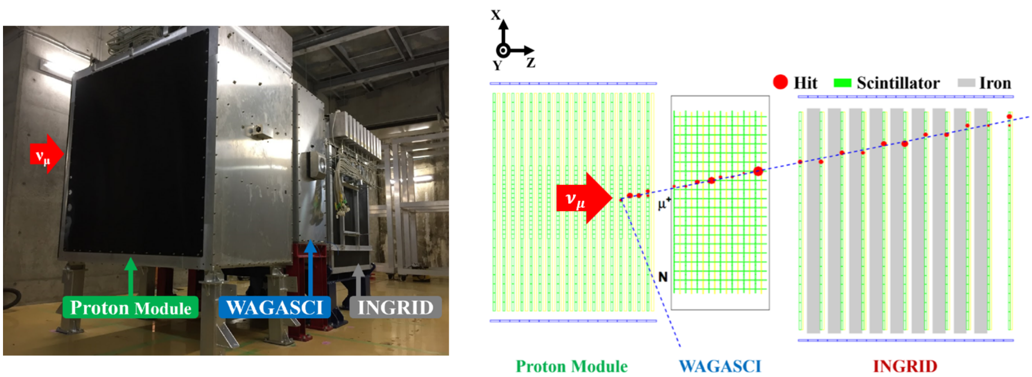

Figure 1: Detectors installed at the J-PARC neutrino-monitor building (left) and an example of the event display (right).

2. Signal Neutrino Interaction

Charged Current Quasi-Elastic (CCQE) interactions which produce one muon and one proton or neutron dominate at the T2K neutrino energy region (<1 GeV). However, due to nuclear effects, it is difficult to identify the interaction mode event-by-event. Therefore, to reduce model dependencies, the signal in this analysis is defined based on final state particles: **CC interaction without detected pions nor protons in the detectable region**. According to the detection efficiency, detectable regions for pions and protons are defined as follows:

- $p_\pi > 0.2$ GeV/c and $\theta_\pi < 70$ degrees for pions,
- $p_p > 0.6$ GeV/c and $\theta_p < 70$ degrees for protons.

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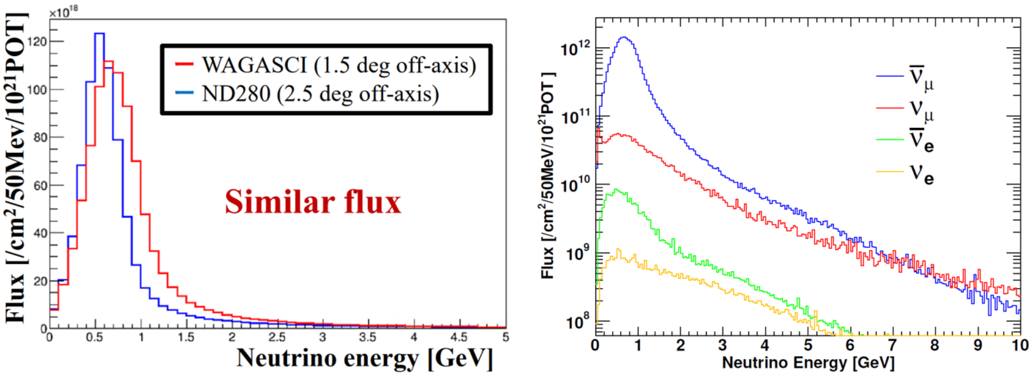

Figure 2: Right: Neutrino flux at the WAGASCI module position (red) and the ND280 position (blue). Left: Neutrino flux for each flavor at the WAGASCI module position.

3. Event Selections

During the anti-neutrino beam operation (October 2017 to May 2018), the statistics of 7.9×10^{20} Protons-On-Target (POT) are collected. To select neutrino event candidates, event selections are applied to these collected data. Firstly, if an MPPC channel has the ADC signal larger than 2.5 p.e. (photon equivalent), it is defined as a “hit”. To reconstruct the track from hits in the detector, more than 2 hits are required. In addition, the most upstream point (vertex) of the reconstructed track is required to be within the fiducial volume (FV) of 70 (X) $\times$ 70 (Y) $\times$ 21 (Z) cm^3. The reconstructed track is required to reach the INGRID module to identify it as a muon track. Figure 3 shows the selection efficiency for the WAGASCI module (left) and the Proton Module (right). Based on these efficiencies, the muon phase space is limited to "$p_\mu > 0.4$ GeV/c" and "$\theta_\mu < 30$ degrees".

Table 1 shows all the events after selections. Backgrounds are estimated by the neutrino event generator, NEUT [5] (5.3.3). In the anti-neutrino beam mode, ν_μ CC interactions are the dominant background sources because the ν_μ has the larger cross-section than that of $\bar{\nu}_\mu$.

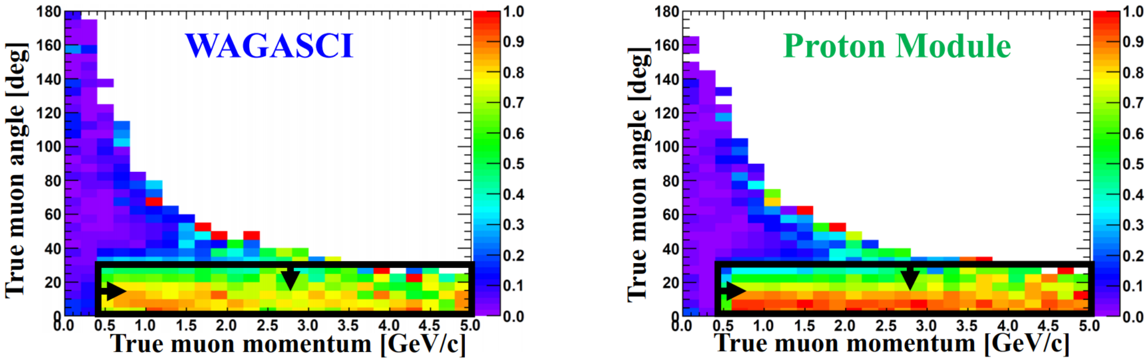

Figure 3: Selection efficiencies for the WAGASCI module (left) and the Proton Module (right).

Table 1: The number of neutrino candidate events after selections. "Non-target" consists of events caused by neutrino interactions in detector components other than the target material. "External BG" contains events from materials around the detector, such as the wall.

	Signal	CC ν_μ	ν_e and $\bar{\nu}_e$	Out of FV	Neutral Current	Non-target	External BG	Total	Data
WAGASCI module	801.1	138.3	16.5	204.4	20.1	9.1	72.3	1261.9	1279
Proton Module	1441.8	348.0	16.5	63.7	25.1	26.0	54.8	1983.1	1967

4. Analysis Strategies

Differential neutrino cross-sections are extracted from equations below:

$$\sigma_{i\ \mathrm{H_2O}} = \sum_j \frac{U_{ij\ \mathrm{WM}}(N^{\mathrm{sel}}_{j\ \mathrm{WM}} - N^{\mathrm{BG}}_{j\ \mathrm{WM}})}{\Phi^{\mathrm{H_2O}}_{\mathrm{WM}} T^{\mathrm{H_2O}}_{\mathrm{WM}} \varepsilon^{\mathrm{H_2O}}_{i\ \mathrm{WM}}}, \tag{4.1}$$

$$\sigma_{i\ \mathrm{CH}} = \sum_j \frac{U_{ij\ \mathrm{PM}}(N^{\mathrm{sel}}_{j\ \mathrm{PM}} - N^{\mathrm{BG}}_{j\ \mathrm{PM}})}{\Phi^{\mathrm{CH}}_{\mathrm{PM}} T^{\mathrm{CH}}_{\mathrm{PM}} \varepsilon^{\mathrm{CH}}_{i\ \mathrm{PM}}}, \tag{4.2}$$

where N^{sel} is the number of selected events, Φ is the integrated $\bar{\nu}_\mu$ flux, T is the number of targets and ε is the signal-selection efficiency. The N^{BG} is the number of expected backgrounds, and $N^{\mathrm{BG}}_{\mathrm{WM}}$ is estimated not only by the MC simulation but also by the calculated cross-section on the CH target in the Proton Module to take into account the contribution from the plastic scintillators in the WAGASCI module. The subscript of i represents binning for true phase space of muons, pions, and protons, and the subscript of j represents binning for reconstructed tracks. The angle bin is divided every 5 degrees. The U_{ij} is an unfolding matrix, which corresponds to a probability that events reconstructed in the j-th bin originate from true phase space of the i-th bin. The iterative unfolding method [6] based on the Bayes' theorem is adopted to reduce smearing effects due to the finite detector resolution. The subscript of the WAGASCI module and the Proton Module are WM and PM, respectively. Superscripts of H_2O and CH represent target materials. To suppress the error from the neutrino flux uncertainty ($\sim$10%), the neutrino cross-section ratio ($\sigma_{\mathrm{H_2O}}/\sigma_{\mathrm{CH}}$) is also extracted in this analysis.

As shown in Tab. 1, CC ν_μ events constitute the dominant and irreducible background in the $\bar{\nu}_\mu$ selection. Considering this fact, we measure not only the $\bar{\nu}_\mu$ cross-section but also the $\bar{\nu}_\mu + \nu_\mu$ cross-section since the latter is less model dependent while the first requires the subtraction of the ν_μ cross-section based on the MC estimation.

5. Results

Figure 4 shows the differential cross-sections on the H_2O and CH target and their ratio. Each cross-section is normalized by the number of nucleons in molecules of H_2O and CH. The integrated cross-sections are summarized as follows:

$$\begin{aligned}
\sigma^{\bar{\nu}_\mu}_{\mathrm{H_2O}} &= \left[1.082 \pm 0.068(\mathrm{stat.})^{+0.145}_{-0.128}(\mathrm{syst.})\right] \times 10^{-39}\mathrm{cm^2/nucleon}, \\
\sigma^{\bar{\nu}_\mu}_{\mathrm{CH}} &= \left[1.096 \pm 0.054(\mathrm{stat.})^{+0.132}_{-0.117}(\mathrm{syst.})\right] \times 10^{-39}\mathrm{cm^2/nucleon}, \\
\sigma^{\bar{\nu}_\mu}_{\mathrm{H_2O}}/\sigma^{\bar{\nu}_\mu}_{\mathrm{CH}} &= 0.987 \pm 0.078(\mathrm{stat.})^{+0.093}_{-0.090}(\mathrm{syst.}),
\end{aligned}$$

$$\sigma_{\mathrm{H_2O}}^{\overline{\nu}_\mu+\nu_\mu} = \left[1.155 \pm 0.064(\mathrm{stat.})^{+0.148}_{-0.129}(\mathrm{syst.})\right] \times 10^{-39}\mathrm{cm}^2/\mathrm{nucleon},$$
$$\sigma_{\mathrm{CH}}^{\overline{\nu}_\mu+\nu_\mu} = \left[1.159 \pm 0.049(\mathrm{stat.})^{+0.129}_{-0.115}(\mathrm{syst.})\right] \times 10^{-39}\mathrm{cm}^2/\mathrm{nucleon},$$
$$\sigma_{\mathrm{H_2O}}^{\overline{\nu}_\mu+\nu_\mu}/\sigma_{\mathrm{CH}}^{\overline{\nu}_\mu+\nu_\mu} = 0.996 \pm 0.069(\mathrm{stat.})^{+0.083}_{-0.078}(\mathrm{syst.}).$$

In this measurement, uncertainties from statistics, neutrino flux, neutrino interaction model, and detector response are considered. By taking the cross-section ratio, the error from the neutrino flux uncertainty is dramatically decreased (∼13% to ∼8%).

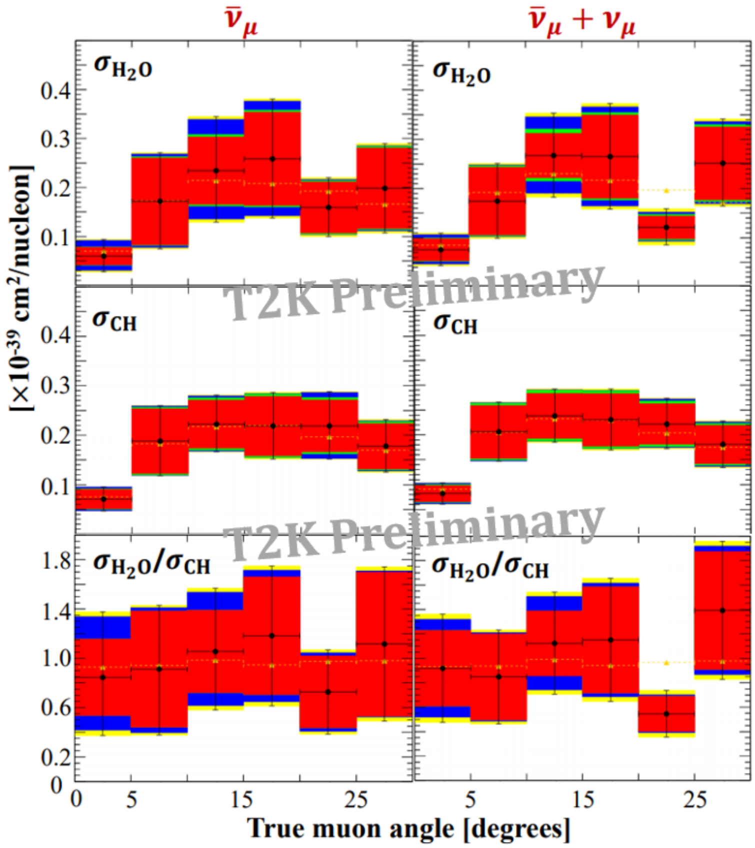

Figure 4: Differential $\overline{\nu}_\mu$ cross-section (left) and $\overline{\nu}_\mu + \nu_\mu$ cross-section (right). Top line: $\sigma_{\mathrm{H_2O}}$. Middle line: σ_{CH}. Bottom line: $\sigma_{\mathrm{H_2O}}/\sigma_{\mathrm{CH}}$ (bottom). Each plot shows the data (black point) and the cumulative quadratic sum of the uncertainties from statistics (red), neutrino flux (green), neutrino-interaction model (blue), and detector response (yellow).

6. Conclusions

We measure anti-neutrino cross-sections on H_2O and CH targets with the WAGASCI module and the Proton Module at an off-axis angle 1.5 degrees. The signal is the charged-current interaction with one muon and no pions nor protons. The differential and integrated cross-sections for the $\bar{\nu}_\mu$ only and $\bar{\nu}_\mu + \nu_\mu$ fluxes are measured. The results agree with the current neutrino-interaction models used in the T2K oscillation analysis within their statistical and systematic errors.

References

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