論文の内容の要旨

Measurements of neutrino charged-current interactions on water and hydrocarbon targets using a sub-GeV anti-neutrino beam
(サブ GeV 反ニュートリノビームを用いた水および炭化水素標的に対するニュートリノ荷電カレント反応の測定)

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Since neutrino oscillation was discovered, various experiments have measured the neutrino oscillation parameters. T2K is a long-baseline neutrino oscillation experiments, using a muon neutrino beam at J-PARC and measuring it by Super-Kamiokande. T2K has successfully observed the electron-neutrino appearance and muon-neutrino disappearance, and now set a goal of the first observation of the CP violation in neutrino sector. However, it is indispensable to reduce the systematic uncertainties for the precise measurements of neutrino oscillation. Especially, poor understanding of neutrino-nucleus interactions gives rise to a large systematic uncertainty in the neutrino oscillation analysis.

In order to measure neutrino interactions with water and hydrocarbon targets, we developed a new detector, WAGASCI. The WAGASCI module is a water target neutrino detector, and has been developed in order to measure neutrino-nucleus interactions with a high signal purity for a large acceptance. It is mainly composed of 0.6-ton water and 3-mm-thick plastic scintillators. Adopting the thin plastic scintillators allows a large fraction of water in the target region, about 80%, for well suppressing background events from neutrino interactions on the scintillators in the target region. This is one of the main background events in the previous analysis using the T2K near detector, since its ratio of water to scintillators is about 50%. In addition, WAGASCI is designed to have the scintillators forming a three-dimensional lattice structure, so that the entire solid angle

acceptance from the water target is covered by the tracking scintillators. It allows the WAGASCI module to have an advantage of large angular acceptance to measure the phase space which is inaccessible with the other near detectors.

The WAGASCI detector is located in the T2K near detector hall, to measure the T2K neutrino beam with a neutrino energy spectrum similar to Super-Kamiokande. In the summer 2017, the WAGASCI detector was arranged with two additional detectors: Proton Module, which is used as a CH-target module, and an INGRID module, which is used as a muon range detector for WAGASCI and Proton Module. The detector configuration is shown in Fig. 1. We achieved the first data taking with WAGASCI from October 2017 to May 2018.

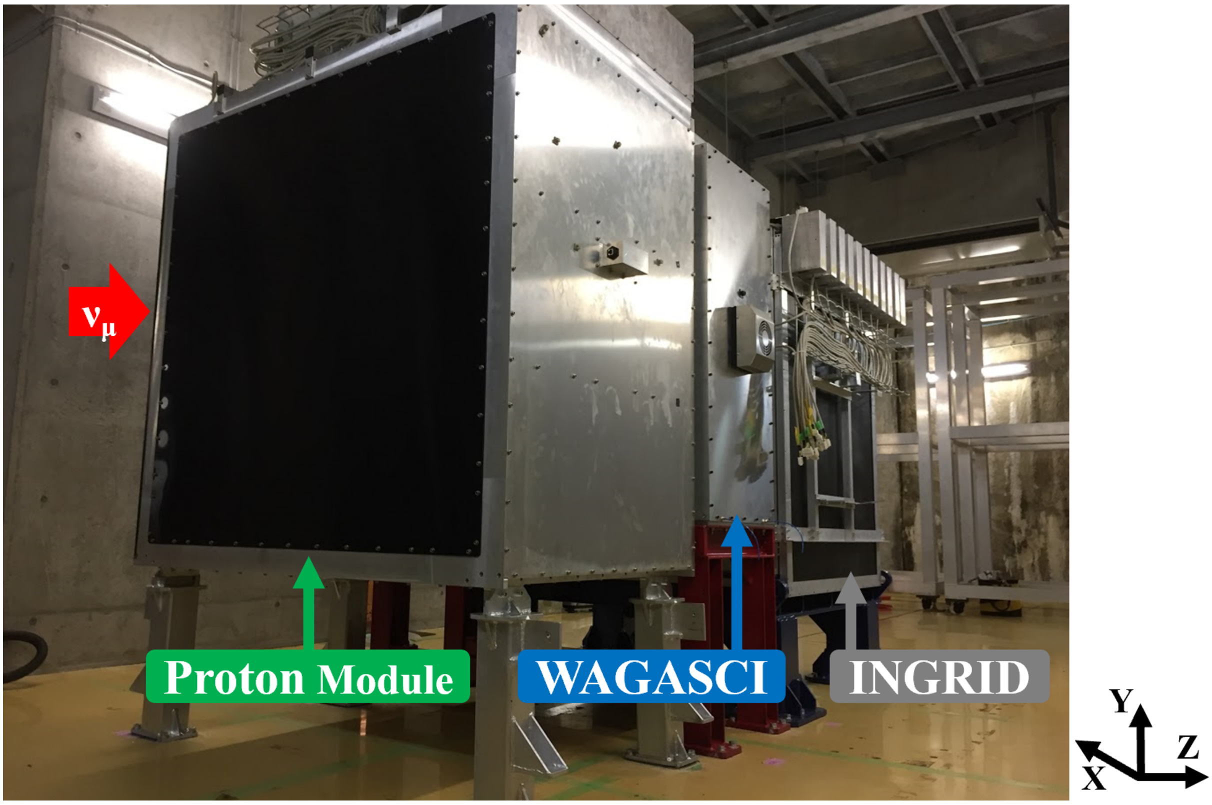

Figure 1: Installed detectors at the B2 floor in the J-PARC neutrino monitor building. The coordinate system used in this note is shown: The beam axis corresponds to Z axis.

This thesis presents measurements of neutrino charged-current interactions using the T2K anti-neutrino beam with the WAGASCI detector. The motivation of this analysis is to provide new samples to improve understanding of anti-muon-neutrino interaction dependency on nuclear targets between water and hydrocarbon. The signal is charged-current interactions with no pions and no protons in the final state (CC0π0p). It corresponds to a characteristic of charged-current quasi-elastic (CCQE), $\overline{\nu}_\mu + p \rightarrow \mu^+ + n$, which is the main signal in the T2K neutrino oscillation analysis.

This analysis uses the data taken with the WAGASCI detector, Proton Module, and an INGRID module with the T2K anti-neutrino beam, in order to measure the neutrino charged-current cross sections on H_2O and CH nucleus as well as their ratio. The focus of this analysis is on providing the flux-integrated $\overline{\nu}_\mu$ charged-current interactions with no charged pions nor proton in the final state, which is known as CC0π0p. The signal is defined based with the topology of the particles in the final state, instead of being defined with the neutrino interaction level such as CCQE. The topology defined as CC0π0p is what is expected in the $\overline{\nu}_\mu$ CCQE interactions, which has only a muon in the final state. This topology-based definition is preferable since it is relatively less dependent of the indistinguishable background events, such as background events from 2p2h interactions with protons absorbed to the signal defined by CCQE. The signal in this analysis is defined with kinematics of muons, charged pions, and protons according to the detection efficiencies in the WAGASCI detector and Proton Module.

In the case of $\overline{\nu}_\mu$ cross sections, ν_μ interactions contribute as one of the dominant background events, since ν_μ interaction has a cross section larger than $\overline{\nu}_\mu$ interaction does and needs to be subtracted based on the Monte Carlo simulation. For the purpose to improve the experimental precision, cross sections including both $\overline{\nu}_\mu$ and ν_μ, which is defined as $\overline{\nu}_\mu + \nu_\mu$ cross sections, are provided as well as $\overline{\nu}_\mu$ cross sections. The neutrino event selections are in common between the $\overline{\nu}_\mu$ and $\overline{\nu}_\mu + \nu_\mu$ cross sections, and the subtraction of the background events is the only difference between those two analysis.

The neutrino cross sections are extracted using the number of selected events on WAGASCI and Proton Module. The neutrino event selection is applied to enrich the charged-current inclusive interactions, and the selected events are categorized according to the number of reconstructed track and the reconstructed angle. Among the calculated cross sections, those of non-CC0π0p and CC0π0p with a large muon angle have strong dependency on the neutrino interaction model due to their small signal purities and low selection efficiencies. Hence, the total cross section is only calculated for CC0π0p with a forward scattering muon, ignoring the two categories largely dependent on the simulation. Most of the background events are estimated by the Monte Carlo simulation and subtracted from the selected events, except for the background events from neutrino interactions on the plastic scintillators in WAGASCI, which are calculated based on the number of selected events in Proton Module.

For the cross section extraction, the D'Agostini unfolding method is used, and the true phase space is iteratively recovered by using the reconstructed phase space in the real data, in order to achieve the prior distribution independent of the simulation. In the final results, the total cross sections of CC0π0p with a muon angle less than 30 degrees and the differential cross sections with respect to the muon's angle are presented. The total cross section is calculated as a sum of the differential cross sections.

Due to the limited statistics, the statistical error is one of the dominant errors on the final results, to be about 5-6% for absolute cross sections, $\sigma_{\mathrm{H_2O}}$ and σ_{CH}, and about 8% for the cross section ratio, $\sigma_{\mathrm{H_2O}}/\sigma_{\mathrm{CH}}$. The systematics errors are estimated with three different sources; neutrino beam flux prediction, neutrino interaction model, and detector response. The absolute cross section measurements suffer from about 10% uncertainty of the neutrino flux, but those uncertainties are mostly canceled in the cross section ratio measurement since the same neutrino beam is measured between the detectors. The uncertainties from neutrino interaction model mainly affect the estimation of detection efficiency and the subtraction of background events. Each parameter relevant to this analysis is varied to cover the current understanding of the model.

The main result is the flux-integrated cross sections of CC0π0p with a muon angle less than 30 degrees on H_2O and CH:

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\begin{aligned}
\sigma^{\overline{\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 \cdot \mathrm{nucleon}^{-1}, \\
\sigma^{\overline{\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 \cdot \mathrm{nucleon}^{-1}, \\
\sigma^{\overline{\nu}_\mu}_{\mathrm{H_2O}}/\sigma^{\overline{\nu}_\mu}_{\mathrm{CH}} &= 0.987 \pm 0.078(\mathrm{stat.})^{+0.093}_{-0.090}(\mathrm{syst.}), \\
\sigma^{\overline{\nu}_\mu+\nu_\mu}_{\mathrm{H_2O}} &= \left[1.155 \pm 0.064(\mathrm{stat.})^{+0.148}_{-0.129}(\mathrm{syst.})\right] \times 10^{-39}\mathrm{cm}^2 \cdot \mathrm{nucleon}^{-1}, \\
\sigma^{\overline{\nu}_\mu+\nu_\mu}_{\mathrm{CH}} &= \left[1.159 \pm 0.049(\mathrm{stat.})^{+0.129}_{-0.115}(\mathrm{syst.})\right] \times 10^{-39}\mathrm{cm}^2 \cdot \mathrm{nucleon}^{-1}, \\
\sigma^{\overline{\nu}_\mu+\nu_\mu}_{\mathrm{H_2O}}/\sigma^{\overline{\nu}_\mu+\nu_\mu}_{\mathrm{CH}} &= 0.996 \pm 0.069(\mathrm{stat.})^{+0.083}_{-0.078}(\mathrm{syst.}),
\end{aligned}
$$

where the cross sections are normalized by all nucleons in molecules of H_2O and CH. The anti-neutrino beam is predicted to have the mean energy at 0.86 GeV, and the peak energy at 0.66 GeV with 1σ spread of +0.40/-0.25 GeV. All of those measured total cross sections agree with the predictions from the nominal simulation within 1σ errors.

This results provides the first sample to show a direct relation between water and hydrocarbon targets for neutrino interaction among the measurements using the T2K anti-neutrino beam. This results are important in the T2K neutrino oscillation analysis since neutrino interactions at the far detector with water target is constrained by the near detector with hydrocarbon target. The WAGASCI project is still going on, and further data taking is planned. Combining the additional detector to cover wider angular acceptance and to identify particle charges by magnetic field, more precise measurements will follow this analysis.