Study of neutrons associated with neutrino and anti-neutrino interactions on water at T2K

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Abstract. The study of neutron production associated with interactions on water in an energy region from sub-GeV up to a few GeV is a key ingredient to improve the physics program of neutrino experiments based on water Cherenkov detectors. To this aim, a precise prediction of such neutron production by Monte Carlo (MC) simulation is essential. However, current predictions have large uncertainties related to the modeling of interactions in the nuclear medium, hadronic final-state interactions (FSI) in nuclei, and secondary interactions (SI) in the detector medium. Therefore, it is worth evaluating the validity of the simulations with beam.

In this work, the status of a measurement of $\nu$ and $\bar{\nu}$ interactions on water in Tokai-to-Kamioka (T2K) experiment is described.

1. Introduction
In experiments employing water Cherenkov detectors such as the SK-Gd and the Hyper-Kamiokande [1], tagging neutrons associated with $\nu$ interactions on water will improve their physics programs such as atmospheric $\nu$ oscillation analyses, supernova relic $\nu$ search, and nucleon decay searches. For this purpose, predicting the production of such neutrons precisely by a MC simulation is essential. Current MC simulations, however, produce different predictions due to large uncertainties on $\nu$-nucleon interactions in nuclear medium, hadronic FSI in nuclei, and SI in detector medium. Recently, such neutrons have been studied on hydrogen and carbon nuclei [2] and for heavy water [3]. It is therefore worth performing similar study on water in terms of both utilization of such neutrons for physics analyses, understanding $\nu$-nucleus interactions, and evaluating how much agreement is realized between data and simulations.

In the T2K long-baseline $\nu$ oscillation experiment [4], a primarily $\nu_\mu$ ($\bar{\nu}_\mu$) beam is produced at the J-PARC with a peak energy of 0.6 GeV, and is detected by the Super-Kamiokande (SK) far detector [5], which is a 50 ktons water Cherenkov detector located 295 km away from the beam source in order to study oscillations. The observed beam-neutrino events at the far detector can be used to study neutron production.

2. Development of neutron tagging algorithm at the far detector
In the far detector, neutrons are eventually captured by hydrogen nucleus with a typical timescale of 200 $\mu$s. The capture produces a single 2.2 MeV $\gamma$, and thus neutrons of any energy can be tagged by detecting the gamma rays.

A neutron tagging algorithm is developed and is purposely designed to minimize the dependence of the tagging efficiency on the modeling of neutron production. The algorithm
Figure 1. Distribution of NN output for neutron candidates (left). The arrow represents the cut threshold on the NN output value. Neutron candidates above the threshold are regarded as tagged neutrons. Distribution of reconstructed capture time after the NN classification (right).

searches for neutron candidates from $+18 \, \mu s$ to $+513 \, \mu s$ after the expected $\nu$ beam arrival timing. A candidate is selected based on number of PMT hits, and then is classified as either “neutron” or “background” using an artificial neural network (NN). The background events are caused by accidental coincidences of noise PMT hits. The NN uses a set of 14 input variables, each of which does not include simulation dependent information explicitly and is calculated based on geometrical or timing spreads of candidate’s PMT hits. The resultant neutron tagging efficiency is $\sim 20\%$ when setting background rate to 0.018.

The developed algorithm is applied to a data set of low energy neutrons from a calibration campaign with an Americium-Beryllium (Am/Be) source. Figure 1 shows the distribution of the NN output for neutron candidates (left) and the distribution of the reconstructed capture time for the tagged neutrons (right) in comparison to the corresponding MC distributions. As shown in figure, the algorithm produces a good agreement between the data and MC expectations.

3. Measurement of mean neutron multiplicity at the far detector

In this measurement, the single-ring (1R) $\nu_{\mu}$ samples of the $\nu$- and $\bar{\nu}$-modes [6] are used with a modification in the definition of the fiducial volume. The samples mainly consist of Charged Current (CC) Quasi-Elastic interaction and contain a high purity of $\nu_{\mu}$ and $\bar{\nu}_{\mu}$ events for the $\nu$- and $\bar{\nu}$-modes, respectively. Since neutrons produced near the inner wall of the far detector can escape from the inner detector before they are captured, a smaller fiducial volume compared to the one used in T2K $\nu$ oscillation analyses [6] is adopted.

The analysis uses three $\nu$ MC event generators: NEUT [7], NuWro [8], and GENIE [9]. NEUT is used as the nominal generator. For all the generators, same Geant3 [10] based detector simulation with an option of GCALOR [11] is used. Neutron productions by $\mu^{-}$ and $\pi^{-}$ captures on oxygen nucleus are newly implemented into the detector simulation by using Geant4 [12] 9.6.p04.

Neutron multiplicity is expected to become large as the four momentum transfer squared $Q^{2}$ to the hadronic system at the primary $\nu$-nucleus interaction increases. Since the direction of beam $\nu$ is known, reconstructed muon transverse momentum $P_{t}$ which is a good indicator of $Q^{2}$ can be calculated. This analysis therefore measures the mean neutron multiplicity as a function of $P_{t}$ using these CC $\nu_{\mu}$ and $\bar{\nu}_{\mu}$ enriched samples as follows:

$$\bar{M}_{i} = \frac{1}{\varepsilon_{i}} \times \frac{(N_{\text{tag},i} - b \times N_{1\mu,i})}{N_{1\mu,i}},$$
where \( i \) represents \( i \)-th \( P_t \) bin, \( N_{tag,i} = \sum m_{ij} \), \( N_{1R,i} \) is number of observed \( 1R \nu_\mu \) events, \( m_{ij} \) is number of tagged neutrons of \( j \)-th \( 1R \nu_\mu \) event, \( b \) is accidental background event rate of the neutron tagging, and \( \varepsilon_i \) is neutron tagging efficiency.

In this measurement \( b \) is estimated by using random trigger data while \( \varepsilon \) is estimated from MC and proper systematics on the latter are considered. Systematic sources which affect neutron simulation, notably due to nucleon secondary interactions, and detector response for 2.2 MeV \( \gamma \) are estimated to be large. Total systematic uncertainty on the averaged neutron tagging efficiency was estimated to be \( \sim 8 \% \). Figure 2 shows the neutron tagging efficiency as a function of \( P_t \) with the estimated total systematic uncertainty (left) and \( P_t \) dependence of mean neutron multiplicity for three different MC event generators (right).

4. Conclusion
Understanding neutrons associated with \( \nu \) interactions on water is important in future water Cherenkov experiments such as the SK-Gd and the Hyper-Kamiokande. For this purpose, a measurement of those neutrons is being performed using CC \( \nu_\mu \) and \( \bar{\nu}_\mu \) enriched samples at the T2K far detector. A new neutron tagging algorithm which is purposely designed to be minimally simulation dependent is developed for this measurement. The analysis measures the mean neutron multiplicity in bins of muon transverse momentum. A preliminary estimation indicate uncertainties on the neutron tagging efficiency of the order of 8 %.

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