2. Neutrons produced in ν interactions on water

- Observed neutrons are expected to be useful for future precise oscillation analyses [2] and have been utilized for proton decay searches [3].
- These analyses need a precise Monte Carlo (MC) simulation to predict neutron multiplicity for ν interactions on water.
- Different MC predictions due to uncertainties on:
  - ν-nucleon interactions in nuclear medium,
  - hadronic-final state interactions in nucleus (FSI), and
  - secondary interactions in detector medium (SI)
- No measurements of the neutron multiplicity have yet been published.

3. Goals of this study

- There are single-Cherenkov ring muon (1-ring μ) samples in the SK, which has been used in the T2K ν oscillation analyses.
- Neutrons associated with ν interactions on water can be studied using the samples.
- Aim to achieve:
  1. Measurement of mean neutron multiplicity and
c  2. Compare the measurement results with theoretical models via MC predictions.

4. Neutron tagging at SK

- Neutron capture
  - Neutrons produced in water are quickly thermalized and then are predominantly captured on a free proton via the reaction:
    \[ n + p \rightarrow d + γ \quad (2.2 \text{ MeV}) \]
- Tagging algorithm
  - There are two steps to tag neutrons.
    1. Primary selection
      - Search for neutron candidates by finding PMT hits clusters due to 2.2 MeV γs.
    2. Neural network (NN) selection
      - Efficient removal of fake neutrons from the neutron candidates.
      - Use 16 input variables to characterize PMT hits cluster of each neutron candidate.

- Neutron calibration
  - Am/Be + BGO calibration has been done to study the neutron tagging.

5. Nominal MC predictions

- MC predictions for the tagged neutrons of the 1-ring μ samples
- The processes of neutron production in the MC were simulated by NEUT [4] v5.3.2 and GCALOR [5].
- Precise estimation of possible model uncertainties
  - To compare the measurement results with theoretical models, several sources of systematic uncertainties in the current MC predictions are under study, such as FSI/SI for π, p, and n.

6. Ongoing works

- SK time variations on neutron tagging
  - Several time varying effects have been observed.
    - PMT gain increase
    - Water transparency
    - Non-uniform water quality
  - Impacts of the time variations in this study have been studied.
- Estimation of possible model uncertainties
  - To compare the measurement results with theoretical models, several sources of systematic uncertainties in the current MC predictions are under study, such as FSI/SI for π, p, and n.
- Modification of the current neural network
  - Some input variables used in the current NN are explicitly model dependent such as the distance between the neutrino interaction and the neutron capture, which we hope to measure in this study.
  - Alternative MC samples produced by different ν event generators will be used to study model dependence after modifying the current NN.

7. Summary

- Neutrons produced in ν interactions on water can be studied for both ν and ν̅ by utilizing the T2K ν and ν̅-mode data.
- MC expectations related to tagged neutrons were presented.
- Precise estimation of time-dependent effects at SK are needed, and are currently under study.
- The measurement will be done once the ongoing works are completed.