1 Introduction

TITUS (Tokai Intermediate Tank with Unoscillated Spectrum) is a proposal for an intermediate detector as part of the Hyper-Kamiokande (HK) experiment. It will be located approximately 2 km from the J-PARC neutrino beam. TITUS is a cylindrical Cherenkov detector, filled with 2 ktonne of Gadolinium (Gd) doped water, aligned with the neutrino beam. A magnetised Iron muon detector is located at the downstream part of the tank to measure muons ranging out of the detector. The Cherenkov effect allows detection and identification of electrons and muons produced in neutrino Charged Current (CC) interactions, and Gd allows the detection of the possible outgoing neutron. The primary goal of TITUS is to constrain the neutrino flux from the J-PARC beam and make neutrino cross section measurements for HK. Furthermore, neutron tagging can be used to differentiate neutrino from anti-neutrino events and measure independently the proportion of neutrinos and anti-neutrinos in the beam. This would reduce the systematic uncertainty based on the wrong sign contamination to enhance the CP violation sensitivity of HK. TITUS can also be used for other physics purposes including detection of supernovae neutrinos, sterile neutrino studies and proton decay searches.

2 Hyper-Kamiokande

Hyper-Kamiokande is a proposed next generation neutrino oscillation experiment using a 1 megatonne water Cherenkov detector[1]. It aims to study CP violation in the lepton sector by measuring precisely the oscillation parameters for neutrinos and anti-neutrinos[2]. To achieve this, the systematic uncertainties need to be greatly reduced from the current neutrino oscillation experiment at T2K. HK will also measure other neutrino oscillation parameters and is expected to probe the proton life-time at an order of magnitude beyond the current limit[1, 2].
3 TITUS

To achieve the required reduction of the systematics uncertainties, precise measurements are required of both the unoscillated neutrino flux and the neutrino cross section. This can be achieved using TITUS, an intermediate detector between the J-PARC beam source and HK. By using the same target as HK (water), it is possible to cancel many of the systematic uncertainties associated with the cross section model. This can be done because the flux at \( \approx 2 \) km is very similar to that at HK. Figure 1 shows the ratio of the flux for different baselines for TITUS and the flux at HK.

![Figure 1: Unoscillated flux ratios (Nominal HK / Near Detector) at different baselines.](image)

3.1 Gadolinium doping

Doping the water with 0.1 % of Gd allows the detection of neutrons produced in neutrino interactions; this is realised because the neutron capture on Gd has a very high cross-section and produces a cascade of photons with total energy of 8 MeV that can be detected\[3\]. From a cross section stand point it is interesting to have the neutron multiplicity after a neutrino interaction and Final State Interaction (FSI) to be able to constrain the cascade model and the Meson Exchange Current (MEC) of our generators. For an oscillation analysis this can provide a very pure sample of CCQE interaction events both when a neutrino is interacting (producing no neutrons) or an anti-neutrino (1 neutron). The effect on the spectrum of the selection can be seen in Figure 2. R&D is ongoing to monitor the feasibility and response of the detector when the water is doped with Gd \[4, 5\].

3.2 Photosensors

Different types of photosensors are currently under investigation. Along with Photomultiplier Tubes (PMT), TITUS may include LAPPDs (Large Area Picosecond Photo Detectors), the next generation photosensors with improved timing resolution of the order of few tens of picoseconds and can reconstruct the hit position on the detector surface to within a few centimetres\[6\]. Adding LAPPDs greatly improves the event reconstruction for low energy events (neutron capture on Gd). These detectors are currently being developed.
Figure 2: The composition of the one muon-like ring sample in TITUS during anti-neutrino mode running. The effect of different neutron selections is shown.

3.3 Magnetised Muon Range Detector

Due to the size of TITUS, 18% of the muons coming from beam neutrino interactions escape the tank. These muons come from neutrinos in the higher end of the spectrum. It is therefore important to quantify their energy after they ranged out of the detector. A Magnetised Muon Range Detector (MMRD) with magnetic field of 1.5 T can provide energy and charge reconstruction. Figure 3 shows the charge reconstruction efficiency dependent on neutrino energy. Combined with the neutron tagging this could give very high purity samples as well as providing a method for validating and calibrating the neutron tagging.

Figure 3: MMRD charge reconstruction efficiency for muons from neutrino interactions.

4 CP violation sensitivity

Due to the very high discrimination of TITUS described in the previous section, the sensitivity of HK to CP violation is increased. In Figure 4 it can be seen that the 90% CL contour is reduced with the addition of neutron tagging, and the time to discovery for CP violation is reduced by a significant reduction in the systematic errors.
Figure 4: CP sensitivity of HK after 10 years of operation with a beam of 750 kW with equal splitting between neutrino and anti-neutrino mode beam. The study was realised assuming $\sin^2(2\theta_{13}) = 0.095$ and $\delta_{CP} = 0$.

5 Summary

The addition of TITUS, a 2 ktonne Gd-doped water Cherenkov detector with magnetised muon range detector, located approximately at 2 km from J-PARC, to the HK project will allow precise measurements of the unoscillated spectrum of the J-PARC neutrino beam. The 0.1 % doping of Gd allows for a detectable signal from neutron capture, and thus the discrimination of neutrino and antineutrino interactions as well as inputs into neutrino cross-section measurements. The downstream MMRD provides a second method for neutrino/antineutrino discrimination through charge reconstruction of muons exiting the tank and also provides energy reconstruction for these muons. These features allow TITUS to significantly reduce systematic errors in CP violation measurements at HK, providing increased sensitivity and reduced time to discovery.

References

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