The Hyper-K Near Detector Programme

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Abstract. The proposed Hyper-Kamiokande experiment (Hyper-K) is a next generation large water Cherenkov (WC) detector with a broad physics program consisting of neutrino beam measurements in search of leptonic CP violation, astrophysical measurements and a search for proton decay. Hyper-K will act as the far detector to measure the oscillated neutrino flux from the long-baseline beam of 0.6 GeV neutrinos/anti-neutrinos produced by a 1.3 MW proton beam at J-PARC in Japan. To minimise systematic uncertainties, particularly due to flux and cross-section uncertainties, detailed measurements of the unoscillated flux are required with a suite of near detectors. We review the challenges, and present the planned components of the near detector measurement suite, including a new intermediate Water Cherenkov Detector.

1. Introduction

Hyper-Kamiokande (Hyper-K) is a next generation underground water Cherenkov detector that will serve as a far detector (295 km baseline), of a long baseline neutrino experiment for the upgraded J-PARC beam. The beam produces a narrow spectrum of muon neutrinos (anti-muon neutrinos in reverse horn current mode) with a peak energy of $\sim$0.6 MeV by employing an off-axis technique such that the far-detector is located $2.5°$ off the beam axis. The experiment aims to measure leptonic CP violation and perform precision measurements of other neutrino oscillation parameters. Additionally, Hyper-K will have sensitivity far exceeding that of its successor, the Super-Kamiokande experiment, to non-beam measurements including proton decay, atmospheric neutrinos and neutrinos from astronomical sources. To reduce systematic uncertainties, especially in the beam measurements, the Hyper-K project requires a dedicated suite of near detectors, which are presented here.

2. Motivation for Near Detectors

An asymmetry in charge-parity, A_{CP}, would manifest as a difference in the rate of muon to electron neutrino and anti-neutrino oscillations, as given in equation 1.

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu_\mu} \to \bar{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\bar{\nu_\mu} \to \bar{\nu_e})} \qquad (1)$$

The rates of these oscillations are determined by measuring the number of (anti-)electron charged-current neutrino interactions in the far detector with either zero or one pion in the final state, from beams of ν_μ or $\bar{\nu_\mu}$. The measured interaction rate in Hyper-K is compared to the expected rate, which depends on: the oscillation probability, the initial neutrino flux, the

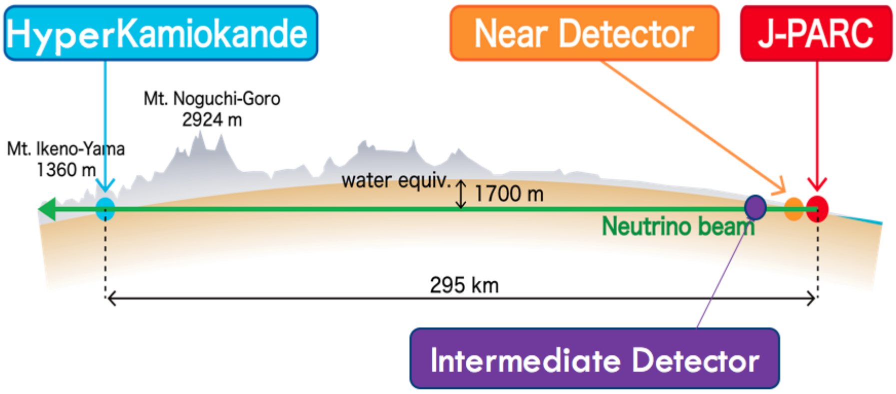

Figure 1. Schematic of the Hyper-K long baseline setup with far, intermediate and near detector components (not to scale).

neutrino interaction cross-sections, the far detector efficiency, and its fiducial mass. Uncertainties in each of these components of the calculation reduce the precision of the CP measurement. Near detectors are vital to characterise the initial neutrino flux and accurately measure interaction cross-sections, thus reducing two of the dominant systematic uncertainty components.

Note that A_{CP} is proportional to a ratio of cross-sections for the interactions of the different neutrino and anti-neutrino species as given in equation 2.

$$A_{CP} \propto \frac{\sigma^{\nu_e}/\sigma^{\nu_\mu}}{\sigma^{\bar{\nu_e}}/\sigma^{\bar{\nu_\mu}}} \tag{2}$$

Some systematic uncertainties, such as detector effects will partially cancel in this ratio, especially if the near detectors are designed to maximise this cancellation: eg. by sampling the same target nuclei, over the same energy range, with the same angular acceptance. We also need to accurately characterise the intrinsic ν_e ($\bar{\nu_e}$) component of the initial beam from muon and kaon decays, which is a background to the appearance signal; wrong sign processes that are a background to the CP-violation measurement; and neutral current processes (NC) that can be mistaken for charged-current (CC) neutrino interactions.

To measure and understand these neutrino interaction processes, a near detector would ideally provide information on the hadronic final states produced in neutrino interactions, with charge information of the final state leptons. We also require a large target to access the small interaction cross-sections of ν_e ($\bar{\nu_e}$) on water. Whilst the former could be delivered by tracking detector technology within a magnetic field, the latter requires a large water target detector, which could naturally provide 4π angular acceptance but would be prohibitively expensive to magnetise. These incompatibilities point towards a suite of near detectors rather than a single detector to deliver all the required measurements.

3. The ND280 Detector and Potential Upgrades

The Hyper-K near detector programme naturally builds upon the near detectors of T2K, which are already located in the JPARC neutrino beam-line. These consist of the INGRID on-axis detector, designed to accurately measure the beam direction through neutrino interactions on an iron-plastic scintillator tracker, and ND280, a tracking detector housed in a 0.2 T magnet and located 280 m downstream in the 2.5° off-axis beam direction towards Super-Kamiokande. The main interaction targets in ND280 are fine grain detectors (FGDs) which are composed of plastic

Journal of Physics: Conference Series 1342 (2020) 012053 doi:10.1088/1742-6596/1342/1/012053

scintillator layers, which are mounted perpendicular to the beamline, sandwiched between three gaseous time projection chambers (TPCs). The downstream FGD includes water layers with a water to scintillator ratio of 40:60. By fitting out the near detector flux and cross-sections, the T2K experiment successfully reduces the systematic uncertainties on the 4 neutrino interactions ($\nu_\mu CC$, $\nu_e CC$, $\bar{\nu_\mu} CC$ and $\bar{\nu_e} CC$) in the far detector to 5–6%[1] compared to 12–13% without ND280.

Since February 2017, the T2K collaboration have been working on a design to upgrade the ND280 detector for the future running of the T2K experiment. The goal is to reduce the total systematic uncertainty in the neutrino event rate in the presence of oscillations at the far detector to better than 4% by increasing the angular acceptance. The current ND280 is optimised in the forward direction with much reduced efficiency for interactions where the charged lepton produced travels at high angles to the beam. The proposed upgrade design maintains the current tracking component of ND280 consisting of the two FGDs and 3 TPCs mounted perpendicular to the off-axis beam, but adds a horizontal target sandwiched between two horizontal TPCs in place of the previous π^0 detector within the magnet. This design increases the target mass from 2.2 tonnes to 4.3 tonnes[2].

A number of technologies are under consideration for the new horizontal target detector that aim to provide improved angular resolution. The current FGDs are composed of 1 cm thick X-Y extruded, TiO_2-coated scintillator bars with MPPC readout at the ends. Due to their orientation, they offer only limited efficiency for vertical tracks. Proposed new technologies include a tracking fibre detector, a SuperFGD[3], a 3D FGD with bars in both the X,Y and Z directions (the packing here includes 25% air), and a WAGASCI-like detector[4] which could also accommodate a water component.

4. An Intermediate Water Cherenkov Detector

Any tracking technology will require a subtraction analysis in order to obtain cross-section measurements on a water target, which results in statistical limitations to the measurement accuracy. Employing water cherenkov techniques in a near detector naturally addresses many of the extrapolation issues in the flux measurement by using the same technology and target as the far detector. Water provides a cheap target medium with 4π angular acceptance and particle ID through the sharpness of the cherenkov rings that allows to select very pure ν_μCC, ν_eCC and NCπ^0 samples. The detector should be large enough to contain the muons produced from the peak beam energy, ~ 0.6 GeV and preferably higher, but must be placed sufficiently down-stream such that pile-up of multiple events from the same beam bunch are not a significant issue – at a so-called ‘intermediate’ distance. Sites in the region 0.7–2 km downstream from the beam are being considered.

Two additional technologies are planned to be incorporated into the intermediate water cherenkov detector design:

4.1. Gd-Loading

Firstly, by loading the water with 0.2% Gadolinium Sulphate, neutrons produced in the interactions can be measured. Neutrons capture on Gd ∼90% of the time with a capture time of ∼25 μs producing ∼8 MeV of gammas (this can be compared to a ∼200 μs capture time on H that releases only a 2.2 MeV gamma). The capture gammas give a clear coincidence signal after the initial charged lepton and provide a handle for statistical separation of interaction modes. In particular, the neutron tag helps to separate neutrino and anti-neutrino interactions, even in the absence of a magnetic field, as ν_μ CC interactions produce a proton and no neutrons in the final state, whereas the inverse beta decay interaction of $\bar{\nu_\mu}$s produces one neutron in the final state. The Gadolinium also provides the ability to measure the final state neutron multiplicity, a measurement that can reduce the large model uncertainties that feed into atmospheric neutrino and proton decay measurements in the Hyper-K detector.

4.2. Off-axis spanning

The second technology is to apply an off-axis spanning technique in which a tall vertical cylinder water cherenkov detector spans a range of off-axis angles from 0–4°. Whilst a primary goal of the near detectors is to measure the unoscillated neutrino flux, we also wish to study cross-sections over the same phase-space as sampled in the far detector. The energy spectrum of the far detector neutrino interactions is modified with respect to that seen in the near detector by the oscillation phenomena. Since the interaction cross-sections can be energy dependent, this results in an additional uncertainty in extrapolation, which the off-axis technique can mitigate. With increasing off-axis angle, the neutrino energy spectrum becomes narrower with a lower peak energy, thus by measuring in different vertical slices, we sample different initial neutrino spectra. By combining linear combinations of the different slices, we can reproduce the expected neutrino energy spectrum, after oscillations, at the far detector, and thus predict the muon or electron kinematic distributions for the oscillated flux.

To span off-axis angles of 0–4°, the longer the baseline, the taller the required cylinder and hence the larger the cost. Therefore, when choosing a location for the intermediate detector an optimisation is required, whilst also ensuring the detector is far enough downstream for pile-up to be manageable. Another approach to reduce costs is to instrument only a portion of the inner detector ($\sim 10\,\mathrm{m}$ high) that is moved vertically within the full cylinder

4.3. ν_e Cross-section measurement

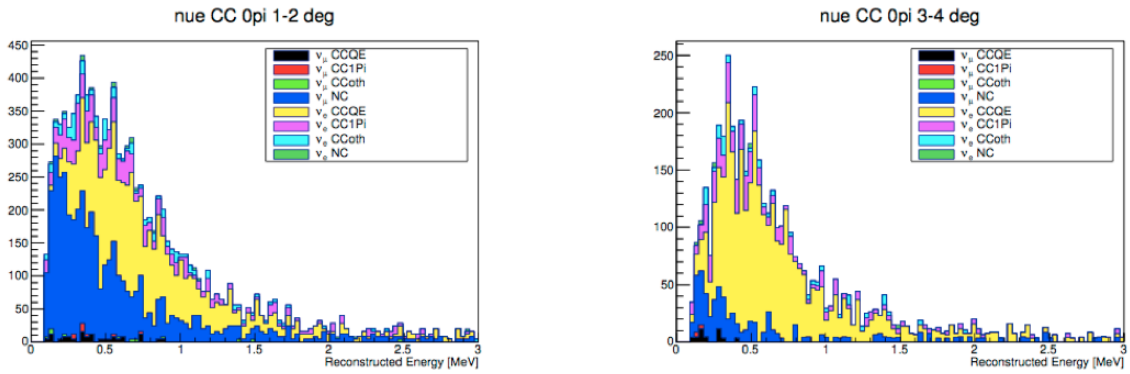

Figure 2. ν_e CC 0π spectra, selected from Monte Carlo studies of a 1 kTon water cherenkov detector at 1 km downstream at different off-axis angles, showing how sample purity increases with off-axis angle. The different colours indicate the different interaction components that make up the event spectrum (yellow - ν_e CC signal, blue - ν_μ NC events, the dominant background).

An important measurement, which the existing T2K near detectors cannot provide, is an accurate measurement of the ν_e interaction cross-section. For an exposure of 10^{21} protons on target (POT) in ν_μ beam mode, a 1 kTon water cherenkov detector at 1 km downstream from the beam would detect thousands of one-ring electron-like events (ν_eCC0π) as shown in table 1, although, since the beam composition is predominantly ν_μ with only a percent-level ν_e component, it is unsurprising that there is significant contamination of the sample, especially from ν_μNC events. Due to a larger contribution from Kaon parents in the beam, the purity of the sample increases with off-axis angle, allowing a more accurate cross-section measurement with the off-axis spanning detector as shown in figure 2.

angle to beam	$N(\nu_e CC0\pi)$ selected	Sample purity
1–2°	11.2k	54%
2–3°	6.9k	71%
3–4°	4.6k	80%

Table 1. The size and purity of samples of one-ring electron like events with no pions in the final state, obtained with a 1 kTon water cherenkov detector 1 km downstream at different angles in the JPARC beamline delivering 10^{21} POT.

4.4. Multi-PMTs
In May 2017, the international J-PARC E61 Experiment was formed, which will incorporate these two intermediate WC detector features. The collaboration is evaluating the use of multi-PMT units for the intermediate detector design, in which a cluster of small (3 inch) PMTs are housed together within a sealed optical unit. The units would also incorporate a smaller number of outward looking PMTs to monitor an outer detector region, used as a background veto region. The multi-PMT unit houses all readout electronics, monitoring and calibration systems for the PMTs and provides both waterproofing and pressure protection. This technology is leveraged on the KM3NeT / IceCube designs and offers a number of advantages including reduced cabling and higher granularity of response compared to the case of larger individual PMTs.

5. Other Technologies
A number of additional approaches are also being evaluated as potential components of the Hyper-K near detector suite including technologies that could be incorporated within the ND280 magnet at a later stage. One option is a High Pressure TPC, in which a range of target gases could be used. This technology could allow the reconstruction of proton tracks down to energies as low as 5MeV providing significant information on final state particles from neutrino interactions. Prototyping for a gaseous TPC is currently underway with a test beam experiment planned at CERN.[5]

Another option is an emulsion detector, as pursued by the NINJA collaboration. The emulsion technique also offers information on final state protons, with prototype experiments demonstrating 84% efficiency for proton track reconstruction above a 10 MeV threshold. Following a series of prototyping stages, the NINJA collaboration proposes to employ a water target between the emulsion layers to provide an accurate ν_e cross-section measurement.

6. Summary
Near detectors are vital to constrain the flux and cross section systematic uncertainties for an accurate CP violation search. Due to the range of conflicting requirements from the near detectors, no single detector technology can provide the necessary information so the Hyper-K collaboration is pursuing a suite of near detectors comprising the upgraded T2K near detectors, INGRID and ND280 and an intermediate off-axis spanning, Gd-loaded water cherenkov detector. A number of novel new techniques and technologies are being pursued and work is now ongoing to finalise the technical designs of the detector components.

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