Sensitivity to the neutrino oscillation parameters in the Hyper-Kamiokande experiment

Linda Cremonesi
School of Physics and Astronomy, Queen Mary University of London, UK
E-mail: l.cremonesi@qmul.ac.uk

Abstract. The Hyper-Kamiokande (Hyper-K) [1, 2] detector is a next generation underground water Cherenkov detector that will serve as the far detector of a long-baseline neutrino experiment (T2HK) located in Japan. T2HK is a natural extension of the very successful T2K experiment.

The upgraded facilities at J-PARC will deliver an off-axis narrow band (∼0.6 GeV) (anti)neutrino beam (750 kW-1 MW) directed to Hyper-K that will be used to measure the appearance and disappearance parameters with unprecedented precision as well as potentially discover CP violation in the lepton sector.

If the mass hierarchy is known, Hyper-K is expected to determine the CP phase to better than 19 degrees for all possible values of \( \delta_{CP} \) and CP violation can be determined at 3\( \sigma \) for 76% of the delta parameter space (considering 5 years exposure to neutrino beam produced by the 1.66 MW J-PARC proton synchrotron) [2].

1. Neutrino oscillations and CP violation

The neutrino mixing matrix (PMNS - Pontecorvo Maki Nakagawa Sakata) translates neutrino mass eigenstates into flavour eigenstates \((\nu_e, \nu_\mu, \nu_\tau)^T = U(\nu_1, \nu_2, \nu_3)^T\).

In the three flavour framework it is parametrised using 3 mixing angles \((\theta_{12}, \theta_{23}, \theta_{13})\), one Dirac CP phase \(\delta\) and two Majorana phases \((\alpha_1, \alpha_2)\).

Neutrino oscillation frequencies are determined by mass parameters \(\Delta m^2_{21} = m_2^2 - m_1^2\) and \(\Delta m^2_{32} = m_3^2 - m_2^2\), where \(m_j\) refers to the mass eigenvalues.

Since oscillation probabilities do not depend on the Majorana phases, the number of relevant parameters is 6, of which: \(\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}\text{eV}^2\), \(\sin^2 2\theta_{12} = 0.857 \pm 0.024\) [3]) have been measured by solar neutrino experiments; \((|\Delta m^2_{32}| = 2.32^{+0.14}_{-0.08} \times 10^{-3}\text{eV}^2, \sin^2 2\theta_{23} > 0.95\) [4]) have been measured by atmospheric neutrino experiments; \(\sin^2 2\theta_{13} = 0.095 \pm 0.010\) [5] has been constrained by reactor experiments.

It is then crucial for neutrino physics to measure the CP violation \(\delta\) phase.

2. Hyper-Kamiokande

The Hyper-Kamiokande (Hyper-K) detector is a next generation underground water Cherenkov detector [1] that aims to study atmospheric and solar neutrinos as well as neutrinos from other astrophysical origins, oscillated neutrinos from an upgraded J-PARC beam, and to observe proton decay.
Table 1: Expected events after the $\nu_e$ ($\bar{\nu}_e$) appearance selection during $\nu$ ($\bar{\nu}$) running mode.

|       | Signal |       | Background |       |       |       | NC | Total |
|-------|--------|-------|------------|-------|-------|-------|----|-------|
| $\nu$  | $\nu_\mu \rightarrow \nu_e$ | $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ | $\nu_\mu$ CC | $\bar{\nu}_\mu$ CC | $\nu_e$ CC | $\bar{\nu}_e$ CC |    |       |
| mode   | 3016   | 28    | 11         | 0     | 503   | 20    | 172| 3750  |
| $\bar{\nu}$ | 396    | 2110  | 4          | 5     | 222   | 396   | 265| 3397  |

In the baseline design, Hyper-K consists of 2 separate caverns each having an egg-shape cross section 48 meters wide, 54 meters tall, and 250 meters long, resulting in a total (fiducial) mass of 0.99 (0.56) million metric tons (about 20 (25) times larger than that of Super-K).

The two water tanks are then divided into 10 compartments (5 each), each been optically separated and consisting of an inner detector (ID) and an outer detector (OD). The ID is viewed by an inward-facing array of 20-inch diameter PMTs. The entire array consists of 99,000 Hamamatsu R3600 photomultiplier tubes (PMTs), uniformly surrounding the region and giving a photocathode coverage of 20%.

The OD region is equipped with 25,000 8-inch diameter PMTs.

The detector simulation has been studied using WCSim [6], a flexible Geant4-based tool developed by Duke University to study a water Cherenkov detector with top and side photomultiplier tubes. The egg-shape geometry of Hyper-K has been implemented in WCSim.

3. Tokai to Hyper-Kamiokande

Hyper-K will serve as the far detector of a long-baseline neutrino experiment (T2HK) located in Japan.

Following the lines of T2K, the facilities at J-PARC will deliver an off-axis narrow band ($\approx$0.6 GeV) (anti-)neutrino beam (750kW-1MW) directed to Hyper-K that will be used to measure the appearance and disappearance spectra.

The near detector complex will include the INGRID and ND280, on- and off-axis near detectors respectively, located 280 m away from the beam target. They are the current T2K near detectors, but will be upgraded for T2HK. A new near detector will possibly be built at 2 km from the target. The near detectors will help constrain the neutrino flux and systematic errors.

Table 1 shows the expected number of events after the $\nu_e$ ($\bar{\nu}_e$) appearance selection. In $\nu$ running mode the main background is composed of beam $\nu_e$ CC and all NC interactions. In $\bar{\nu}$ running mode, the wrong sign appearance is also non-negligible.

The reconstructed neutrino energy distributions of $\nu_e$ events for several values of $\delta_{CP}$ are shown in the top plots of Figure 1. The bottom plots show the difference of reconstructed energy spectrum from $\delta_{CP} = 0$, for the cases $\delta_{CP} = \pi/2$, $\pi$, $3\pi/2$. By using not only the total number of events but also the reconstructed energy distribution, the sensitivity to $\delta_{CP}$ can be improved, and one can discriminate all the values of $\delta_{CP}$, including the difference between $\delta_{CP} = 0$ and $\pi$.

4. CP violation discovery sensitivity

Sensitivity studies have been performed taking into account an integrated beam power of 7.5 MW $\times 10^7$ sec (corresponding to $1.56 \times 10^{22}$ protons on target with 30 GeV J-PARC beam) and a 1:3 ratio of neutrino to anti-neutrino running.

Figure 2(left) shows the expected significance to exclude $\sin \delta_{CP} = 0$ (CP conserved case) with different systematic uncertainty hypotheses. The significance is calculated as $\sigma = \sqrt{\Delta \chi^2}$, where $\Delta \chi^2$ is the difference of the trial value of $\delta_{CP}$ and $\delta_{CP} = 0$ or 180 (the smaller value of the difference is taken).
Figure 1: Top: Reconstructed neutrino energy distribution for several values of $\delta_{CP}$. Bottom: Difference of the reconstructed neutrino energy distribution from the case with $\delta_{CP} = 0$. The error bars represent the statistical uncertainties of each bin.

Figure 2 (centre) shows the fraction of $\delta_{CP}$ for which $\sin\delta_{CP} = 0$ can be excluded at $3\sigma$ for different values of $\sin^2 2\theta_{13}$: if $\sin^2(2\theta_{13}) > 0.03$, CP violation in the lepton sector can be observed with $3\sigma$ for 76% of the delta parameter space.

Figure 2 (right) shows the $1\sigma$ uncertainty for $\delta_{CP}$ as a function of the integrated beam power: considering full Hyper-K statistics (i.e. 5 years exposure to neutrino beam produced by the 1.66 MW J-PARC proton synchrotron) the $\delta_{CP}$ phase could be determined to better than 19 degrees for all possible values of $\delta$.

Figure 2: Expected significance to exclude $\sin\delta_{CP} = 0$ (left). Fraction of $\delta_{CP}$ for which $\sin\delta_{CP} = 0$ can be excluded at $3\sigma$ for different values of $\sin^2 2\theta_{13}$ (centre). $1\sigma$ uncertainty for $\delta_{CP}$ as a function of the integrated beam power (right).

References

[1] Abe K et al 2011 Letter of Intent: The Hyper-Kamiokande Experiment—Detector Design and Physics Potential arXiv preprint hep-ex 1109.3262

[2] Hyper-Kamiokande Working Group, Abe K et al 2014 A Long Baseline Neutrino Oscillation Experiment Using J-PARC Neutrino Beam and Hyper-Kamiokande arXiv preprint physics.ins-det 1412.4673

[3] Abe K et al 2011 Search for differences in oscillation parameters for atmospheric neutrinos and antineutrinos at Super-Kamiokande Phys. Rev. Letters 107 241801

[4] Adamson P et al 2011 Measurement of the neutrino mass splitting and flavor mixing by MINOS Phys. Rev. Letters 106 181801

[5] Beringer J and Particle Data Group et al 2012 Phys. Rev. D 86 010001

[6] GitHub repository for WCSim: https://github.com/WCSim/WCSim