Sensitivity of new physics by joint analysis of neutrino oscillation on Hyper-Kamiokande

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Abstract. Hyper-Kamiokande (Hyper-K) is a proposed next generation underground water Cherenkov detector with a total (fiducial) mass of 516 (374) kilotons, approximately 10 (17) times as large as that of Super-Kamiokande. It will serve as a far detector of a long baseline neutrino oscillation experiment envisioned for the upgraded J-PARC and will also observe atmospheric neutrinos. The design of Hyper-K is based on the highly successful Super-Kamiokande (Super-K), making full use of a well-proven technology. In this work, we will discuss Hyper-K’s sensitivity to the leptonic CP violation and the neutrino mass hierarchy by studying the oscillations of both beam and atmospheric neutrinos. The combined analysis can increase both the sensitivity of mass hierarchy and CP violation. The sensitivity of mass hierarchy can reach 5σ and the fraction of 3σ to observe leptonic CP violation can reach 90%, with $\sin^2\theta_{23} = 0.5$ after 10 years running (a 2.6 Mton-year exposure).

1. Hyper-Kamiokande Project
Hyper-Kamiokande (Hyper-K) is a next generation gigantic underground Cherenkov ring imaging detector, which is designed to study a wide range of topics in physics and astrophysics, including leptonic CP violation, neutrino oscillation, nucleon decay, super-nova relic neutrinos and dark matter search. It consists of two water tanks with the dimensions of the 74 m (D) × 78 m (H) for each. The total fiducial water mass will be 0.37 million tons, approximately 17 times as large as that of Super-Kamiokande (Super-K) [1].

2. Neutrino oscillation
Neutrino oscillation is a phenomenon that a neutrino will change its flavour with a periodic probability when it travels. If the probability that a neutrino with flavour $\alpha$ changes to one with flavour $\beta$ in vacuum $P(\nu_\alpha \to \nu_\beta)$, is different from the probability of corresponding antineutrinos, $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$, the CP symmetry in leptonic sector is violated.

Neutrinos are scattered by matter when they travel through the Earth. This scattering can occur via both of charged current and neutral current. Due to the presence of electrons in matter only electron neutrinos undergo charged current coherent scattering effects, which introduces an asymmetry among the neutrino flavors. For sufficient matter densities and neutrino energies this asymmetry leads to enhanced oscillation probabilities for either neutrinos or antineutrinos, depending on the mass hierarchy. By comparing the survival possibility of atmospheric electron neutrinos and antineutrinos crossing the Earth’s core the mass hierarchy can be revealed.
3. Neutrino source
Both of accelerator neutrinos and atmospheric neutrinos are used in this study. The accelerator neutrinos can be reconstructed with high precision, in particular their energy, while its fixed beam line will lead to oscillation parameter degeneracies between the CP phase and the mass hierarchy. On the other hand, the atmospheric neutrinos have very high statistics and their beamlines vary largely. Thanks to the long travel length in the Earth, the atmospheric neutrinos are sensitive to the mass effect which is important to measure the neutrino mass hierarchy. However, the measurement for atmospheric neutrinos is not so precise, especially the direction. As a result, the joint analysis is expected to combine both advantages of them.

3.1. Accelerator neutrino
The accelerator neutrinos are produced at the Japan Proton Accelerator Research Complex (J-PARC) using 30 GeV proton beam. The neutrinos are directed 2.5 degrees away from the Hyper-K detectors for a narrow band beam with a spectrum peaked at 600 MeV, the first oscillation maximum for the Hyper-K baseline, 295 km. The beam power is expected to be 1.3 MW, corresponding to $2.7 \times 10^{22}$ protons on target (P.O.T.) for 10 years. Both neutrino-enhanced and antineutrino-enhanced beam data are used, in a ratio of 1:3 by P.O.T. In order to measure the neutrino's energy precisely, charged current quasi-elastic interactions from $\nu_\mu$, $\nu_e$, and their antiparticles are selected for analysis.

3.2. Atmospheric neutrino
The atmospheric neutrinos are generated by the collision between cosmic ray and molecules of the atmosphere. They come from all directions and range in energies from 100 MeV to 10 TeV and beyond, which makes their precise measurement difficult. Events are divided into several categories according to their energy, PID (e.g. e-like or $\mu$-like), and the number of visible Cherenkov rings. Additional selections, such as the number of decay electrons from pions, are made to the multi-GeV e-like samples to separate them into antineutrino-like and neutrino-like subsamples, which can improve the sensitivity to the mass hierarchy.

4. Method
The sensitivity analysis specifies a set of oscillation parameters for the MC, which is oscillated accordingly to calculate the expected number of events in each bins. A goodness of fit is defined using a $\chi^2$ method, to judge the agreement between the oscillated MC with true parameter and test parameter. The systematic errors are included in this calculation via a pull method. The $\chi^2$ function is defined as below:

$$
\chi^2_{\text{pull}} = 2 \sum_{i=1}^{n\text{Bins}} \left( N_{i}^{\text{Test}} + \sum_{k=1}^{n\text{Syst}} c_{i}^{k} \xi_{k} \right) - N_{i}^{\text{True}} \ln \left( \frac{N_{i}^{\text{True}}}{N_{i}^{\text{Test}} \left( 1 + \sum_{k=1}^{n\text{Syst}} c_{i}^{k} \xi_{k} \right)} \right) + \sum_{k=1}^{n\text{Syst}} \sum_{h=1}^{n\text{Syst}} \xi_{k} \left[ \sigma_{kh}^{2} \right]^{-1} \xi_{h}
$$

The first term is the modified Poisson likelihood ratio after considering the systematic error, the second one is the penalty term. $N_{i}^{\text{Test}}$ and $N_{i}^{\text{True}}$ are the expected events in the $i$-th bin with test oscillation parameters and true parameters. $n\text{Bins}$ and $n\text{Syst}$ represents the number of analysis bins and systematic errors. $c_{i}^{k}$ is the fractional change of the number of events in the $i$-th bin due to a 1$\sigma$ variation of the $k$-th systematic error. $\left[ \sigma_{kh}^{2} \right]^{-1}$ is the covariance matrix representing the correlation between systematic errors. The value $\xi_{k}$ are the fit parameters that are allowed to vary. At each point in the oscillation parameter space, a fit is performed to find the values of $\xi_{k}$ that give the minimum $\chi^2$ at that point. The systematic errors are from flux, cross section, detector efficiency and reconstruction modeling. The estimation of the systematics for accelerator neutrinos is based on the T2K experiment and that for atmospheric neutrinos


is based on the Super-K experiment. Currently, the correlation between the systematics of the two kinds of neutrino sources is not considered except the energy scale on Hyper-K.

5. Result
The result shown here is the expected sensitivity assuming two tanks after 10 years, and the second detector is assumed to begin taking data six years after the start of experiment. The exposure is expected to be 2.6 Mton-year.

5.1. Mass hierarchy
The atmospheric neutrinos show higher sensitivity comparing with accelerator neutrinos because matter effects are strong in the resonance-enhanced oscillation region of the atmospheric neutrino energy spectrum (2-10 GeV), while the energy of accelerator neutrinos are low. However, accelerator neutrino data provides a clean measurement of the atmospheric mixing parameters which determines the size of the matter effects. As a result, the joint analysis of these two kinds of neutrinos shows better sensitivity (Fig. 1).

5.2. CP violation and CP phase
Sensitivity to the observation leptonic CP violation (exclude $\sin \delta_{CP} = 0$) is mainly determined by the accelerator neutrino data. However, with only a fixed baseline, uncertainty in the mass hierarchy leads to parameter degeneracies that weaken the beam constraint on $\delta_{CP}$. Atmospheric neutrino can resolve this issue (Fig. 2).

![Figure 1. Neutrino mass hierarchy sensitivity as a function of the true value of $\sin^2 \theta_{23}$. The true hierarchy is assumed to be normal hierarchy. Similar result is seen when inverted hierarchy is true. True $\sin^2 \theta_{13}$ is assumed as 0.1. Error bar shows the uncertainty from $\delta_{CP}$.](image1)

![Figure 2. Accelerator and atmospheric neutrino constraints on $\delta_{CP}$ after running 10 years with assuming normal mass hierarchy and $\delta_{CP} = 0$. True $\sin^2 \theta_{13}$ ($\sin^2 \theta_{23}$) is assumed as 0.1 (0.5).](image2)

6. Conclusion
Hyper-K has strong potential to discover leptonic CP violation and determine neutrino mass hierarchy by the observation of accelerator and atmospheric neutrino oscillation. Joint analysis of these two kinds of neutrinos at Hyper-K can improve its sensitivity further. After 10 years running (a. 2.6 Mton-year exposure), the 68% CL uncertainty of $\delta_{CP}$ could reach 6° for true $\delta_{CP} = 0°$ and the significance to reject wrong mass hierarchy is expected to reach 5$\sigma$, when $\sin^2 \theta_{23} = 0.5$.

References
[1] See talk by F. Di Lodovico in these proceedings.