PROCEEDINGS OF SCIENCE

The Hyper-Kamiokande Experiment

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The Hyper-Kamiokande (Hyper-K) experiment [1] is proposed as a next generation underground water Cherenkov detector. It will serve as a far detector of a long baseline neutrino oscillation experiment envisioned for the upgraded J-PARC, and as a detector capable of observing – far beyond the sensitivity of the Super-Kamiokande (Super-K) detector – proton decays, atmospheric neutrinos, and neutrinos from astronomical origins. The baseline design of Hyper-K is based on the highly successful Super-K, taking full advantage of a well-proven technology.

In this conference, we focus on the potentials of the *CP* phase δ and the mass hierarchy determination. With a total exposure of 10 years (one year being equal to 10^7 sec) to a 2.5-degree off-axis neutrino beam produced by the 0.75 MW J-PARC proton synchrotron, it is expected that the *CP* phase δ can be determined to better than 18 degrees for all possible values of δ and *CP* violation can be established with a statistical significance of 3σ for 74% of the δ parameter space if the mass hierarchy is known. In addition, a high statistics data sample of atmospheric neutrinos will allow us to extract the information on the mass hierarchy and the octant of θ_{23}. With a full 10 year duration of data taking, the significance for the mass hierarchy determination is expected to reach 3σ or greater if $\sin^2\theta_{23} > 0.4$.

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1. Introduction

Neutrino oscillations are considered to be a consequence of the presence of neutrino mass. The gap between weak eigenstates and mass eigenstates U is a unitary matrix, and can be parametrized, for example, as;

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

where $\theta_{ij} = [0, \pi/2]$ is the 3 neutrino mixing angles and $\delta = [0, 2\pi]$ is Dirac CP violation phase. The next crucial step in neutrino physics will be the search for this CP violation phase. A comparison of muon-type to electron-type transition probabilities between neutrinos and anti-neutrinos is one of the most promising methods to reach δ.

The Hyper-K detector will serve as a far detector of a $L = 295$ km baseline neutrino oscillation experiment envisioned for the upgraded J-PARC. Figure 1 shows $P(\nu_\mu \to \nu_e)$ and $P(\overline{\nu}_\mu \to \overline{\nu}_e)$ as a function of the true neutrino energy for "J-PARC Hype-K" case. The Hyper-K detector will also provide a high statistics data sample of atmospheric neutrinos. Figure 2 shows $P(\nu_\mu \to \nu_e)$ and $P(\overline{\nu}_\mu \to \overline{\nu}_e)$ as a function of the atmospheric neutrino energy and the cosine zenith angle.

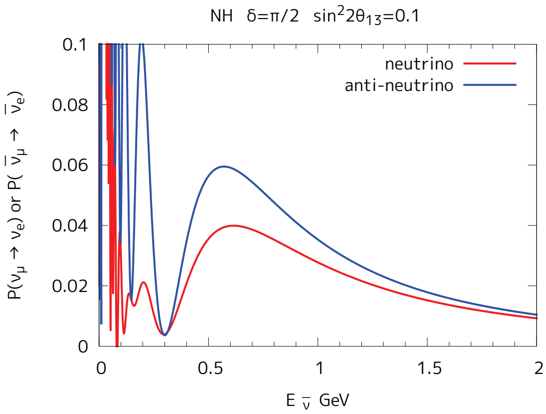

Figure 1: The oscillation probabilities of $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ for "J-PARC Hype-K". The oscillation parameters other than δ and θ_{13} are L= 295 km, $\Delta m^2_{12} = 7.6 \times 10^{-5}\,\mathrm{eV}^2$, $\Delta m^2_{23} = 2.4 \times 10^{-3}\,\mathrm{eV}^2$, $\sin^2\theta_{12} = 0.31$, $\sin^2\theta_{23} = 0.5$, and the density of the earth = 2.8 g/cm^3

2. Detector

The schematic view of the Hyper-K detector is shown in Figure 3, that is composed of two horizontally lying cylindrical tanks with the dimension of 48m(W) $\times$ 54m(H) $\times$ 250m length, holding total volume of 1 megaton ultra pure water. Table 1 summarizes baseline parameters of the proposed Hyper-K detector, which the physics sensitivities discussed in this article are based on.

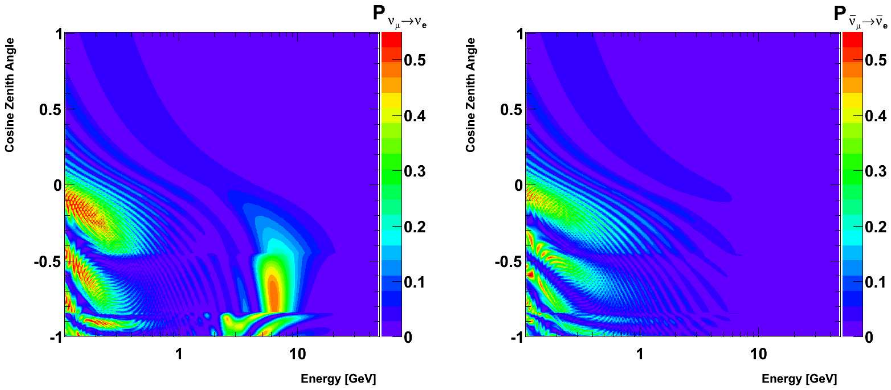

Figure 2: The atmospheric oscillation probabilities of $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ for Hype-K. The oscillation parameters are same as in the previous figure. Cosine zenith angle $= 1$ corresponds $L \sim 15$ km, and -1 corresponds $L \sim 13000$ km.

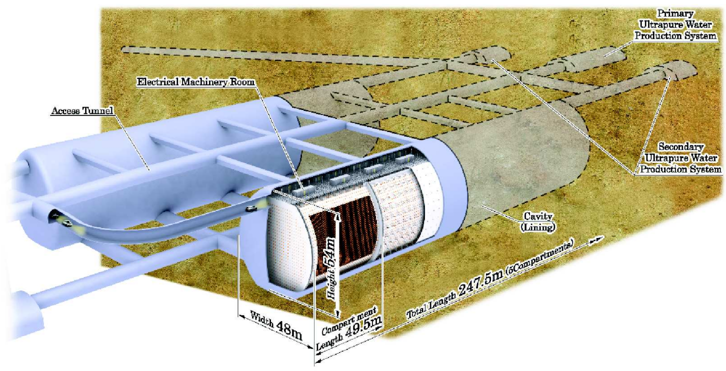

Figure 3: Schematic view of the Hyper-K detector.

3. Neutrinos from J-PARC

The J-PARC neutrino beamline, which currently provides a neutrino beam to the T2K experiment, is designed to have a common off-axis angle to Super-K (one Hyper-K candidate cite) and the other candidate Hyper-K site, 8 km south from Super-K.In this study, the off-axis angle is set to 2.5°, the same as the current T2K configuration. A beam power of 0.75 MW is assumed as the nominal case based on the KEK roadmap.

The neutrino beam simulation based on the hadron production cross section measured by NA61 experiment, the neutrino interaction simulation with the NEUT program library, and the simulation of the response of the detector using Super-K analysis software packages have been conducted to give a realistic estimate of the “J-PARC to Hyper-K" performance. The reconstructed neutrino energy distributions for several values of δ, with $\sin^2 2\theta_{13} = 0.1$ and the normal mass hierarchy, are shown in Figure 4. The running time of 3.0 (7.0) years are assumed for neutrino

Table 1: Detector parameters of the baseline design.

Candidate site	Overburden	648 m rock (1,750 m water equivalent)
	Cosmic Ray Muon flux	$1.0 \sim 2.3 \times 10^{-6}\ \mathrm{sec}^{-1}\mathrm{cm}^{-2}$
	Off-axis angle for the J-PARC ν	2.5° (same with Super-Kamiokande)
Detector geometry	Total Volume	0.99 Megaton
	Inner Volume (Fiducial Volume)	0.74 (0.56) Megaton
	Outer Volume	0.2 Megaton
Photo-multiplier Tubes		102,000 50 cm ϕ PMTs
		20% photo-coverage
Water quality	light attenuation length	$>$ 100 m @ 400 nm
	Rn concentration	$<$ 1 mBq/m^3

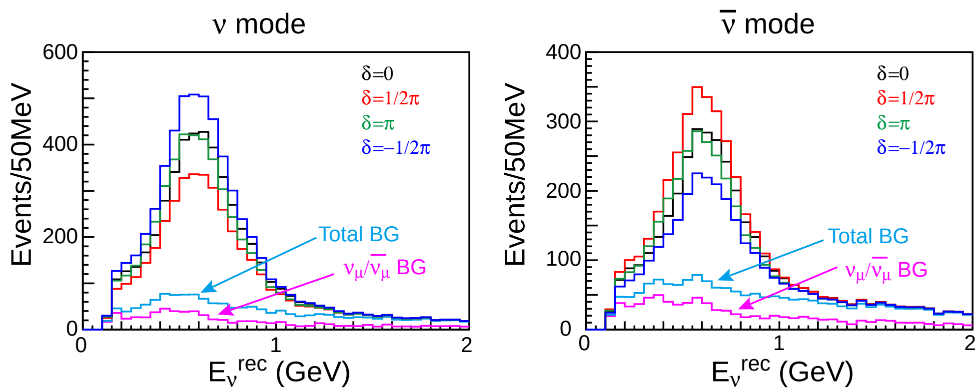

Figure 4: Reconstructed neutrino energy distribution for several values of δ, for 3.0 (7.0) years of running with neutrino (anti-neutrino) mode, with 0.75 MW beam power and a fiducial volume of 0.54 Mton. $\sin^2 2\theta_{13} = 0.1$ and normal hierarchy is assumed.

(anti-neutrino) mode. Here, *One year* is assumed to correspond to 10^7 sec of running time. The effect of δ is clearly seen using reconstructed neutrino energy.

Figure 5 shows the parameter regions where $\sin\delta = 0$ is excluded with running time of 10 years, i.e. *CP* is found to be violated in the lepton sector, with 1σ, 2σ, and 3σ significance, in the case of normal hierarchy and the mass hierarchy is known. The ratio of neutrino and anti-neutrino mode is fixed to 3:7. The sensitivity to *CP* violation as a function of the integrated beam power is also shown in Figure 5. The vertical axis shows the fraction of δ for which $\sin\delta = 0$ is excluded with 3σ significance. Solid and dashed lines correspond to the case the mass hierarchy is known and unknown, respectively. The true mass hierarchy is normal in both cases. *CP* violation in the lepton sector can be observed with 3σ significance for 74% of the possible values of δ. If we assume that the mass hierarchy is not known, the sensitivity to *CP* violation is reduced due to degeneracy. Even for this case, *CP* violation can be observed with 3σ significance for 55% of δ

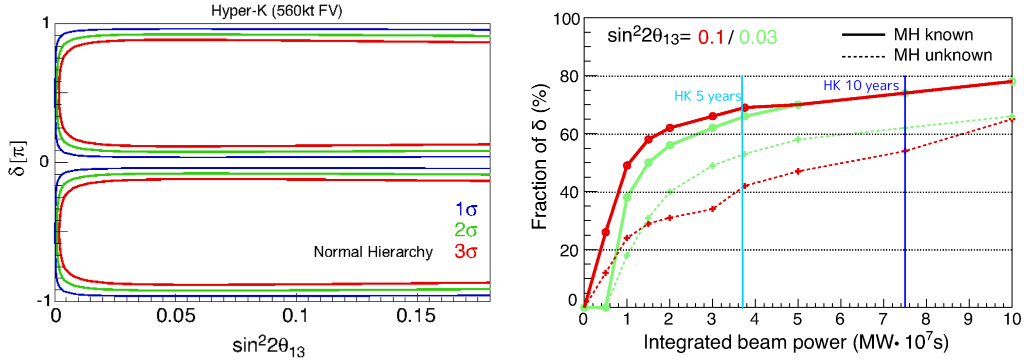

Figure 5: Left: Sensitivity to CP violation. For the region inside a line, $\sin\delta = 0$ is excluded with 3σ(red), 2σ(green) and 1σ(blue). The running time of 3.0 years in neutrino mode and 7.0 years in anti-neutrino mode (total 10 years) is assumed with 0.75 MW of beam power. Right: Fraction of δ for which $\sin\delta = 0$ can be excluded with 3 σ as a function of the integrated beam power.

parameter space if $\sin^2 2\theta_{13} = 0.1$

4. Atmospheric neutrino

Atmospheric neutrinos are a guaranteed neutrino source in the Hyper-K experiment. Now that θ_{13} is known to be large, there will be a good chance to determine the sign of Δm^2_{32} through the atmospheric $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ channels.

Based on the Super-K analyses by using reconstructed variables such as visible energy, the number of Cherenkov rings, particle type (e-like or μ-like), the number of muon decay electrons, and so on, the atmospheric events are divided into several sub-samples. In addition, the multi-GeV single-ring and multi-ring e-like events are regrouped into ν_e-like and $\overline{\nu}_e$-like samples in the following manner. In the charged current (CC) non quasi-elastic (QE) interaction components among the single-ring sample, $\pi^+(\pi^-)$ is expected to be more copiously produced in $\nu_e(\overline{\nu}_e)$ interactions because the secondary charged lepton is $e^-(e^+)$. The π^+ decays into μ^+ which in turn produces a delayed signal of a decay electron, while in the case of π^- it is often absorbed in water before decaying into μ^-, so no decay electron would be produced. Therefore, events with more than one decay electron are classified as ν_e-like, while events having no decay electron are classified as $\overline{\nu}_e$-like. As for the multi-GeV multi-ring e-like sample, the events are also divided into ν_e-like and $\overline{\nu}_e$-like samples via a likelihood method. CC ν_e interactions tend to have a larger Feynman y distribution than CC $\overline{\nu}_e$, therefore CC ν_e is expected to have larger transverse momentum, more rings, and more muon decay electrons. Hence these three observables are used in the construction of a likelihood function, and multi-ring events are divided into ν_e-like and $\overline{\nu}_e$-like sub-samples by applying the likelihood cut.

In Figure 6, the expected zenith angle distributions of e-like events are shown separately for multi-GeV ν_e-like, and multi-GeV $\overline{\nu}_e$-like sub-samples as the ratio against the non-oscillated case. We expect a sizable difference between normal (dashed lines) and inverted (solid lines) hierarchy both in the ν_e-like and $\overline{\nu}_e$-like samples. The difference becomes larger for larger $\sin^2\theta_{23}$.

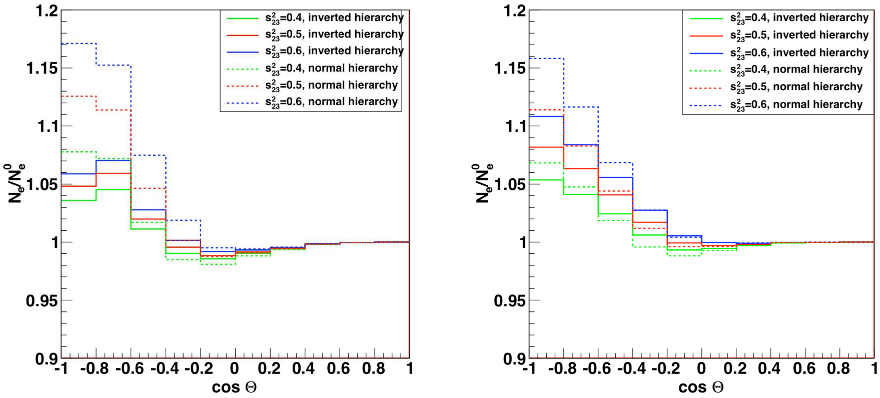

Figure 6: Expected event rate changes in (left) multi-GeV ν_e-like, and (right) multi-GeV $\bar{\nu}_e$-like event samples. The vertical axis shows the ratio of oscillated e-like event rate to the non-oscillated one. Mass hierarchy is normal for dashed lines and inverted for solid lines. Colors show $\sin^2\theta_{23}$ values as 0.4 (green), 0.5 (red), and 0.6 (blue).

Sensitivity for determining the neutrino mass hierarchy with Hype-K 10 years operation is studied and shown in Figure. 7. The $\Delta\chi^2$ for the wrong mass hierarchy assumption, – interpreted as significance of the mass hierarchy determination – is shown as a function of $\sin^2\theta_{23}$. This clearly shows that the neutrino mass hierarchy can be determined for most cases.

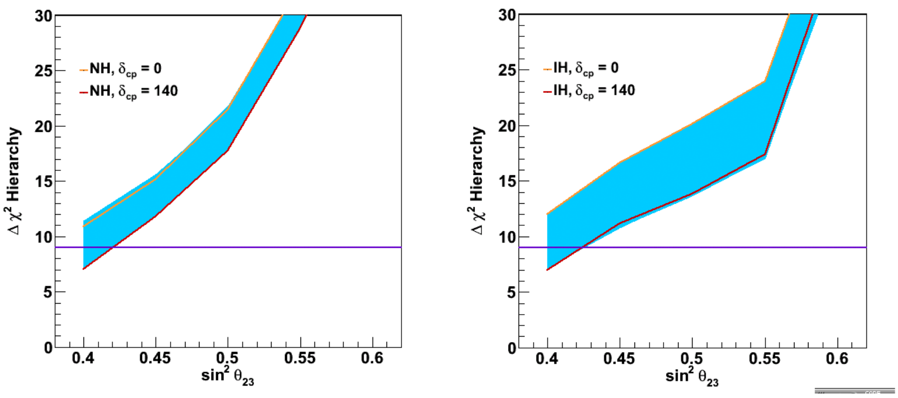

Figure 7: Expected significance for the mass hierarchy determination. In the left panel, normal mass hierarchy is the case and χ^2 for the wrong assumption; $\Delta\chi^2 \equiv \chi^2_{\rm min}({\rm inverted}) - \chi^2_{\rm min}({\rm normal})$ is shown for various true values of $\sin^2 2\theta_{23}$. $\sin^2 2\theta_{13}$ is fixed at 0.1. The right panel is for the inverted hierarchy case. Each colors show the case of $\delta = 0^\circ$ (orange) and 140° (red), and the cyan band corresponds to full δ variation. The blue horizontal lines show $3\sigma(\Delta\chi^2 = 9.0)$.

References

[1] K. Abe et al., arXiv:1109.3262.