Status and neutrino oscillation physics potential of the Hyper-Kamiokande Project in Japan

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Abstract.   Hyper-Kamiokande (Hyper-K), a proposed one-megaton water Cherenkov detector to be built in Japan, is the logical continuation of the highly successful program of neutrino (astro)physics and proton decay using the water Cherenkov technique. In its baseline design, the Hyper-K detector consists of two cylindrical tanks lying side-by-side, the outer dimensions of each tank being 48m x 54m x 250m. The inner detector region will be instrumented with 99,000 20-inch photo-sensors. An international proto-collaboration has been intensively working on the R&D of key components such as optimization of cavern, tank construction, development of high performance photo-sensors, design of new near detectors and improvements to the J-PARC neutrino beam. Hyper-K will study the CP asymmetry in neutrino oscillations using the neutrino and anti-neutrino beams produced at J-PARC. With an exposure of 7.5 MW $\times$ 10^7 seconds, CP violating parameter delta can be measured to better than 19 degrees at all values of delta, and CP violation can be detected with more than 3 sigma significance for 76% of the values. An overview of the status of project and the studies of the sensitivity of this detector to physics quantities governing neutrino oscillation is presented.

1. Introduction

The Hyper-K detector is designed as a next generation underground water Cherenkov detector. Its rich program in a wide range of science includes, in addition to long baseline (LBL) neutrino oscillation measurements, main focus of this contribution, observation of atmospheric and solar neutrinos, proton decay and neutrinos from other astrophysical origins. The baseline design of Hyper-K is based on the well-proven water Cherenkov technologies employed and tested at Super-K.

The LBL exposure of Hyper-K as far detector will have superior statistics of neutrino events thanks to the larger fiducial mass and higher power J-PARC neutrino beam, the same as T2K with the same off-axis configuration. Thanks to the T2K experience, the properties and the operation of the high power neutrino beam are well understood, as well as the systematic errors. With these features, Hyper-K will be one of the most sensitive experiments to probe neutrino CP violation.

2. Experimental setup

In Hyper-K, the total (fiducial) mass of the detector is 0.99 (0.56) million metric tons, which is about 20 (25) times larger than that of Super-K. The proposed location for Hyper-K is about 8 km south of Super-K (and still 295 km away from J-PARC) and 1,750 meters water equivalent (or

648 m of rock) deep. The inner detector region is viewed by 99,000 20-inch PMTs corresponding to the PMT density of 20% photo-cathode coverage [1].

The long baseline neutrino oscillation program is based on neutrino and antineutrino beam produced at J-PARC (Japan Proton Accelerator Research Complex), currently serving the T2K experiment. Hyper-K will utilize the full potential of this existing facility with future upgrades to reach the design power of 750 kW in forthcoming years. A new plan for power upgrade of J-PARC will provide a value of 900 kW by 2020 and ~ 1.3 MW by ~ 2024. Details on J-PARC and neutrino beamline can be found in [2].

The Near Detector complex allows to characterize the neutrino beam on site at the J-PARC accelerator complex, and to measure neutrino cross sections. The T2K near detectors[3], INGRID and ND280, will be used, possibly with an upgrade, but new near detectors that may address important uncertainties in the neutrino flux or cross-section modeling are also being considered.

The ND280 off-axis detector, located 280 m downstream from the T2K target at an angle of 2.5 degrees away from the beam axis, consists of the P0D π^0 detector, of time projection chambers (TPCs), of fine grain scintillator bar detectors (FGDs) and of surrounding electromagnetic calorimeters (ECALs). The detectors are immersed in a 0.2 T magnetic field and the magnetic yoke is instrumented with plastic scintillator panels for muon range detection. The magnetic field allows for momentum measurement and sign selection of charged particles, particularly important for operation in antineutrino mode where the neutrino background is large. The P0D and FGDs act as the neutrino targets, while the TPCs provide measurements of momentum and of ionizing energy loss for particle identification. Several upgrade possibilities at the ND280 site are under investigation. These include a high pressure TPC with various noble gases (He, Ne, Ar) as the target and tracking medium, allowing a study of the A-dependence of the cross-sections and final state interactions. Other options under study are described in [4].

To constrain the uncertainties on the modeling of neutrino interactions related to uncertainties on nuclear effects, the ideal near detector should include the same nuclear targets as the far detector. The WAGASCI concept has been developed to measure neutrino cross-sections on water, at the JPARC near detector station. The water sections of the WAGASCI detector consists of 80% water within a mesh of thick plastic scintillators assembled into a 3D grid-like structure. The scintillator is read-out with Wave-length shifting fibers connected to new Multi-Pixel Photon Counters (MPPCs). The detector is complemented by an instrumented muon range detector comprising a magnetic spectrometer (Baby-MIND). Details can be found in [5]. An alternative approach is to build a water Cherenkov (WC) near detector to measure the cross section on H_2O directly. Two conceptual designs for possible intermediate WC detectors have been studied. TITUS is a 2 kiloton WC detector located about 2 km from the target at the same off-axis angle as the far detector. At this baseline, the fluxes for the neutral current and ν_e backgrounds are almost identical to the Hyper-K fluxes. The detector geometry and the muon range detector are optimized to detect the high momentum tail of the muon spectrum. The addition of Gadolinium (Gd) and Water-based Liquid Scintillator (WbLS) compounds to water to separate neutrino and antineutrino interactions is under study. The νPRISM detector is located 1 km from the target and is 50 m tall, covering a range of off-axis angles of 1-4 degrees. The instrumented portion of the tank moves vertically to sample different off-axis angle regions. The νPRISM detector sees a range of neutrino spectra, peaked at energies from 0.4 to 1.0 GeV depending on the off-axis angle. By using these spectra, νPRISM will probe the relationship between the incident neutrino energy and final state lepton kinematics.

3. Physics Sensitivities
Since the oscillation probabilities depend differently on the value of δ_{CP}, a comparison of muon-type to electron-type transition probabilities between neutrinos and anti-neutrinos is one of the

Table 1. The expected number of ν_e appearance candidate events. Normal mass hierarchy with $\sin^2 2\theta_{13} = 0.1$ and $\delta_{cp} = 0$ are assumed.

	signal		BG						Total
	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	BG Total	
ν mode	3016	28	11	0	503	20	172	706	3750
$\bar{\nu}$ mode	396	2110	4	5	222	396	265	891	3397

Table 2. The expected number of ν_μ survival candidate events.

	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	$\nu_\mu \to \nu_e$	total
ν mode	17225	1088	11	1	999	49	19372
$\bar{\nu}$ mode	10066	15597	7	7	1281	6	26964

most promising methods to observe the lepton CP asymmetry.

The analysis method and the estimation of the systematic uncertainties are based on a framework developed for the T2K sensitivity study reported in [6]. In the following, the integrated beam power of 7.5 MW$\times 10^7$ sec is assumed and the sensitivity to CP violation has been studied with various assumptions of neutrino mode and anti-neutrino mode beam running time ratio for both normal and inverted mass hierarchy cases. The dependence of the sensitivity on the $\nu : \bar{\nu}$ ratio is found to be not significant between $\nu : \bar{\nu}$=1:1 to 1:5. Here, the ratio of integrated beam power for the neutrino and anti-neutrino mode is fixed to 1:3 so that the expected number of events are approximately the same for neutrino and anti-neutrino modes.

The criteria to select ν_e and ν_μ candidate events are based on those developed for and established with the Super-K and T2K experiments. Details on simulation, reconstruction and selection strategy can be found in [1].

The expected number of ν_e appearance candidate events is shown in Table 1 for each signal and background component. In the neutrino mode, the dominant background component is the intrinsic ν_e contamination in the beam. In the anti-neutrino mode, in addition to $\bar{\nu}_e$ and $\bar{\nu}_\mu$, ν_e and ν_μ components have non-negligible contributions due to larger fluxes and cross-sections compared to their counterparts in the neutrino mode. Table 2 shows the number of ν_μ survival candidate events for each signal and background component. For the neutrino mode, most of the events are due to ν_μ, while in the anti-neutrino mode the contribution from wrong-sign ν_μ components is significant.

The reconstructed neutrino energy distributions of ν_e events for several values of δ_{CP} are shown in Figure 1. The effect of δ_{CP} is clearly visible. The bottom plots show the difference of reconstructed energy spectrum from $\delta_{CP} = 0°$ for the cases $\delta_{CP} = 90°$, $\delta_{CP} = -90°$ and $\delta_{CP} = 180°$. The error bars correspond to the statistical uncertainty. By using also the reconstructed energy distribution, the sensitivity to δ_{CP} can be improved, and one can discriminate all the values of δ_{CP}, including the difference between $\delta_{CP} = 0$ and π. Figure 2 shows the fraction of δ_{CP} for which $\sin \delta_{CP} = 0$ is excluded with more than 3σ and 5σ of significance as a function of the integrated beam power. The normal mass hierarchy is assumed, but the results for the inverted hierarchy is almost the same. CP violation in the lepton sector can be observed with more than $3(5)\sigma$ significance for $76(58)\%$ of the possible values of δ_{CP}. The 68% CL uncertainty of δ_{CP} as a function of the integrated beam power is also shown. With 7.5 MW$\times 10^7$sec of exposure (1.56×10^{22} protons on target), the value of δ_{CP} can be determined to better than $19°$ for all values of δ_{CP}.
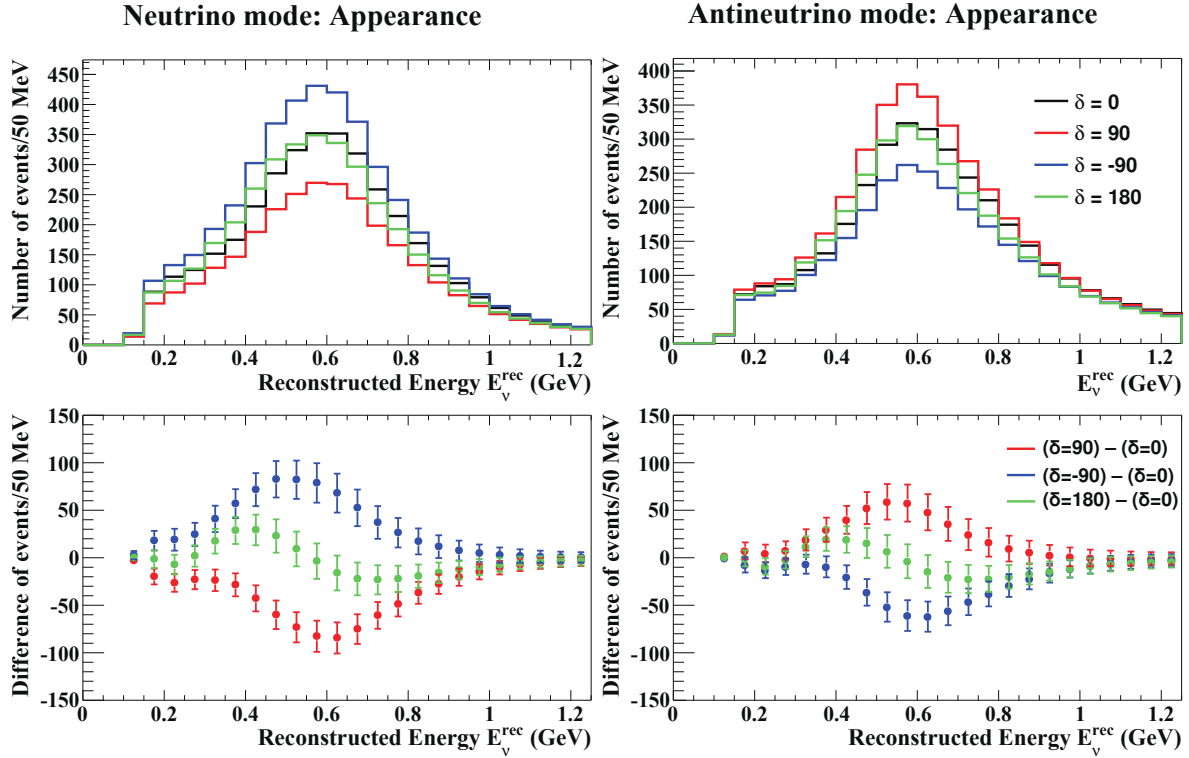
Figure 1. Top: Reconstructed neutrino energy distribution of the ν_e candidate events for several values of δ_{cp}. $\sin^2 2\theta_{13} = 0.1$ and normal hierarchy is assumed. Bottom: Difference of the reconstructed neutrino energy distribution from the case with $\delta_{cp} = 0°$ [1].
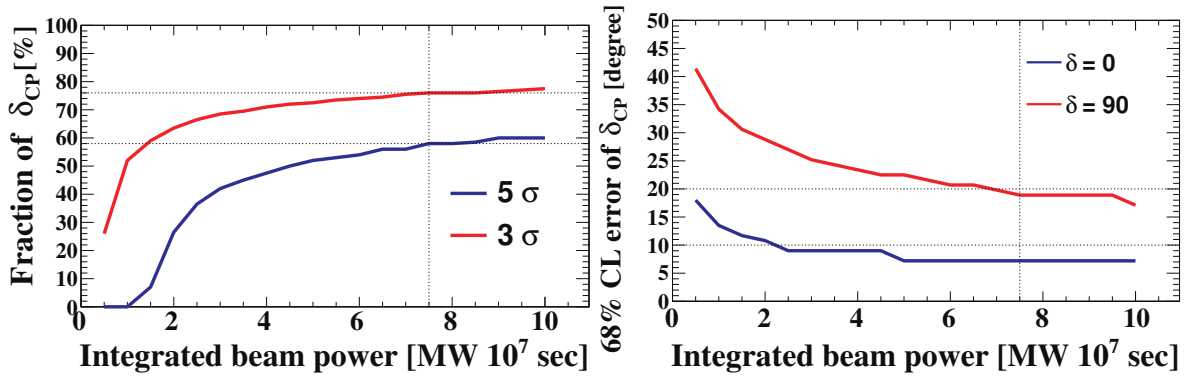

Figure 2. Left: Fraction of δ_{CP} for which $\sin \delta_{CP} = 0$ can be excluded with more than $3\,\sigma$ (red) and $5\,\sigma$ (blue) significance as a function of the integrated beam power. For the normal hierarchy case. The ratio of total beam power in neutrino and anti-neutrino mode is fixed to 1:3. Right: Expected 68% CL uncertainty of δ_{cp} as a function of integrated beam power.

Using both ν_e appearance and ν_μ disappearance data, a precise measurement of $\sin^2 \theta_{23}$ will be also possible with an expected 1σ uncertainty of 0.015(0.006) for $\sin^2 \theta_{23} = 0.5(0.45)$.

Figure 3 shows the 90% CL allowed regions for the assumed true value of $\sin^2 \theta_{23} = 0.5$ together with the 90% CL contour by T2K ν_μ disappearance measurement [7] and with a reactor constrain.
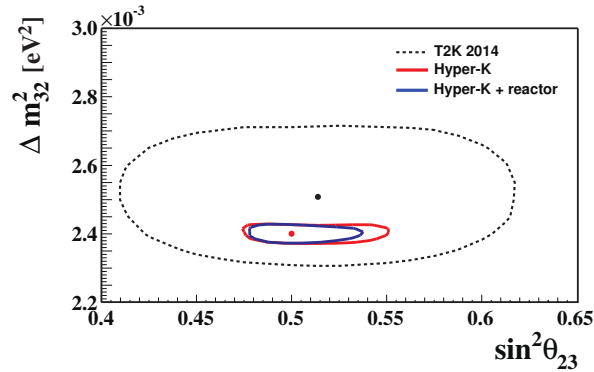
Figure 3. The 90% CL allowed regions in the $\sin^2\theta_{23}$–Δm^2_{32} plane. The assumed true values are $\sin^2\theta_{23} = 0.5$ and $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2 (red point). Effect of systematic uncertainties is included. The red (blue) line corresponds to the result with Hyper-K alone (with a reactor constraint on $\sin^2 2\theta_{13}$). The dotted line is the 90% CL contour from T2K experiment [7] with the best fit values indicated by a black point.

4. Conclusion

The sensitivity to CP asymmetry in leptonic sector of Hyper-Kamiokande experiment exposed to the J-PARC neutrino beam has been studied by means of full simulation of beamline and detector. By assuming an integrated beam power of 7.5 MW$\times 10^7$ sec, the value of δ_{CP} can be determined to better than 19° for all values of δ_{CP}. Leptonic CP violation can be observed with more than 3 σ (5 σ) significance for 76% (58%) of the possible values of δ_{CP}.

References

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