PROCEEDINGS OF SCIENCE

The Hyper-Kamiokande Experiment

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The Hyper-Kamiokande experiment is a proposed next generation underground water Cherenkov detector. The baseline design of Hyper-Kamiokande is based on the highly successful Super-Kamiokande experiment, taking full advantage of a well-proven technology. It will serve as the far detector of a long baseline neutrino oscillation experiment envisioned for the upgraded J-PARC beam, and as a detector capable of observing – far beyond the sensitivity of the Super-Kamiokande detector – proton decays, atmospheric neutrinos, and neutrinos from astronomical origins. Assuming a total exposure of 7.5 MW $\times$ 10^7 sec integrated proton beam power (corresponding to 1.56×10^{22} protons on target with a 30 GeV proton beam) to a 2.5-degree off-axis neutrino beam, it is expected that the leptonic CP phase δ_{CP} can be determined to better than 19 degrees for all possible values of δ_{CP}, and CP violation can be established with a statistical significance of more than $3\,\sigma$ ($5\,\sigma$) for 76% (58%) of the δ_{CP} parameter space. Using both ν_e appearance and ν_μ disappearance data, the expected 1σ uncertainty of $\sin^2\theta_{23}$ is 0.015(0.006) for $\sin^2\theta_{23} = 0.5(0.45)$.

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1. Introduction

The Hyper-Kamiokande (Hyper-K) experiment (see Refs. [1], [2], [3]) is the next generation flagship experiment for the study of neutrino oscillations, nucleon decays, and astrophysical neutrinos. The detector is a third generation underground water Cherenkov (WC) detector situated in Kamioka, Japan. It consists of a 1 million tonne water target which is about 20 times larger than that of the existing Super-Kamiokande (Super-K) detector. It will serve as the far detector for a long baseline neutrino oscillation experiment planned for the upgraded J-PARC beam. It will also serve as a detector capable of observing proton decays, atmospheric neutrinos, and neutrinos from astronomical origins enabling measurements that far exceed the current world best measurements.

In the following sections, we first describe the current status of the experiment, then a description of the accelerator complex, the near and far detectors will be given, finally the physics potential of the experiment will be described with particular focus on the sensitivity to CP violation.

2. Hyper-Kamiokande Experiment Status

The Hyper-K experiment is currently a proto-collaboration established on January 31 2015, when the Inaugural Symposium of the Hyper-Kamiokande Proto-Collaboration and Signing Ceremony was held at Kashiwa-no-ha Conference Center. The signing ceremony marked an agreement for the promotion of the project between the Institute for Cosmic Ray Research (ICRR) of the University of Tokyo and the Institute of Particle and the Nuclear Studies of the High Energy Accelerator Research Organization (KEK). The Hyper-Kamiokande proto-collaboration includes members of 12 states, and has an international management. R&D is carried out both in Japan and in the other member Countries, where different level of funding are secured. The proto-collaboration is currently writing a design report describing both the optimized detector and physics reach.

3. Experimental Setup

3.1 J-PARC

J-PARC (Japan Proton Accelerator Research Complex) [4] is an accelerator research complex currently providing the beam to several experiments, among which the T2K experiment, to which it provides a 2.5° narrow-band off-axis neutrino (antineutrino) beam.

The Hyper-K experiment will utilize the full potential of this existing facility. The current plan is to upgrade the beam to reach the design power of 750 kW. This will double the current repetition rate by (i) replacing the magnet power supplies, (ii) replacing the RF system, and (iii) upgrading injection/extraction devices. The design power of 750 kW will be achieved before Hyper-K will start data taking. Conceptual studies on how to realize 1$\sim$2 MW beam powers are also under way.

3.2 Near Detectors

The neutrino flux and cross-section models can be constrained by data collected at near detectors, situated close enough to the neutrino production point so that oscillation effects are negligible. Their data addresses important uncertainties in the neutrino flux or cross-section modeling.

The conceptual design of the near detectors is being developed based on the physics sensitivity studies to optimize the potential of the experiment.

There are ongoing discussions on using the T2K near detectors [1], INGRID and ND280, possibly with upgrades, for Hyper-K [5], including the deployment of heavy water (D_2O) within the passive water targets in FGD2 and the use of a water-based liquid scintillator (WbLS) developed at BNL [6], in the context of a tracking detector with comparable or finer granularity than the FGD. Either would significantly enhance the study of neutrino interactions on water by reducing the reliance on subtraction and enhancing the reconstruction capabilities relative to the currently deployed passive targets. Finally, a high pressure TPC that can contain various noble gases (He, Ne, Ar) to serve both as the target and tracking medium is being studied.

While the above options would be deployed within the UA1 magnet, another proposal would place a scintillating tracking detector outside of the magnet on the B2 floor of the NU1 building surrounded by range detectors to measure the muon momentum over a large range of angles.

Since many of the uncertainties on the modeling of neutrino interactions arise from uncertainties on nuclear effects, the ideal near detector should include the same nuclear targets as the far detector. In T2K near detectors, the P0D [7] and FGD [8] detectors include passive water layers, however extracting water only cross sections requires complicated analyses that subtract out the interactions on other materials in the detectors. An alternative approach is to build a water Cherenkov (WC) near detector to measure the cross section on H_2O directly and with no need for a subtraction analysis.

Two conceptual designs for possible intermediate WC detectors have been studied. The Tokai Intermediate Tank for Unoscillated Spectrum (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 detector sees fluxes for the neutral current and ν_e backgrounds that are nearly identical to the Hyper-K fluxes. The detector geometry and the presence of a muon range detector are optimized to detect the high momentum tail of the muon spectrum. The use of Gd in TITUS allows to separate neutrino and antineutrino interactions. The νPRISM detector is located 1 km from the target and is 50 m tall, covering a range of off-axis angles from 1-4 degrees, exploiting the corresponding spectra to better probe the relationship between the incident neutrino energy and final state lepton kinematics, a part of the interaction model with larger uncertainties arising from nuclear effects.

3.3 The Hyper-Kamiokande Detector

The Hyper-K detector is a water Cherenkov detector in the Tochibora mine (8 km South of Super-Kamiokande , but same off-axis angle) one order of magnitude larger than Super-K. The current design is being optimized, the nominal design foresees a total (fiducial) mass of 0.99 (0.56) million metric tons, approximately 20 (25) times larger than that of Super-Kamiokande.

For the baseline design, the Hyper-K detector is composed of two separated caverns as shown in Fig. 1 (left), each having an egg-shape cross section 48 meters wide, 54 meters tall, and 250 meters long as shown in Fig. 1 (right). The welded polyethylene tanks are filled up to a depth of 48 m with ultra-pure water: the total water mass equals 0.99 million tons.

Each tank will be optically separated by segmentation walls located every 49.5 m to form 5 (in total 10) compartments, such that event triggering and event reconstruction can be performed in each compartment separately and independently. Because the compartment dimension of 50 m

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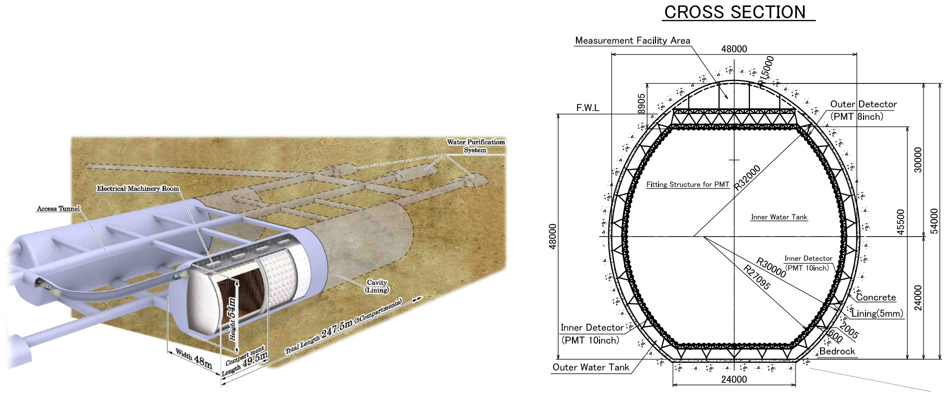

Figure 1: Schematic view (left) and cross section (right) view of the Hyper-K detector.

Table 1: The expected number of ν_e and ν_μ candidate events for the appearance and disappearance final states, respectively. Normal Hierarchy (NH), $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$ are assumed. The background is categorized by the flavor before oscillation.

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

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

is comparable with that of Super-K (36 m) and is shorter than the typical light attenuation length in water achieved by the Super-K water filtration system (> 100 m @ 400 nm), we expect that the detector performance of Hyper-K will be basically the same as that of Super-K. The water in each compartment is further optically separated into three regions. The inner region has a barrel shape of 42 m in height and width, and 48.5 m in length, and is viewed by an inward-facing array of 20-inch diameter photomultiplier tubes (PMTs). The entire array consists of 99,000 Hamamatsu R3600 PMTs, uniformly surrounding the region and giving a photocathode coverage of 20%. The PMT type, size, and number density are subject to optimization, currently underway in the eGADS detector (see e.g. Ref. [9]) in the Kamioka mine.

An outer region (OD) completely surrounds the 5 (in total 10) inner regions and is equipped with 25,000 8-inch diameter PMTs. This region is 2 m thick at the top, bottom, and barrel sides, except at both ends of each cavern, where the outer region is larger than 2 m due to rock engineering considerations. A primary function of the OD is to reject entering cosmic-ray muon backgrounds and help to identify nucleon decays and neutrino interactions occurring in the inner detector.

4. Physics Potential

A recent update of the previous sensitivity studies for Hyper-Kamiokande [1] is presented in Ref. [3]. It uses a framework for the oscillation analysis developed by T2K [10] and then adapted to Hyper-Kamiokande, and the latest systematic errors based on the experience and prospects of the T2K experiment. A document that contains an update on the R&D of the experiment as well was submitted in April 2014 to the J-PARC Programme Advisory Committee (PAC) [2]. An integrated beam power of 7.5 MW$\times 10^7$ sec is assumed in this study. It corresponds to 1.56×10^{22} protons on target (POT) with a 30 GeV J-PARC beam. The ratio of neutrino and anti-neutrino running time is assumed to be 1:3. The oscillation parameters used for the sensitivity analysis are: $\sin^2 2\theta_{13}$ (0.1, fitted), δ_{CP} (0, fitted), $\sin^2\theta_{23}$ (0.5, fitted), Δm^2_{32} (2.4×10^{-3} eV^2, fitted), mass hierarchy (normal, fitted), $\sin^2 2\theta_{12}$ (0.8704, fixed) and Δm^2_{12} (7.6×10^{-5} eV^2, fixed), where in parenthesis the nominal values used in the fits and the treatment used in the fits are indicated. 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, and the corresponding number of expected events is shown is Table 1.

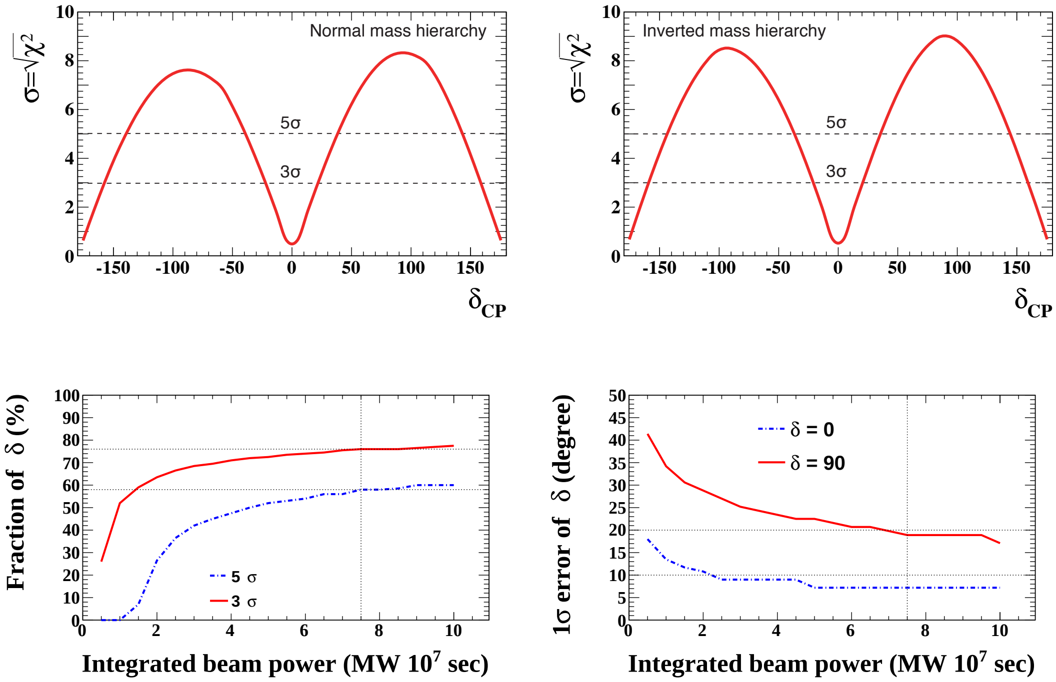

Figure 2: Upper row: expected significance to exclude $\sin\delta_{CP} = 0$. Left: normal hierarchy case. Right: inverted hierarchy case. Bottom row: fraction of δ_{CP} for which $\sin\delta_{CP} = 0$ can be excluded with 3 σ (red solid line) and 5 σ (blue dashed line) significance as a function of the integrated beam power (NH). Right plot: expected 1 σ uncertainty of δ_{CP} as a function of integrated beam power.

Figure 2, upper row, shows the expected significance to exclude $\sin\delta_{CP} = 0$ (the *CP* conserved case), for the normal (left) and inverted (right) mass hierarchy. The significance is calculated as $\sqrt{\Delta\chi^2}$, where $\Delta\chi^2$ is the difference of χ^2 between the *trial* value of δ_{CP} and either $\delta_{CP} = 0°$ or

180° (the smaller value of the difference is taken). We have also studied the case with a reactor constraint [11], but the result changes only slightly. Figure 2 (bottom row, left) shows the fraction of δ_{CP} for which $\sin\delta_{CP} = 0$ is excluded with 3 σ and 5 σ of significance as a function of the integrated beam power. The normal mass hierarchy is assumed. The result for the inverted hierarchy is almost the same. *CP* violation in the lepton sector can be observed with 3(5) σ significance for 76(58)% of the possible values of δ_{CP}. Figure 2 (bottom row, right) shows the 1 σ uncertainty of δ_{CP} as a function of the integrated beam power. With 7.5 MW$\times 10^7$sec of exposure (1.56×10^{22} POT), the value of δ_{CP} can be determined to better than 19° for all values of δ_{CP}. The use of ν_μ sample in addition to ν_e enables us to also measure $\sin^2\theta_{23}$ and Δm^2_{32} and Hyper-K will be able to provide a precise measurement of $\sin^2\theta_{23}$ and Δm^2_{32}. Figure 3 (left) shows the 90% CL allowed regions on the $\sin^2\theta_{23}$-Δm^2_{32} plane, for the true values of $\sin^2\theta_{23} = 0.45$ and $\Delta m^2_{32} = 2.4\times 10^{-3}$ eV^2. With a constraint on $\sin^2 2\theta_{13}$ from the reactor experiments (right), the octant degeneracy is resolved and θ_{23} can be precisely measured.

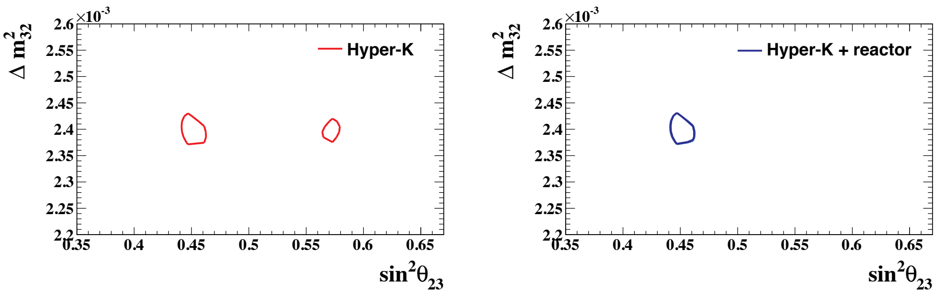

Figure 3: 90% CL allowed regions in the $\sin^2\theta_{23}$–Δm^2_{32} plane. The true values are $\sin^2\theta_{23} = 0.45$ and $\Delta m^2_{32} = 2.4\times 10^{-3}$ eV^2. The effect of the systematic uncertainties is included. Left plot: Hyper-K only. Right plot: With reactor constraint.

Atmospheric Neutrinos

Atmospheric neutrinos can provide independent and complementary information to the accelerator beam program on the study of neutrino oscillation. Assuming a 10 year exposure, Hyper-K's sensitivity to the mass hierarchy and the octant of θ_{23} by atmospheric neutrino data are shown in Fig. 4, left and right figures, respectively. Depending upon the true value of θ_{23} the sensitivity changes considerably, but for all currently allowed values of this parameter the mass hierarchy sensitivity exceeds 3 σ independent of the assumed hierarchy. If θ_{23} is non-maximal, the atmospheric neutrino data can be used to discriminate the octant at 3 σ if $\sin^2 2\theta_{23} < 0.99$.

Proton Decay Search

Large water Cherenkov detectors have excellent sensitivities for nucleon decays. For more than a decade Super-Kamiokande has had the world's best limits, generally by an order of magnitude or more, on most of the current theoretically favored decay modes. Among many possible nucleon decay modes $p \to e^+\pi^0$ and $p \to \overline{\nu}K^+$ have been the subjects of the most intense interest. Figure 5 (left) shows the sensitivity of Super-Kamiokande and Hyper-K as a function of the year. The nucleon decay results from Hyper-K can supercede the ones from Super-Kamiokande within a single year of running. Moreover, many other nucleon decay searches in Hyper-K have been studied.

Supernovas

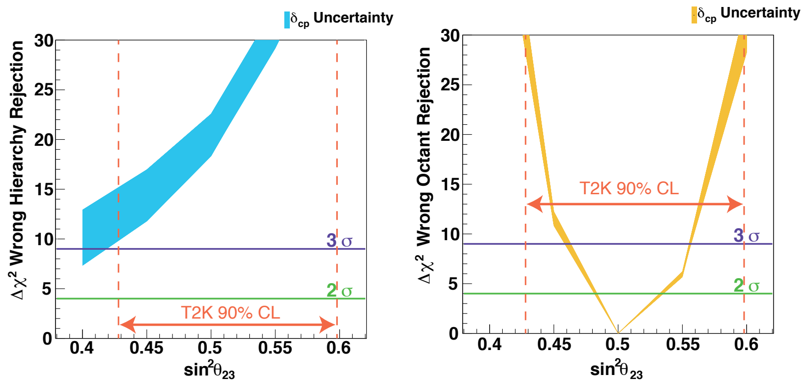

Figure 4: Atmospheric neutrino sensitivities for a ten year exposure of Hyper-K assuming the mass hierarchy is normal. Left: the $\Delta\chi^2$ discrimination of the wrong hierarchy hypothesis as a function of the assumed true value of $\sin^2\theta_{23}$. Right: the discrimination between the wrong octant for each value of $\sin^2\theta_{23}$. The uncertainty from δ_{cp} is given by the thickness of the band.

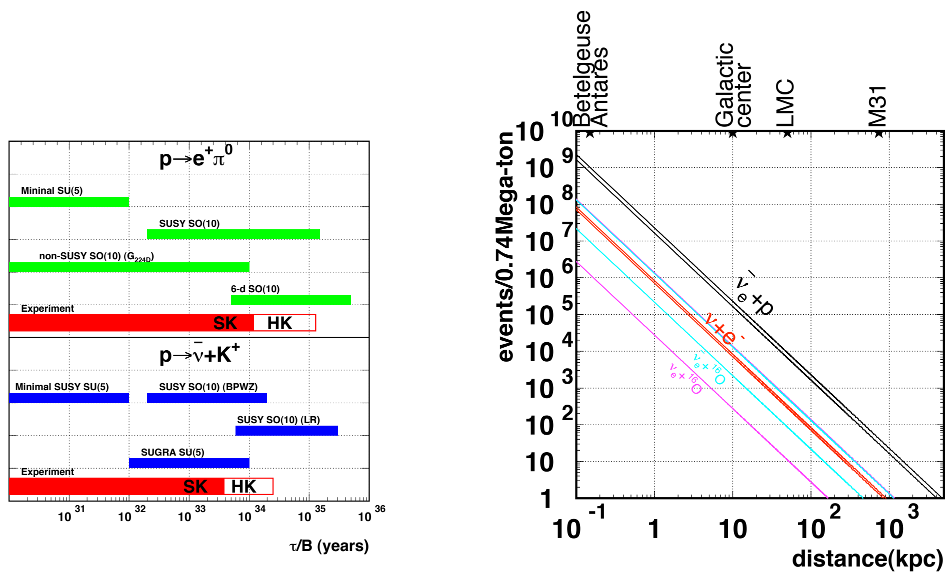

Figure 5: Left plot: Proton lifetime predictions of several GUT models, the current experimental limits (90% CL) by Super-K, and the sensitivities of Hyper-K with a 5.6 Megaton·year exposure. Hyper-K can cover most of the predicted range of the leading GUT models. Reght plot: Expected number of supernova burst events for each interaction as a function of the distance to a supernova. The band of each line shows the possible variation due to the assumption of neutrino oscillations.

Since neutrinos interact weakly with matter, almost 99% of the released energy from an exploding star is carried by neutrinos. As a result, the detection of supernova neutrinos gives direct information of energy flow during the explosion. Figure 5 (right) shows the expected number of supernova neutrino events at Hyper-K versus the distance to a supernova. Moreover, the neutrinos produced by all the supernova explosions since the beginning of the universe are called supernova relic neutrinos (SRN), and should fill the present universe. In order to reduce background, lower the energy threshold, individually identify true inverse beta events by tagging their neutrons, and thereby positively detect SRN signals, an addition of about 0.1% gadolinium to the tank is proposed, based on Ref. [12] for Super-K. But, in order to measure the spectrum of the SRN and analyze the history of the universe, we need Hyper-K, a megaton-scale detector.

Further Measurements

Hyper-K will be able to perform several other high sensitivity measurements and searches on solar neutrinos, indirect dark matter search, transient astrophysical sources (e.g. GRB neutrinos, solar flares, etc.), exotic physics (sterile neutrinos, Lorentz Violation, Non Standard Interactions etc.) and finally also geoneutrinos (see Ref. [1]).

5. Conclusions

Hyper-K is the next generation long baseline neutrino experiment in Japan. It will be able to measure δ_{CP} with 3(5) σ significance for 76(58)% of the possible values of δ_{CP} to better than 19° for all values of δ_{CP}. Complementing the beam results with the atmospheric neutrinos it will also be able to measure the mass hierarchy and the octant of θ_{23}. Moreover, it is capable of observing, far beyond the sensitivity of the current experiments, proton decays, atmospheric neutrinos, and neutrinos from astrophysical origins.

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