The Hyper-Kamiokande Experiment

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Abstract. The Hyper-Kamiokande experiment consists of a 260 kt underground water Cherenkov detector with a fiducial volume more than 8 times larger than that of Super-Kamiokande. It will serve both as a far detector of a long-baseline neutrino experiment and an observatory for astrophysical neutrinos and rare decays. The long-baseline neutrino experiment will detect neutrinos originating from the upgraded 1.3 MW neutrino beam produced at the J-PARC accelerator 295 km away. A near detector suite, close to the accelerator, will help characterise the beam and minimise systematic errors. The experiment is now under construction and due to start data taking in 2027. The experiment will investigate neutrino oscillation phenomena (including CP-violation and mass ordering) by studying accelerator, solar and atmospheric neutrinos, neutrino astronomy (solar, supernova, supernova relic neutrinos) and nucleon decays. This paper gives an overview of the Hyper-Kamiokande experiment, its physics goals and the current status.

1. Introduction

Hyper-Kamiokande will be the next experiment in the successful Kamiokande neutrino programme, dedicated to the search for nucleon decay and the study of neutrino phenomena and neutrino sources. A series of water Cherenkov neutrino detectors have been constructed over the years, starting with the original 3 kton Kamiokande detector (1983–1996), followed by the 50 kton Super-Kamiokande detector that is still operating today. The T2K long-baseline neutrino oscillation experiment utilises Super-Kamiokande as a far detector to measure oscillations of neutrino and anti-neutrino beams generated at the J-PARC facilty 295 km away. The Hyper-Kamiokande project builds on this world-leading neutrino programme, with a new 260 kton water Cherenkov detector (the Hyper-Kamiokande Detector) that will give unprecedented statistics, alongside upgraded beam and near detectors for a long-baseline programme.

2. The Far Detector

The Hyper-Kamiokande Detector will consist of a cylindrical tank 71 m in height and 68 m high filled with 260 kton ultra-pure water. To house this collosal detector, a new cavity is required, to avoid interference with existing experiments in the Kamioka laboratory where Super-Kamiokande is located. Construction has commenced (ground-breaking ceremony May 2021) for the Hyper-Kamiokande site located under Mt. Nijugoyama near Kamioka in western Japan.

The fiducial volume of Hyper-Kamiokande will be ∼188 kton (8 times that of Super-Kamiokande). Cherenkov light generated from events in the inner detector region will be read out by an array of inward looking photomultiplier tubes (PMTs). 20,000 50 cm diameter PMTs will provide 20% surface area coverage. These PMTs have been developed by Hamamatsu with a box and line style dynode to give 2.6 ns timing resolution. Mass production of these PMTs will take nearly 6 years to completed and has already commenced with a programme of quality assurance established for the PMTs as they are delivered.

In addition to the 50 cm PMTs, will we enhance the inner detector (ID) light detection with up to 10,000[1] additional multi-PMT units. These will consist of 19 8 cm diameter PMTs arranged within a single pressure vessel that also contains the electronics. The inclusion of mPMTs units not only increases the overall light collection, but simulation studies also show them to improve angular acceptance and increase the dynamic range of the detector. The arrangement of the 19 PMTs within the unit provides some intrinsic directional sensitivity and information from local coincidences is also beneficial. Thus the inclusion of mPMT units in the design provides valuable cross-calibration of the detector energy response.

An outer detector (OD) region will act as both a passive shield for low energy backgrounds and an active veto for cosmic ray muons. The expected cosmic ray muon rate through Hyper-Kamiokande is around 45 Hz so this system is required to veto nearly 4 million muons per day. The OD region surrounds the inner detector, and is 1 m wide in the barrel region and 2 m deep at the top and bottom of the cylinder. It will be instrumented with 10,000 outward looking 8 cm PMTs, each mounted within a $\sim$ 30 cm sided WLS plate that serves to increase the coverage and collection efficiency. Another important component of the OD system is highly reflective tyvek ($\sim 90\%$ reflectivity) covering all surfaces of the OD volume.

All of the photo-sensors and their readout electronics (which will be contained with underwater pressure vessels) will be mounted on a cylindical support structure that contributes a 60 cm ‘dead space’ between the ID and OD regions.

3. The Neutrino Beam

The J-PARC beam line that currently provides a 500 kW neutrino (anti-neutrino) beam to the T2K experiment will be upgraded over the next decade to 1.3MW beam power. This will be achieved in two stages with a main ring power supply upgrade and a subsequent radio frequency upgrade to allow the repetition rate to be doubled. Like the T2K experiment, the Hyper-Kamiokande long baseline programme will benefit from a 2.5° off axis beam, which optimises the neutrino energies around the first oscillation maximum at 0.6 GeV and reduces the high energy tail. The far detector is not in the same location as Super-Kamiokande but still 2.5° off-axis.

4. Near Detectors

Near detectors are an essential component of the long baseline experiment, allowing measurements to constrain the flux and neutrino interaction model uncertainty. The Hyper-Kamiokande project will inherit the INGRID on-axis detector and the ND280 off-axis detector from the T2K experiment, including upgrades to the improve the angular acceptance of the ND280 tracking detector that will be implemented in 2021/22.

An additional detector will be added approximately 1 km downstream from the beam production point. This so called ‘Intermediate Water Cherenkov Experiment’ (IWCD) comprising $\sim$600 ton of ultra-pure water target and mPMT readout will provide large pure samples of ν_e and $\bar{\nu_e}$ events that will be used to constrain the electron to muon neutrino cross section ratio, a dominant systematic uncertainty for the CP violation measurement. This detector can be moved in a vertical shaft allowing measurements at different off-axis angles between $1^\circ - 4^\circ$, thus mapping the relationship between neutrino energy and final state observables in water.

[1] The exact number of mPMTs is being optimised and currently we plan for between 2000-5000 units.

5. Physics Sensitivities

In this section we discuss the physics sensitivities of the Hyper-Kamiokande project, starting with the long baseline measurments. Hyper-Kamiokande is sensitive to the oscillation parameters Δm^2_{32} through beam ν_μ disappearance and to $\theta_{23}, \theta_{13}, \delta_{CP}$ through beam ν_e appearance. These measurements are performed by floating the oscillation parameters in a simultaneous fit to both near and far detector samples, with additional inputs from global cross section data and hadron production data.

5.1. CP violation

Hyper-Kamiokande will perform a precise study of CP asymmetry in the lepton sector through direct comparison of the oscillation probabilities for neutrinos and anti-neutrinos. This measurement is significant since the existence of leptonic CP violation may be a necessary condition to explain the matter-antimatter asymmetry of the Universe. Figure 1 shows the expected ν_e and $\bar{\nu}_e$ appearance signal at the far detector for 10 years of running assuming a ratio of 1:3 $\nu : \bar{\nu}$ beam time, where different colours indicate different values of δ_{CP}. In figure 2 this is translated into sensitivity to exclude CP conservation for the same data assuming that the mass ordering is already known. The dotted blue line shows the sensitivity with current T2K cross-section systematic uncertainties, whilst the red dashed line shows the improvement if the $\nu_e : \bar{\nu}_e$ cross section ratio uncertainty is reduced to 2.7% through Hyper-Kamiokande near detector measurements. With the improved systematics, Hyper-Kamiokande can exclude $\delta_{CP} = 0$ at 5σ for over 60% of true δ_{CP} parameter space in 10 years.

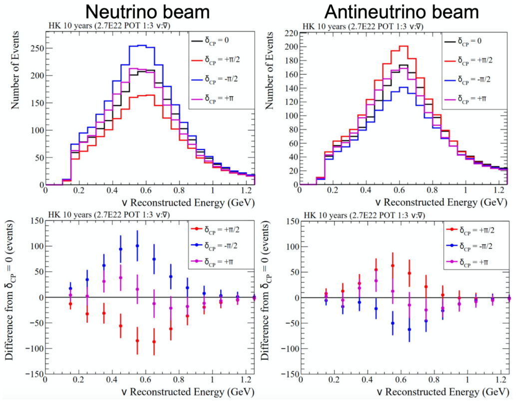

Figure 1. Predicted ν_e (left) and $\bar{\nu}_e$ appearance events for 10 years of operation for different values of δ_{CP}.

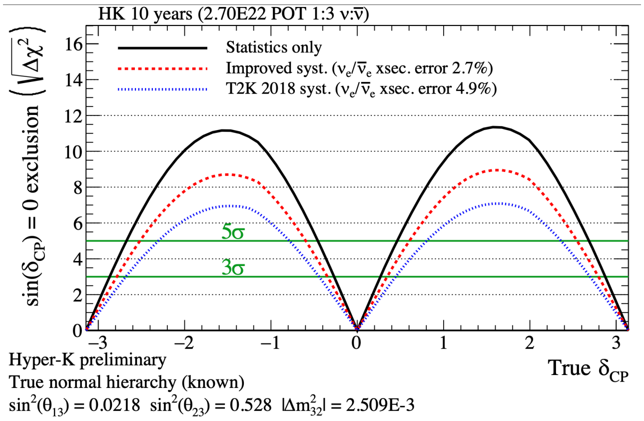

Figure 2. Sensitivity to exclude $\delta_{CP} = 0$ for different true values of δ_{CP} under different systematic uncertainty scenarios.

5.2. Mass ordering

The 295 km baseline between J-PARC and the far detector is not sensitive to significant matter effects so the neutrino mass ordering cannot be measured with beam neutrinos alone in Hyper-Kamiokande. However, the huge sample of atmospheric neutrinos, produced isotropically about the Earth with path-lengths ranging from orders 10 km to more than 10,000 km provide an excellent means to measure such effects. A combined fit to atmospheric and beam neutrino data has the sensitivity to reject the wrong mass hierarchy at 3σ within 3 years of running for a true value of $\sin^2\theta_{23} = 0.5$ as shown in figure 3.

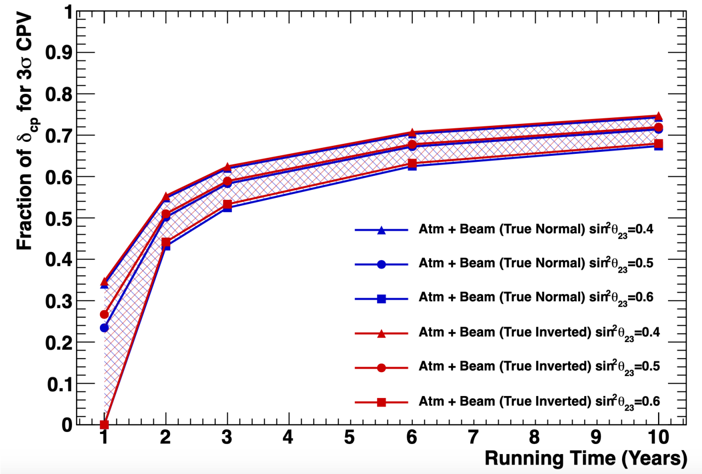

Figure 3. Fraction of δ_{CP} phase space at which a 3σ observation of CP violation can be made as a function of time assuming $\sin^2\theta_{23} = 0.4$ (triangle), 0.5 (circle), and 0.6 (square) from a combined analysis of atmospheric and accelerator neutrinos data at Hyper-K. Blue (red) colours denote the normal (inverted) hierarchy.

5.3. Solar neutrinos

The low energy of solar neutrinos (MeV scale) means that the major challenge for this measurement is the control and rejection of low energy backgrounds: from radioactive daughters of ^{222}Rn in the water and spallation products created by cosmic ray muons. The former is achieved by careful control of radiopurity during construction and a complex water purification system. With it's huge fiducial volume, Hyper-Kamiokande will have unprecedented statistical power and will be able to measure short period solar flux variations, realising a real-time monitor of the Sun's core temperature. We will also be able to make a precision measurement of day:night asymmetry in the solar neutrino flux, which should resolve the existing tension between reactor and solar measurements in the Δm^2_{21} value with just 2 years of Hyper-Kamiokande data.

5.4. Supernovae

Figure 4 shows the expected time profile and event numbers in Hyper-Kamiokande for a supernova at 10 kpc from Earth using the Livermore simulation model. The peak rate for inverse beta decay events, shown in black in this figure exceeds 50 kHz so capabilities to record such high event rates for short periods are part of the Hyper-Kamiokande detector data acquisition system design. The huge events samples yielded by such an event allow detailed analysis to probe both neutrino oscillation parameters and supernova modelling [1]

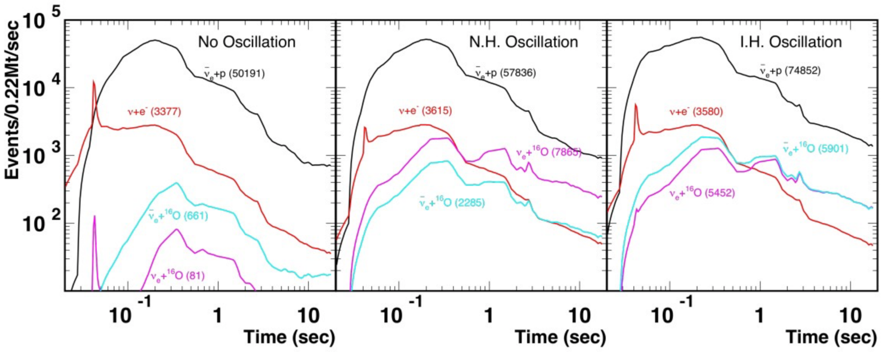

Figure 4. Expected time profile and event numbers in HK for a supernova at 10 kpc (Livermore simulation).

5.5. Proton decay

Proton decay into a positron and a neutral pion ($p \rightarrow e^+ + \pi^0$) creates a back-to-back topology of three electromagnetic showers within Hyper-Kamiokande: the two showers from the pion decay appear opposite that from the positron allowing full reconstruction of the mass and momentum of the initial proton. Hyper-Kamiokande will have unprecedented sensitivity in this channel, extending sensitivity over current limits by an oder of magnitude as shown against time in figure 5. The primary background to this is atmospheric neutrinos where charged current single-pion production processes such as $\nu_e + n \rightarrow e^- + \pi^0 + p$ can mimic the signal if the proton is below the cherenkov threshold.

Hyper-Kamiokande can also set world-leading limits on proton decay through the $p \rightarrow \bar{\nu} + K^+$ channel even though it is not possible to fully reconstruct the initial proton kinematics since the neutrino is essentially invisible. The search for this decay mode is performed by identifying a monochromatic kaon with the appropriate momentum (it is emitted with 340 MeV/c, below the cherenkov threshold) by reconstructing its decay particles: $K^+ \rightarrow \nu + \mu^+$ (64% branching ratio) and $K^+ \rightarrow \pi^+ + \pi^0$ (21% branching ratio). Figure 6 shows the Hyper-Kamiokande sensitivity to this channel, which again extends upon existing limits by an order of magnitude and exceeds the predicted sensitivities of both the JUNO and DUNE experiments.

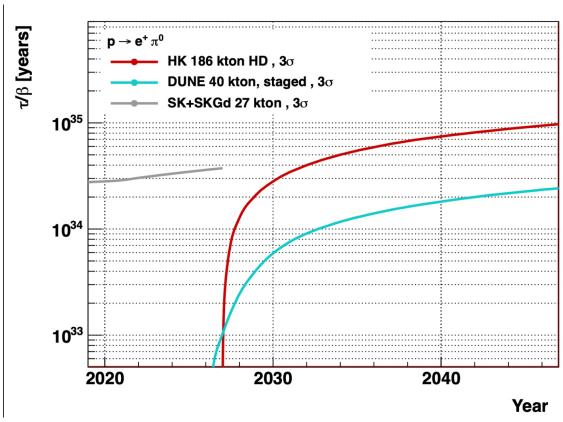

Figure 5. Hyper-Kamiokande predicted sensitivity to the $p \rightarrow e^+ + \pi^0$ proton decay channel against time compared to Super-K-Gd and DUNE capabilities.

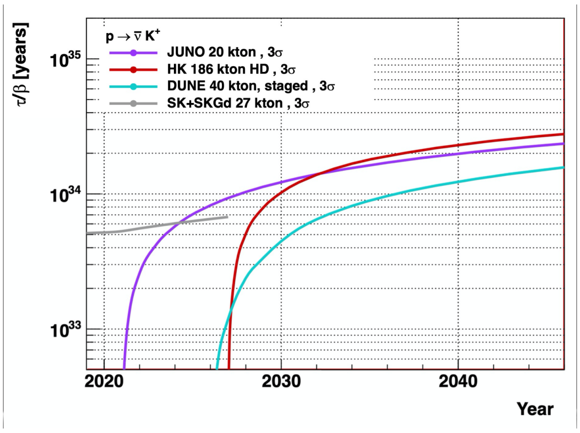

Figure 6. Hyper-Kamiokande predicted sensitivity to the $p \rightarrow \bar{\nu} + K^+$ proton decay channel against time compared to Super-K-Gd, JUNO and DUNE capabilities.

6. Summary

We have presented a brief discussion of the Hyper-Kamiokande experiment and its physics capabilities, showing that this next generation neutrino experiment has capabilities to answer many key questions in both particle physics and astrophysics. Construction has started with data taking planned to commence in 2027.

References

[1] "Supernova Model Discrimination with Hyper-Kamiokande", K.Abe *et al*, 2021, ApJ 916 p15