The Hyper-Kamiokande Experiment: design, status of construction and physics goals

F. J. P. Soler
School of Physics and Astronomy,
University of Glasgow, UK
On behalf of the Hyper-Kamiokande collaboration

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Abstract

Hyper-Kamiokande (HK) is the next generation water Cherenkov detector being constructed in Japan, following in the footsteps of the very successful Kamiokande, Super-Kamiokande and T2K experiments. The HK far detector (258 kton) is planned to be instrumented with 20,000 50 cm diameter photomultiplier tubes (PMTs) and about 1,000 multi-PMT optical sensors (each containing 19 7.6 cm PMTs) looking inwards at the detector and around 3,600 PMTs of 7.6 cm diameter looking outwards to veto cosmic radiation and other backgrounds. The design and construction of the detector is at an advanced stage. HK is expected to be commissioned in 2027. The experiment will also count with an Intermediate Water Cherenkov Detector (IWCD) at a site approximately 900 m from the target used to produce neutrino beams at the J-PARC accelerator facility, while the HK far detector is located 295 km away. The main physics goals of the experiment are to significantly improve the precision of neutrino oscillation measurements using the upgraded J-PARC neutrino beam, including the potential discovery of CP violation in the leptonic sector of the Standard Model, measurement of neutrino oscillation parameters, neutrinos from astrophysical sources, such as cosmic rays, solar neutrinos and neutrinos originating from supernovae, and a world-leading search for proton decay.

The design of the HK far and intermediate water Cherenkov detectors, the status of their construction and the expected physics capabilities of the experiment will be described.

1 Introduction

The Hyper-Kamiokande (HK) detector [1] is the next generation water Cherenkov detector in Kamioka, Japan, with an accelerator and near detector complex at J-PARC in Tokai, Ibaraki prefecture. The far detector will contain 258 kton of water, with a fiducial mass about 8 times larger than Super-Kamiokande (SK). The baseline detector includes 20,000 50 cm photomultiplier tubes (PMT), about 1,000 multi-PMT modules and about 3,600 outer detector 7.6 cm PMTs with wavelength shifting (WLS) panels. The HK project also includes a neutrino beam, a near detector and an intermediate water Cherenkov detector at the J-PARC facility.

HK is both a microscope and a telescope. It will measure the properties of neutrinos in neutrino oscillation and scattering measurements and perform a search for proton decay that will probe Beyond Standard Model (BSM) physics. Neutrino oscillation measurements from accelerator [2], atmospheric [3] and solar neutrinos [4, 5] will probe matter effects, the neutrino mass ordering, CP violation in neutrinos and will search for sterile neutrinos and non-standard interactions. Furthermore, it will perform unprecedented searches in neutrino astrophysics, by searching for supernova bursts [6], pre-supernova neutrinos [7] and supernova relic neutrinos.

Neutrino oscillations are now well established as due to mixing between the neutrino flavour states $(\nu_e, \nu_\mu, \nu_\tau)$ and neutrino mass states (ν_1, ν_2, ν_3), through the PMNS matrix relevant for Dirac neutrinos:

$$U_{PMNS} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}, \tag{1}$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$, where θ_{ij} are the neutrino mixing angles, and δ_{CP} is the complex CP-violation phase. The probability for ν_μ to ν_e oscillation in the three-neutrino picture is given by

$$\begin{aligned} P_{\nu_\mu\to\nu_e(\bar{\nu}_\mu\to\bar{\nu}_e)} = {} & \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2\left[(A-1)\,\Delta_{31}\right] \\ & \mp \alpha\frac{J_0\sin\delta_{CP}}{A\,(1-A)}\sin\Delta_{31}\sin\left(A\Delta_{31}\right)\sin\left[(1-A)\,\Delta_{31}\right] \\ & + \alpha\frac{J_0\cos\delta_{CP}}{A\,(1-A)}\cos\Delta_{31}\sin\left(A\Delta_{31}\right)\sin\left[(1-A)\,\Delta_{31}\right] \\ & + \alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2(A\Delta_{31}), \end{aligned} \tag{2}$$

where $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$, with $\Delta_{ij} = \Delta m^2_{ij}L/4E$, $A = (-)\,2\sqrt{2}G_F n_e E/\Delta m^2_{31}$ and $J_0 = \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$, and where $\Delta m^2_{ij} = m^2_i - m^2_j$. Differences between neutrino and antineutrino oscillations are a sign of CP violation after taking into account any matter effects.

While the mixing angles are relatively well known, there are remaining questions: what is the CP-violation phase, what is the mass ordering (the sign of Δm^2_{13}) and whether θ_{23} is maximal?

2 Detector

The HK far detector consists of a water tank, with a diameter of 68 m and a depth of 71 m, for a total of 258 kton of water (Figure 1, Left). There will be a new Intermediate Water Cherenkov Detector (IWCD), with a diameter of 8 m and a depth of 6 m. The main characteristic of this detector is that it will be able to move vertically to span a beam off-axis angle range from 1° – 4°, in order to change the mean neutrino energy and constrain the ν_e and $\bar{\nu}_e$ cross sections in a wide energy range (Figure 1, Right).

The neutrino beam is offset by a 2.5° off-axis angle with respect to the HK far detector and the ND280 near detector, achieving a maximum neutrino flux at the oscillation maximum

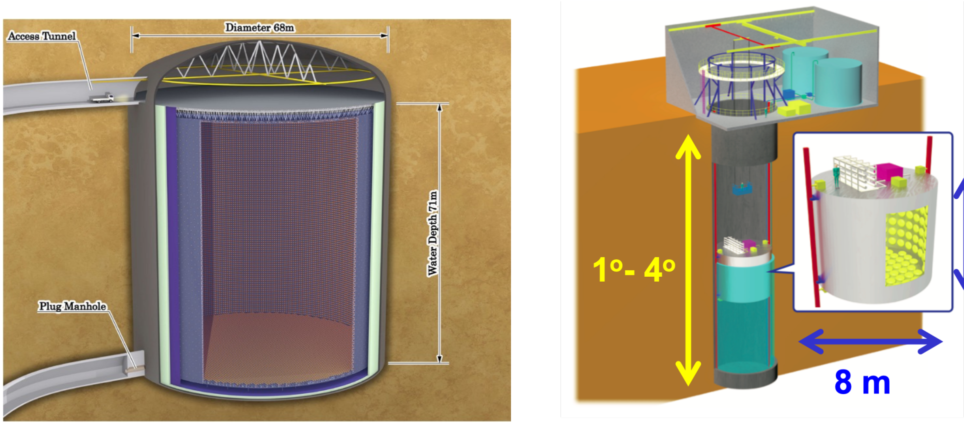

Figure 1: (Left) HK far detector. (Right) Intermediate water Cherenkov detector.

of 0.6 GeV. The neutrino beam at the J-PARC accelerator centre is also being upgraded from 515 kW to 1.3 MW. There is a power supply upgrade that delivers a current of 320 kA to the magnetic horns of the beamline, compared to the existing 250 kA, and the duty cycle of the accelerator will be reduced from 2.48 s/cycle to 1.32 s/cycle and then to 1.16 s/cycle.

The ND280 is currently being upgraded [8] to include a new Super-Fine Grained Detector (SFGD) with about 2 million 1 cm^3 scintillator cubes read out by wavelength-shifting fibres and multi-pixel photon counters (MPPC), a high-angle TPC to measure the momentum of high-angle tracks and a Time-of-Flight system. These systems reduce the proton tracking threshold down to 300 MeV, give sensitivity to neutron detection and increase the acceptance of ND280 at all angles, with about a 70% detection efficiency.

Data taking is scheduled to start in 2027. The access tunnels are completed and cavern excavation has also commenced. The centre of the dome was reached in June 2022. The cavern dome is being excavated in consecutive rings, with the first to fourth rings complete and good progress being made on the fifth ring (as of August 2023). Therefore, the excavation of the dome and the civil engineering is on track.

There will be 20,000 Hamamatsu 50 cm box-and-line PMTs installed on a frame surrounding the Inner Detector (ID). PMT production and quality assurance has already started. Furthermore, there will also be about 1,000 multi-PMT modules for the ID, consisting of 19 7.6 cm Hamamatsu PMTs each module, which will provide better timing and vertex resolution performance. Finally, there will be about 3,600 Outer Detector (OD) 7.6 cm PMTs with wavelength shifting panels to veto cosmic muons and other radioactive and cosmogenic background from the walls of the cavern. There have been ongoing studies to optimise the number of OD PMTs, by using ID reconstruction.

Front-end electronics will be placed in underwater vessels. There are two types of underwater electronics vessels being considered: one fully ID vessel, containing two digitizer printed circuit boards (PCB) that read out 24 ID channels, and a hybrid outer and inner detector vessel, with two ID digitizer PCBs reading out 20 ID channels and two OD digitizer PCBs reading out 12 OD channels. Inside the vessels, there will also be high-voltage and low-voltage power supplies, and data processing and timing boards that link up to external Global Positioning Systems.

3 Physics sensitivity

The sensitivity to the 5σ discovery of CP violation, assuming a neutrino beam-antineutrino beam weighting of 1:3, is shown in Figure 2. With optimistic systematic uncertainties and known mass ordering (MO), one expects to achieve 5σ sensitivity to exclude CP conservation in about 2-3 years. After 10 years of operation, 60% of the δ_{CP} values will be excluded at more than 5σ.

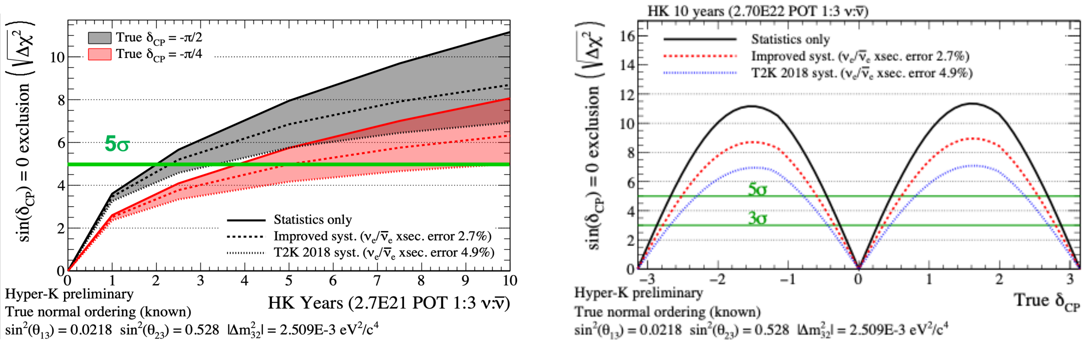

Figure 2: (Left) HK CP sensitivity. (Right) HKδ_{CP} phase coverage.

By measuring the direction of the provenance of atmospheric neutrinos, the path-length of neutrinos through the Earth can be measured, and this is sensitive to the MO [4]. There is an enhancement of the probability for $\nu_\mu \to \nu_e$ for normal ordering (NO) and $\bar{\nu}_\mu \to \bar{\nu}_e$ for inverted ordering (IO). The sensitivity to the 5σ discovery of CP violation, by adding the atmospheric neutrino samples, assuming a neutrino-antineutrino beam weighting of 1:3, with and without the knowledge of the MO, can be seen in Figure 3. After 10 years of operation, the mass ordering can be determined with 4σ - 5σ (Figure 4, Left).

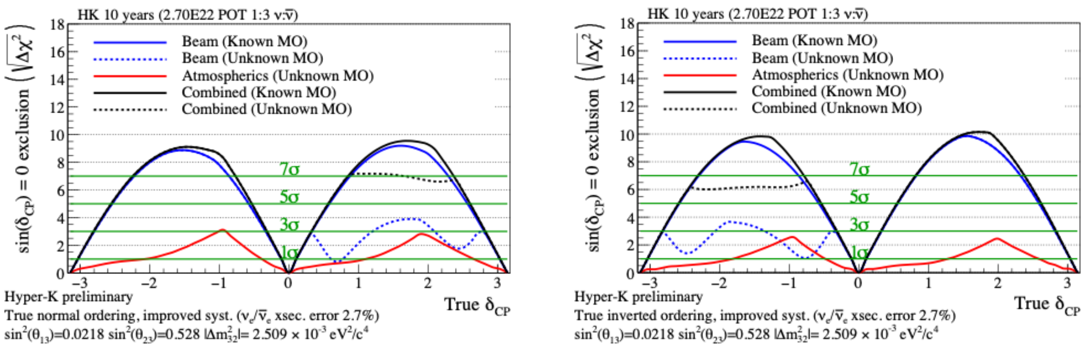

Figure 3: HK CP violation sensitivity with atmospheric neutrino samples for Normal Ordering (Left) and Inverted Ordering (Right).

Solar neutrino oscillations are enhanced by matter (MSW) effects as a function of energy. Low-energy solar neutrinos from the pp chain, ^{7}Be and proton-electron capture (pep) have higher survival $\nu_e \to \nu_e$ probability than those from the higher energy ^{8}B decay, which are dominated by the MSW effect. HK will collect data in the intermediate energy range between 2 MeV to 7 MeV, to determine the upturn curve, which is sensitive to new physics models, such as the inclusion of sterile neutrinos or non-standard interactions [5]. The upturn discovery sensitivity depends on the HK energy threshold, and is shown in Figure 4 (Right).

HK is sensitive to neutrinos from core-collapse supernova bursts and to the integrated relic supernova neutrino background [9]. It also has sensitivity to the pre-supernova phase of the star, due to silicon burning, approximately two days before the core collapse. Sensitivity can be enhanced if HK is loaded with gadolinium, to increase neutron efficiency.

As an example of the typical event rates expected, if Betelgeuse were to collapse, it would generate $\sim 10^8$ events. A supernova in the galactic centre ($\sim$ 10 kpc) would generate 50k-90k events, in the Large Magellanic Cloud ($\sim$ 50 kpc) about 3,000 events and in the Andromeda (M31) galaxy, which is at a distance of 780 kpc, we expect about 10 events (Figure 5, Left).

HK also has sensitivity to the integrated Supernova Relic Neutrino (SRN) background, which is the diffuse rate of neutrinos coming from all past supernovae. Below 16 MeV the solar neutrino signal dominates, and above 30 MeV the rate is dominated by atmospheric neutrinos. We

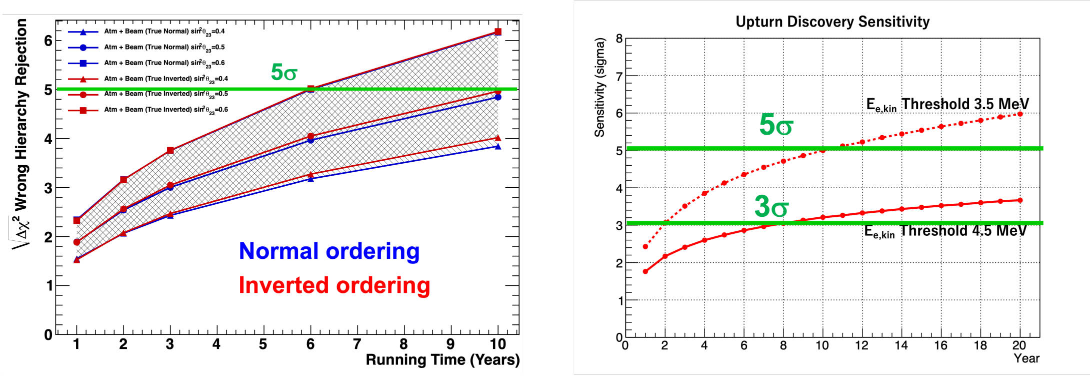

Figure 4: (Left) HK mass ordering sensitivity. (Right) Solar neutrino upturn sensitivity as a function of neutrino energy threshold.

expect about 200 supernova relic neutrinos in the 16-30 MeV window, with a 6 MeV neutrino temperature (Figure 5, Right).

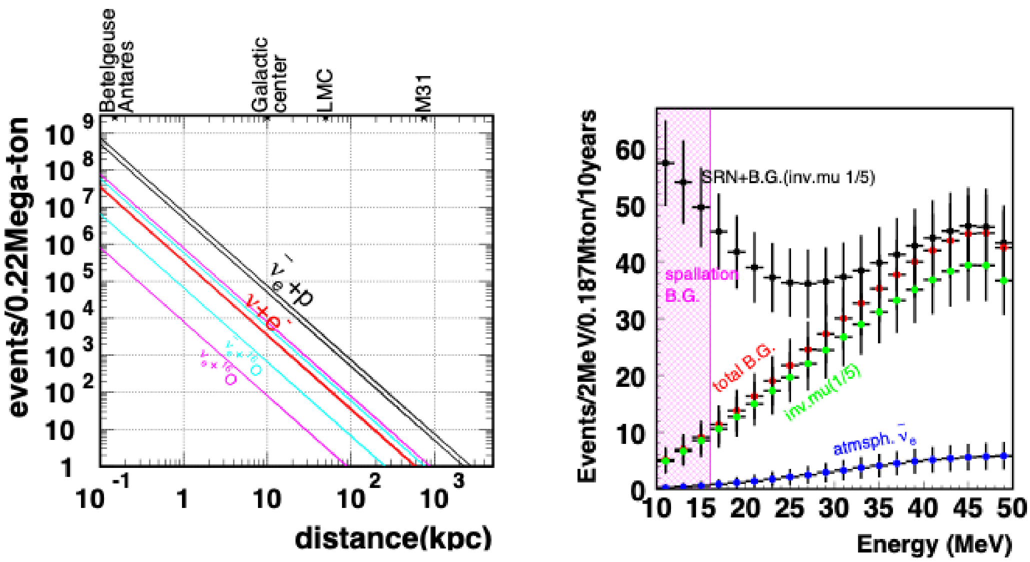

Figure 5: (Left) Number of events in HK for a core collapse supernova as a function of distance. (Right) Relic Supernova Neutrino background rate over 10 years in the 16-30 MeV energy range.

Finally, HK will produce world-leading sensitivity in the search for proton decay, which would be evidence of Beyond Standard Model (BSM) and Grand Unified Theories (GUT). Examples of proton decay sensitivity in the most sensitive $p \to e^+\pi^0$ mode and the $p \to \bar{\nu}_e K^+$ decay mode can be seen in Figure 6. One can reach proton decay lifetime sensitivity in excess of 10^{35} years from 10 years of data taking.

4 Conclusion

HK is the next generation water Cherenkov detector under construction in Japan. It will produce world-leading results in neutrino oscillations, including a search for CP violation (with 5σ sensitivity in 60% of δ_{CP} values) and determination of the neutrino mass ordering. It will also produce world-leading results in solar and atmospheric neutrinos, core-collapse supernova burst neutrinos and supernova relic neutrinos. Furthermore, it will deliver world-leading proton decay searches with an expected lifetime sensitivity that will exceed 10^{35} years in 10 years of data taking.

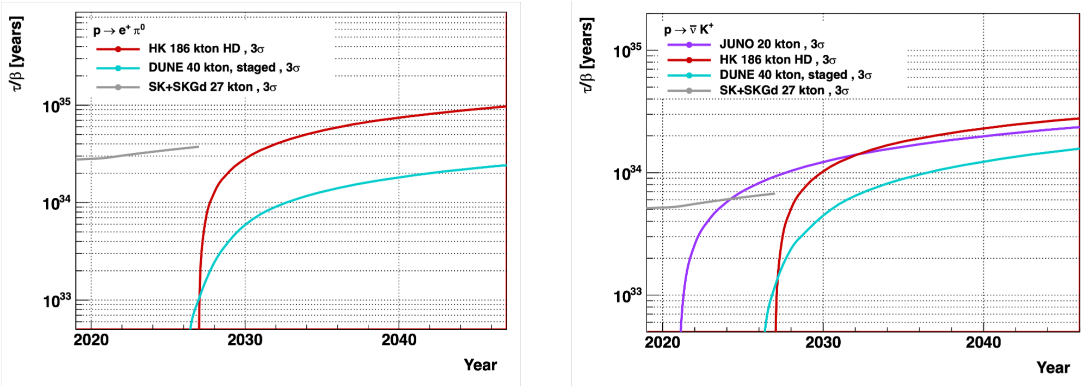

Figure 6: Proton decay lifetime sensitivity for $p \to e^+\pi^0$ (Left) and $p \to \bar{\nu}_e K^+$ (Right).

HK construction is on schedule, with expected first commissioning and data taking in 2027. It will be the world's largest underground facility, with a 258 kton water Cherenkov detector. All civil engineering is on track, and photomultiplier production and quality assurance is currently under way. The electronics will be housed in underwater electronics vessels to read out the 20,000 ID PMTs and about 3,600 OD PMTs. The $\sim 1,000$ multi-PMT modules (19 PMTs per module) will have their own internal readouts. HK will also benefit from an upgraded neutrino beam of 1.3 MW, a near detector upgrade and a new intermediate water Cherenkov detector.

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