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The Hyper-Kamiokande experiment: Status and prospect

Umut Kose, on behalf of Hyper-Kamiokande collaboration

ETH Zurich, Institute for Particle physics and Astrophysics, Zurich, Switzerland

Umut.Kose@cern.ch

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Abstract

Hyper-Kamiokande is the next-generation neutrino observatory, aiming to tackle a broad spectrum of physics programs. These include probing leptonic CP violation through long baseline accelerator neutrino oscillations, determining neutrino mass ordering, potentially discovering the proton decay, and capturing neutrinos from supernova relics, other astrophysical sources, and the sun. As the world's largest underground Cherenkov detector, Hyper-Kamiokande boasts a fiducial volume eight times that of its predecessor, Super-Kamiokande. With 258 kton of ultrapure water as its medium, Hyper-Kamiokande is scheduled to begin its groundbreaking operations in 2027, located in Kamioka, Japan. This proceeding outlines the ambitious physics program of Hyper-Kamiokande, details of the design of the detector, and provides an update on its current status.

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1 Introduction

The Hyper-Kamiokande (Hyper-K) detector is a next-generation underground water Cherenkov detector [1], following the legacy of the Super-Kamiokande (Super-K) experiment [2]. It will function as a far detector of the long baseline neutrino experiment using the upgraded J-PARC neutrino beam [3]. The experiment is focused on the determination of CP violation, and will also be capable of searching proton decay, atmospheric neutrinos, and neutrinos from astronomical origins.

The Hyper-Kamiokande Far Detector is a 68 m diameter and 71 m in height cylindrical-shaped water tank filled with 258 ktons of ultrapure water. The detector will be located in a new cavern, under construction, located about 8 km south of Super-K under the peak of Mt. Nijugoyama, with 650 m of rock, an overburden of 1750 meters water equivalent. The intensive geological surveys and site preparation work were launched in 2020. The cavern excavation has started and the access tunnel has been completed in June 2022. The center of the cavern dome was reached in June 2023, marking to be the largest human-made underground

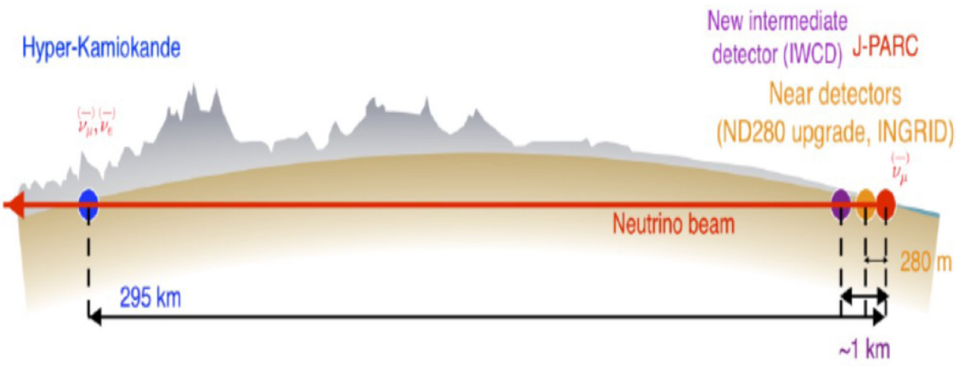

Figure 1: Hyper-K infrastructure and baseline. Adapted from [4], copyright: Jan Kisiel for the Hyper-Kamiokande collaboration.

space. The Hyper-K experiment will start collecting data for physics oscillation measurements in 2027 with full configuration, i.e. both the near detectors and far detector fully operative, with the potential of CP violation (CPV) discovery a few years after the start of data taking.

2 The Hyper-Kamiokande experiment

The experiment includes a neutrino beamline, near detector complex, and an intermediate water Cherenkov detector, and the far detector Hyper-Kamiokande as depicted in Figure 1.

Neutrino and antineutrino beams at J-PARC, located in Tokai, are produced by impinging 30 GeV protons onto a graphite target. The proton accelerator at J-PARC underwent a major upgrade to progressively enhance the neutrino beam intensity by increasing the beam power from 515 kW to 1.2 MW by 2027 and then reaching a maximum power of 1.3 MW in 2028. These upgrades include upgrading the power supply from 250 kA to 320 kA, delivering to the magnetic horns of the beamline, and improving the focusing of the produced particles. Furthermore, the operational duty cycle of the accelerator has been refined, reducing from 2.48 s/cycle to 1.32 s/cycle and then with subsequent adjustment to 1.16 s/cycle.

Hyper-K will inherit the existing near detector complex situated 280 m from the neutrino target, located within the J-PARC neutrino beam line. This complex includes the INGRID on-axis detector [5], consisting of an array of iron-scintillator modules arranged in a cross shape centered on the beam axis. INGRID monitors the direction and intensity of the neutrino beam by measuring the neutrino interaction rates in each module. Moreover, the T2K off-axis near detector, called ND280, is located at 2.5 degrees off-axis to characterize the neutrino beam before oscillation occurs as well as to measure interaction cross-sections. The ND280 underwent a major upgrade [6] consisting of installing three novel detectors. The neutrino active target, known as SuperFGD, is made of optically isolated scintillator cubes read out in three orthogonal directions, improving hadron reconstruction. SuperFGD is placed between two high-angle time projection chambers detecting and reconstructing large-angle outgoing charged particles. The entire structure is then surrounded by the time-of-flight detector, providing the accurate time of the charged particles and improving the reconstruction of their direction as well as the particle identification. This upgrade allows to reduce the systematic uncertainties associated with neutrino beam flux and neutrino cross-sections for neutrino oscillation studies.

Additionally, a new Intermediate Water Cherenkov Detector (IWCD) [7], with an inner detector with a diameter of 8 m and a height of 6 m, providing 300 t fiducial volume, will be constructed and placed at a distance of 1 km from the neutrino target. The IWCD will be equipped with 500 multi-PMT photon detector modules. Thanks to better timing, it will allow to improve the neutrino-nucleus interaction vertex resolution. The detector, based on the "PRISM" technique, moving vertically, will scan the neutrino beam at different off-axis angles from 1^o to 4^o to provide neutrino fluxes peaked from 0.4 GeV to 1 GeV. The neutrino energy measured spectra at different positions of IWCD, which depend on the neutrino flux and the neutrino cross-sections, can be combined to extract information about the cross-sections. Relatively large ν_e samples can be obtained at further off-axis angles due to the 1% intrinsic ν_e contamination produced by hadron decays, helping constrain the relative ν_e and ν_μ interaction cross sections.

The Hyper-K far detector is located at the baseline of 295 km and 2.5 degrees off-axis so that the neutrino beam is centered on the first oscillation maximum at 0.6 GeV. The detector is divided into two optically separated parts: the "Inner Detector" (ID) as the main active volume (fiducial volume of 188 kton), and the "Outer Detector" (OD), covering the ID to act as a veto against incoming particles. In Hyper-K, charged particles passing through the ultrapure water emit Cherenkov light, detected by ultrasensitive photosensors, photomultiplier tubes (PMTs), mounted on the support frame. The ID will be surrounded by 20000 20-inch diameter PMTs, providing the time of reconstructed neutrino interaction vertex, the energy loss by charged particles, and their momentum. This will provide photo-coverage of 20% of the ID cylindrical surface. In the OD part 3600 outward-looking 3-inch diameter PMTs with wavelength shifting plates will be installed to identify and reject the cosmic-ray muon backgrounds.

2.1 Photomultiplier tubes for Hyper-K

Hyper-K's 20-inch PMT (Hamamatsu Photonics R12860) is an evolution of Super-K 20-inch PMTs (Hamamatsu Photonics R3600). It is a box-and-line dynode PMT, providing a more uniform drift path for electrons, improving the time resolution, and reducing the probability that an electron misses the first dynode, improving the collection efficiency. Compared to Super-K 20-inch PMT, it has two times higher photodetection efficiency with a lower dark count rate (∼4 kHz compared to 5 kHz), a twice better charge resolution (∼30% to ∼60%), better timing resolution (1.5 ns), and almost twice the water pressure tolerance (1.25 MPa). The quantum efficiency of the photocathode is about 30% compared to 22% at the peak wavelength of about 400 nm.

In addition to 20-inch PMTs, the ID part will be equipped also with 800 multi-PMTs, consisting of 19 3-inch PMTs (Hamamatsu Photonics R14374) in a pressure-tight housing based on a concept designed by KM3Net. It will allow both to increase overall the light collection and with their higher granularity improve the vertex resolution and the particle identification in the whole detector.

The mass production of the 20-inch PMTs launched in 2021, and more than 6000 PMTs out of 20000 already delivered to Kamioka where quality assurance and performance tests are ongoing and the details can be found elsewhere [8, 9].

2.2 Hyper-K electronics

In Hyper-K, the front-end electronics (Data Processing board and Digitizer boards), low voltage (LV) and high voltage (HV) power supply boards will be placed inside a watertight case, in an underwater pressure vessel, submerged in the water. This configuration will not only allow a short distance between the front-end electronics and photosensors but also help reduce the cable length and prevent signal deterioration. However, this implies that the front-end electronics, LV and HV power supplies will not be accessible while the water is filled, for about 10 years. Therefore a significant system test is ongoing to ensure the electronics' long-term reliability, redundancy, performance of the components, and their mechanical integration. Furthermore, the pressure and water tightness of the vessel and the cable feedthroughs are in

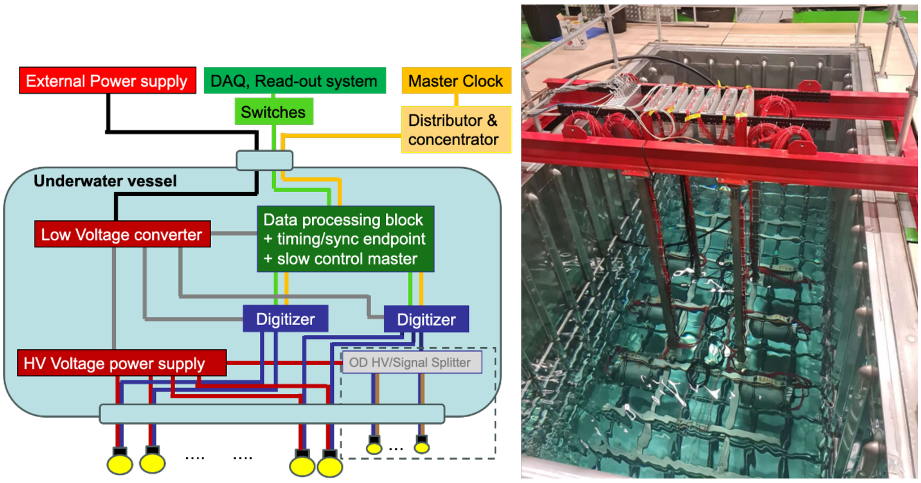

Figure 2: Left: Hyper-K underwater electronics block diagram. Right: Underwater vessel test in water.

progress. Moreover, 10-unit tests, Figure 2, are being performed by use of both dummy front-ends together with LV and HV boards and fully integrated underwater vessel to identify possible failure modes of the complete system, whether related to mechanical, thermal, or electrical interference, or due to the setup itself, as well as to study and optimize ground configurations.

Underwater electronics units will operate the ID and OD PMTs, see Figure 2. There will be two kinds of these units, one serving twenty-four 20-inch PMTs, called pure-ID, and the other serving twenty 20-inch and twelve 3-inch PMTs, called the hybrid vessel. The single underwater electronics unit provides high voltage to PMT bases (with a range of 0-2500 V), independently digitizes the analog PMT signal, and then sends it to the out-of-water Data Acquisition System via optical cable with lengths up to $\sim$150 m. The allowed power consumption and the heat dissipation of the electronics are limited by the cooling capability inside the vessel. Cooling is performed by bolting the units to the aluminum support structure and transferring major heat with the help of thermal conductive gel between them. To minimize electromagnetic interference, appropriate shielding is provided to the power supply boards.

The timing system consists of GPS receivers, a Rubidium atomic clock, a master clock generator, along with distributors, and receivers. It distributes timing signals throughout the clock distribution network, ensuring synchronization across the whole electronics with sub-ns precision. Both the GPS and the atomic clock provide a precise and stable time reference, aligning the system's clock with GPS time.

3 Physics sensitivity

Hyper-Kamiokande will perform a precise study of CPV in the lepton sector through a direct comparison of the oscillation probabilities for neutrinos and anti-neutrinos. The combination of a high-intensity beam and a massive far detector will significantly enhance the number of neutrino interactions. Moreover, the near detectors and the intermediate detector allow for constraining the systematic uncertainties related to the neutrino cross-section and flux. Hyper-K will be able to accurately determine the CP-violating phase (δ_{CP}), enabling the experiment to potentially exclude the CP conservation theory ($\sin\delta_{CP}$=0) in approximately 60% of the potential true δ_{CP} values with a five-sigma confidence level, and about 80% at a three-sigma level within five years of data collection, as shown in Figure 3. A CP violation discovery could be possible in less than three years of data taking if δ_{CP}=$-\pi/2$, or with an additional three

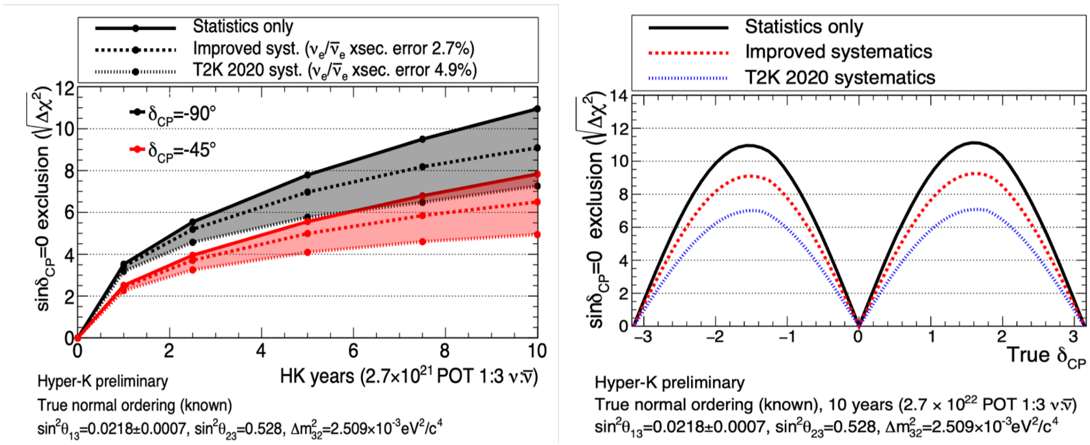

Figure 3: Left: Hyper-K CP sensitivity. Right: Hyper-K δ_{CP} phase coverage. Credit and Copyright: Plots by Denis Carabadjac & Claire Dalmazzone; The Hyper-Kamiokande collaboration (Carabadjac & Dalmazzone 2023) [10].

years for δ_{CP}=$-\pi/4$. Overall, δ_{CP} will be measured with a resolution better than 23° for any possible true value. Moreover, Hyper-K will measure the neutrino mass hierarchy with a significance between four and six standard deviations depending on the true value of $\sin^2\theta_{23}$ by combining neutrino accelerator and atmospheric data. Beyond its primary focus on long-baseline neutrino measurements, Hyper-K will provide a rich program in a wide range of science [11, 12]. Hyper-K will have the world-leading sensitivity in the search for proton decay, which may bring to the experimental proof of the Grand Unified Theories. With 20 years of data, Hyper-K will reach a proton decay sensitivity of 10^{35} years for $p \rightarrow \pi^0 e^+$ and 3×10^{34} years for $p \rightarrow \bar{\nu} K^+$.

Furthermore, Hyper-K has the potential to achieve new discoveries with observations of astrophysical neutrinos, such as solar and supernova neutrinos, and will play an important role in multi-messenger astronomy at lower energies relative to the IceCube experiment [11].

4 Conclusion

Hyper-Kamiokande will be a next-generation large water Cherenkov detector, filled with 258 kton ultrapure water, being the world's largest underground facility. Hyper-K is currently in the construction phase and its operations are scheduled to start in 2027. Hyper-K will benefit from upgraded neutrino beam of 1.3 MW, as well as upgraded near detector and new intermediate water Cherenkov detector.

With its increased fiducial mass and improved detection capabilities, Hyper-K will produce world-leading results in neutrino oscillations, including a search for CP violation with 5σ sensitivity in 60% of δ_{CP} values, as well as determining the neutrino mass hierarchy. In addition, it will deliver the world-leading nucleon decay searches with an expected lifetime sensitivity exceeding 10^{35} years in 10 years of data taking. Beyond long baseline neutrino oscillation studies, Hyper-K will precisely study atmospheric and solar neutrinos as well as search for neutrinos from other astronomical sources, including Supernova.

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