Hyper-Kamiokande

Y. Kudenko on behalf of the Hyper-Kamiokande Proto-Collaboration

\textit{a} Institute for Nuclear Research of RAS, 60 October Revolution Pr 7a, Moscow, Russia  
\textit{b} Moscow Institute of Physics and Technology, Institutskiy per. 9, Dolgoprudny, Moscow Region, Russia  
\textit{c} Moscow Engineering Physics Institute, Kashirskoe shosse 31, Moscow, Russia

E-mail: kudenko@inr.ru

ABSTRACT: A next generation water Cherenkov detector Hyper-Kamiokande to be built in Japan is described. The main goals of this project include a sensitive measurement of CP violation in neutrino oscillations, a search for proton decay and study of solar, atmospherics and astrophysical neutrinos. Key features of the Hyper-Kamiokande detector are described. The main emphasis is put on large photosensors. The recent progress in development of near neutrino detectors is also presented.

KEYWORDS: Neutrino detectors; Cherenkov detectors; Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others); Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)
1 Introduction

A next generation underground water Cherenkov detector Hyper-Kamiokande is being developed by an international collaboration as a leading worldwide experiment to address fundamental unsolved questions in particle physics and cosmology [1, 2]. It will be used as a far neutrino detector in the long baseline experiment with the intensive neutrino and antineutrino beams from the upgraded Japan Proton Accelerator Research Complex (J-PARC). The main goal of these measurements is a sensitive search for CP violation in the leptonic sector of the Standard Model. As seen from figure 1, which shows the expected significance to exclude $\delta_{CP} = 0$ or $\pi$ (the CP conserving cases) after 10 years of data taking, CP violation in neutrino oscillations can be observed with $\geq 5 \sigma$ significance for 57(80)% of the possible values of $\delta_{CP}$. Exclusion of $\delta_{CP} = 0$ can be obtained with a significance of $8 \sigma$ in the case of maximal CP violation with $\delta_{CP} = -\pi/2$. Hyper-Kamiokande will also increase existing sensitivity to proton decay predicted in Grand Unified Theories by an order of magnitude. Atmospheric neutrinos will be used to study the neutrino mass hierarchy. Hyper-Kamiokande will provide the conclusive evidence of the day-night solar flux asymmetry and will make a sensitive measurement of the solar neutrino spectrum upturn. The excellent ability of Hyper-Kamiokande to distinguish the charge current $\nu_\mu$ and $\nu_e$ interactions allows the detector to test the mass hierarchy in both $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ channels. In the case of a nearby Supernova, Hyper-Kamiokande will observe a large number of neutrino events, providing important experimental results to understand the mechanism of the explosion. Hyper-Kamiokande will help to improve our understanding of some phenomena in the Universe by detecting astrophysical neutrinos from sources such as dark matter annihilation, gamma ray burst jets, and pulsar winds.
Figure 1. Expected significance to exclude CP conservation ($\delta_{CP} = 0$ or $\pi$) for the normal mass order. The significance is calculated as $\sqrt{\Delta \chi^2}$, where $\Delta \chi^2$ is the difference of $\chi^2$ for the trial value $\delta_{CP}$ and for $\delta_{CP} = 0$ or $\pi$. The smaller value of difference is taken.

Figure 2. Schematic view of the Hyper-Kamiokande detector.
2 Hyper-Kamiokande detector

Hyper-Kamiokande is based on the proven technology of the highly successful Super-Kamiokande detector [3]. The Hyper-Kamiokande detector (figure 2) will be located in a new cylindrical shaped cavern that will be excavated at the Tochibora mine, about 8 km south of Super-Kamiokande, with an overburden of 1750 m.w.e. It will consist of the cylindrical tank (73 m high and 69 m in diameter) and have a total (fiducial) mass of 237 (187) kton, making it 5 (7.5) times larger than its predecessor Super-Kamiokande. Similar to Super-Kamiokande, an outer detector with the layer width of 1 m will help to constrain the external background. Hyper-Kamiokande will be the largest underground water Cherenkov detector in the world and will be instrumented with 40000 newly developed high-efficiency and high-resolution PMTs in the baseline design. The detector will be filled with highly transparent ultra-pure water with a light attenuation length of above 100 meters is expected to be achieved.

The water volume of the tank contains two photo-sensitive segments optically separated by a 60 cm thick insensitive region. The inner segment called the Inner Detector (ID) has a cylindrical shape of 67 m in diameter and 69 m in height. This main active volume is viewed by an array of inward-facing 40000 50 cm PMTs. The outer segment monitored by outward-facing photosensors (15000 7.5 cm PMTs) called the Outer Detector (OD), which acts mainly as a veto for entering particles such as cosmic muons. The OD water thickness is 1 meter in the barrel region and 2 meters in the top and bottom regions as shown in figure 3. Because of the lower density of OD photosensors, the photocathode coverage of the OD wall is expected to be about 1%. The

![Figure 3](image)

**Figure 3.** The Hyper-Kamiokande bottom region: the Inner Detector (ID) with the barrel and bottom regions of the Outer Detector (OD) are shown.
photosensors for ID and OD are mounted on a stainless steel supporting framework. The space between the ID PMTs is lined with opaque black sheets to prevent light leaks, while the gaps between the OD photosensors are lined with reflective sheets to enhance light collection in OD. The design of the Hyper-Kamiokande water purification system will be based on the current Super-Kamiokande water system. In order to keep the water transparency the circulation of water should occur at a speed of about 300 tons/hour. The radon concentration in the tank is expected to be below 1 mBq/m³.

3 New photodetectors

In order to achieve broad scientific goals, particles with a wide range of energies should be reconstructed. The number of Cherenkov photons that hit each photosensor ranges from one to several hundred. Thus, the photosensors are required to have a high photon detection efficiency, a wide dynamic range, a low dark rate, and a good linearity. The location of the neutrino interaction vertex is reconstructed using the Cherenkov photon arrival timing information at each PMT. Therefore, good timing resolution of photosensors is essential, and the jitter of the transit time is required to be less than 3 ns (1σ) for a single photon. The dark rate of about 4 kHz at the temperature of the Hyper-Kamiokande water is required for the solar neutrino measurements with low energy threshold. To meet these requirements, a new 50 cm diameter Hamamatsu PMT R12860 with a Box&Line dynode has been developed for Hyper-Kamiokande. The Box&Line PMT [4] realized a high collection efficiency of photoelectrons at the first box-shape dynode, and narrow timing variation by line-focused dynodes. It has a faster time response and a better collection efficiency compared to the Venetian blind dynode Hamamatsu PMT R3600 that has been used successfully in the Super-Kamiokande detector. It is expected that the required dark rate of about 4 kHz will be obtained with a low RI glass. An improved photocathode of R12860 is expected to enable it to reach the quantum efficiency of 30% at 400 nm, about 1.4 times higher than that of the Super-Kamiokande PMTs. The photoelectron collection efficiency of R12860 is also much higher. As a result, the total efficiency for the single photon detection of Hamamatsu R12860 is almost twice higher than that of the Super-Kamiokande PMTs, as shown in figure 4. The charge resolution of single photoelectron of R12860 is evaluated to be 35%, while the transit time spread measured for single photoelectrons at a fixed threshold is about 2.6 ns (full width at half maximum). To avoid a chain implosion of the Hyper-Kamiokande PMTs in deep water a cover made of a stainless steel and a UV transparent acrylic is developed. All tests in water at the depth of up to 80 m confirmed that the cover can be used to prevent chain implosions in Hyper-Kamiokande [4]. Since the photon collection efficiency of a Box & line PMT decreases by about 3% at a magnetic field of about 200 mG perpendicular to the PMT direction, a geomagnetic field compensation coil will be used to keep the remaining magnetic field perpendicular to PMTs smaller than 100 mG. It is worth noting that 136 R12860 PMTs were installed in Super-Kamiokande instead of failed PMTs during the Super-Kamiokande refurbishment in summer 2018. As tests showed, parameters of these R12860 PMTs met the requirements of the experiment [5].

Hyper-Kamiokande performance can be improved by using new photosensors which are under development for other projects. For example, an interesting option could be a multi-PMT optical module (mPMT) based on the KM3NeT design [6]. The first prototype of such a module was built at TRUIMF [7]. It comprises of 19 Hamamatsu R14374 8 cm PMTs, as shown in figure 5.
Figure 4. The single photon detection efficiency as a function of incident positions on the photocathode of the Hamamatsu PMT R12860 developed for Hyper-Kamiokande [4]. Also shown parameters of the Super-Kamiokande Hamamatsu PMT R3600.

Figure 5. Multi-PMT optical module consisting of nineteen 8 cm PMTs.

Multi-PMTs are less sensitive to magnetic field and provide better timing resolution (about 0.6 ns) and better vertex resolution near the detector walls.

Large area PMTs based on Micro Channel Plates (MCPs) [8] initially developed for the JUNO experiment can be also used in Hyper-Kamiokande. MCP-PMTs are produced by the North Night Vision Technology Company in China. The original design of these photosensors was significantly improved: the transit time spread was reduced from 14 ns to about 5 ns and a charge peak resolution
of about 43% was obtained for a single photoelectron signal. The MCP-PMTs have the quantum efficiency of ≈ 30% at 400 nm that meets the requirements of Hyper-Kamiokande. An important feature of these devices well suited for Hyper-Kamiokande is their low sensitivity to the magnetic field.

4 Neutrino beam and the near detector complex

For oscillation measurements Hyper-Kamiokande will use the same beam line as the T2K experiment [9] with the same off-axis configuration. The neutrino beam produced by 30 GeV protons extracted from the J-PARC accelerator is aimed 2.5° away from Hyper-Kamiokande as well as from Super-Kamiokande to take advantage of the pion decay kinematics to produce a quasi-monoenergetic beam with a spectrum peaked at 600 MeV well adjusted to the first oscillation maximum for a baseline of 295 km. The beam intensity of more $2.6 \times 10^{14}$ proton-per-pulse (the pulse width is 5 μs, repetition period is 2.48 c) has been achieved in T2K, corresponding to the 515 kW beam power. After the proton driver upgrade, the beam power of the main ring is expected to reach 1300 kW with $3.2 \times 10^{14}$ protons-per-pulse and a 1.16 s repetition period by 2027, i.e. before the start of Hyper-Kamiokande.

The T2K near detector ND280 [9, 10] measures neutrino beam close enough to the pion-production target so that oscillation effects are negligible. Measurements of forward-going muons on the carbon target by the existing near detector are translated into constraints on the 4π muon angular distribution on a water target seen at Super-Kamiokande. To reduce the systematic uncertainties to ≤ 4% on the total event prediction in the far detector, in presence of oscillation, the ND280 near detector will be upgraded [11] for T2K measurements before the start of Hyper-Kamiokande and then will be used for measurement of CP asymmetry in neutrino oscillations in Hyper-Kamiokande. An intermediate water Cherenkov detector (IWCD) based on the design of the NuPRISM detector [12] is proposed to be constructed at a distance of 1-2 km from the target. It will measure muon and electron neutrino (antineutrino) cross sections on water with the same solid angle as the far detector. A combination of data obtained in both the magnetized ND280 detector and IWCD will help to further reduce systematic uncertainties in oscillation measurements.

4.1 ND280 upgrade

The upgrade keeps the current ND280 tracker, i.e. three vertical TPCs and two FGDs. The main part of the POD detector will be replaced by a new highly granular fully active scintillator neutrino detector, two new TPCs, and time-of-flight (TOF) planes. The highly granular scintillator detector SuperFGD of a mass of about 2 tons is comprised of ~ $2 \times 10^6$ small scintillator cubes with 1 cm side, each read out with WLS fibers in the three orthogonal directions coupled to compact photosensors, Micro Pixel Photon Counters. SuperFGD will serve as an active neutrino target and a 4π detector of charged particles from neutrino interactions. SuperFGD is sandwiched between two High-Angle TPCs, readout by resistive Micromegas detectors, with a compact and light field cage. These detectors are surrounded by six large TOF planes to determine the track direction and improve the particle identification, as shown in figure 6. SuperFGD (see figure 6 (right)) is an innovative device with excellent detector performance. The beam tests at CERN PS showed that a MIP crossing a single cube produces about 40 photoelectrons per WLS fiber in realistic conditions. The timing resolution per fiber is obtained to be better than 1 ns [13, 14]. SuperFGD has a very good
capability to track muons, pions and protons stopping in this detector over $4\pi$ solid angle. Moreover its high granularity will allow us to distinguish electrons produced by electron neutrino interactions from converted photons. Studies are ongoing to evaluate the SuperFGD potential to detect neutrons. Beam tests of a High-Angle TPC prototype at CERN also showed good performance of resistive Micromegas detectors: excellent uniformity of the gain, a deposited energy resolution $dE/dx$ of about 9%, and a spatial resolution of better than 300 $\mu$m were obtained [15].

4.2 Intermediate water Cherenkov detector

The baseline design of IWCD considers the location of the detector at about 1 km downstream of the neutrino interaction target in a 50 m deep shaft. The detector must span the off-axis range $1^\circ$–$4^\circ$ and its diameter should be large enough to contain the required muon momentum of 1 GeV/c. This corresponds to a 50 m tall tank with a 6 m diameter inner detector and a 10 m diameter outer detector, as shown in figure 7. The novel feature of this detector is the ability to raise and lower the instrumented section of the tank in order to span the full off-axis range. The inner detector will be instrumented with multi-PMT optical modules described in section 3. Compact size and high timing resolution of 8 cm PMT’s will allow us to improve the vertex resolution and particle identification in comparison with Box&Line PMTs.

5 Conclusion

The Hyper-Kamiokande project is officially approved and the detector is expected to be constructed and ready for physics measurements in 2027. This new experiment is based on the experience and facilities of the already existing and very successful Super-Kamiokande and T2K and will use novel photosensors for detection of the Cherenkov light. The J-PARC proton accelerator will be upgraded to reach a MW beam for Hyper-Kamiokande. A complex of near detectors which includes the upgraded ND280 detector and IWCD will be of great importance for a sensitive search for CP violation in neutrino oscillations. Hyper-Kamiokande will be a multipurpose neutrino detector with a rich physics program that includes the observation of the leptonic CP violation, a search for the proton decay, detection neutrinos from Supernova, and astrophysical neutrinos.
Figure 7. The configuration of the intermediate water Cherenkov detector. The instrumented section of the tank moves vertically to cover different off-axis angle regions.

Acknowledgments

This work was supported by the RFBR-JSPS grant # 20-52-50010.

References

[1] Hyper-Kamiokande proto-collaboration, Hyper-Kamiokande Design Report, arXiv:1805.04163

[2] Hyper-Kamiokande proto-collaboration, Physics potential of a long-baseline neutrino oscillation experiment using a J-PARC neutrino beam and Hyper-Kamiokande, PTEP 2015 (2015) 053C02 [arXiv:1502.05199].

[3] Super-Kamiokande collaboration, The Super-Kamiokande detector, Nucl. Instrum. Meth. A 501 (2003) 418.

[4] Y. Nishimura, New large aperture photodetectors for water cherenkov detectors, Nucl. Instrum. Meth. A 958 (2020) 162993.

[5] C. Bronner, Y. Nishimura, J. Xia, T. Mochizuki and M. Chabera, Performances of the Hyper-Kamiokande 20″ PMT, JPS Conf. Proc. 27 (2019) 011013.
[6] KM3Net collaboration, *Letter of intent for KM3NeT 2.0*, J. Phys. G 43 (2016) 084001 [arXiv:1601.07459].

[7] S. Cuen-Rochin, *Multi-photomultiplier tube module development for the next generation Hyper-Kamiokande neutrino experiment*, talk presented at 20th International Workshop on Next generation Nucleon Decay and Neutrino Detectors (NNN19), Medellin, Colombia, 7–10 November 2019.

[8] Y. Wang et al., *A new design of large area MCP-PMT for the next generation neutrino experiment*, Nucl. Instrum. Meth. A 695 (2012) 113.

[9] T2K collaboration, *The T2K Experiment*, Nucl. Instrum. Meth. A 659 (2011) 106 [arXiv:1106.1238].

[10] Y. Kudenko, *The Near neutrino detector for the T2K experiment*, Nucl. Instrum. Meth. A 598 (2009) 289 [arXiv:0805.0411].

[11] K. Abe et al., *Proposal for an Extended Run of T2K to $20 \times 10^{21}$ POT*, arXiv:1609.04111.

[12] nuPRISM collaboration, *Letter of Intent to Construct a nuPRISM Detector in the J-PARC Neutrino Beamline*, arXiv:1412.3086.

[13] O. Mineev et al., *Parameters of a fine-grained scintillator detector prototype with 3D WLS fiber readout for a T2K ND280 neutrino active target*, Nucl. Instrum. Meth. A 936 (2019) 136.

[14] O. Mineev et al., *Beam test results of 3D fine-grained scintillator detector prototype for a T2K ND280 neutrino active target*, Nucl. Instrum. Meth. A 923 (2019) 134 [arXiv:1808.08829].

[15] D. Attié et al., *Performances of a resistive MicrOMEGAs module for the Time Projection Chambers of the T2K Near Detector upgrade*, Nucl. Instrum. Meth. A 957 (2020) 163286 [arXiv:1907.07060].