PROCEEDINGS OF SCIENCE

The Hyper-Kamiokande Project

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The Hyper-Kamiokande is a project of a large water Cherenkov detector to be built in Japan. The design allows to address a wide physics program, including the studies of neutrino oscillations with the beam and atmospheric neutrinos, neutrino astrophysics and the searches for the proton decay. The article summarizes shortly the Hyper-Kamiokande technical design and the physics potential.

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1. Introduction

The Hyper-Kamiokande is a project of a next generation large water Cherenkov detectors in Japan. It will be a continuation of renown Kamiokande and Super-Kamiokande experiments, benefiting from the experience gained over the years of operation and evolving photosensor technology.

The Letter of Intent was published in 2011 and since then the effort was made to optimize the design, resulting in a Design Report submitted in March 2016 [1], where all the details on the detector technology and physics program can be found.

The project was selected as one of important large scale projects by Science Council in Japan and recently also included in the Roadmap for Large Projects of Japanese Ministry of Education, Culture, Sports, Science and Technology.

2. The technical design

The current project is to build two identical vertical tanks. The advantage of such solution is significant reduction of costs and possible building in stages. Each of the tanks will contain 260 kilotons of water with the fiducial volume of 190 kilotons (10 times larger than Super-Kamiokande). The planned dimensions of the tanks are 60 meters of height and 74 meters of diameter.

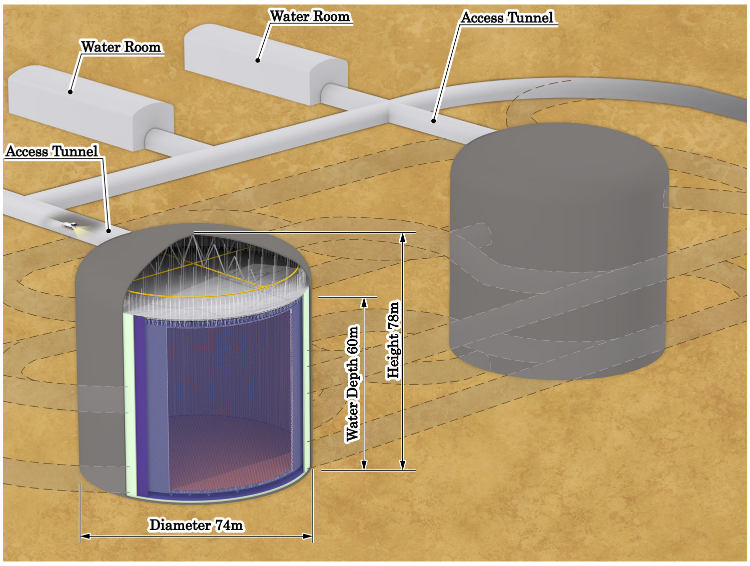

Figure 1: A schematic view of Hyper-Kamiokande tanks.

The tank will be optically divided into inner and outer detector. The inner detector will be instrumented with 40 000 large photomultipliers (PMT, 50 cm diameter), so the PMT coverage will be equal to 40%. The outer detector will be equipped with 6 700 smaller PMTs (20 cm diameter) to tag the incoming or escaping particles.

The plan is to use newly developed Hamamatsu PMTs with improved dynode system (box-and-line dynode). Their most important features are two times higher photon detection efficiency and timing resolution compared to those used in Super-Kamiokande. Thanks to that fact the detector will have better capabilities for low energy events, increasing the physics potential of Hyper-Kamiokande. The PMTs have also higher pressure tolerance, which allows them to be used in more deep tanks, although the protective cover is also foreseen. Other possible choices of photosensors are under study.

The tanks will be located in a new cavern, excavated in Tochibora mine under Mt. Nijugoyama, about 8 km south from Super-Kamiokande site. Such location ensures the same baseline (295 km) and off-axis angle (2.5°) with respect to J-PARC neutrino beam as presently in T2K experiment in which Super-Kamiokande is used as the far detector. The rock overburden in the candidate site is 648 m (1750 m water equivalent). The performed detailed geological survey showed the suitable bedrock condition.

The possible starting date of the experiment depends on the approval process. With funding assumed from 2018 the first tank should be ready and filled with water in 2025 and the second tank would start operation 6 years later.

3. Physics program

Hyper-Kamiokande has a broad physics program, including neutrino oscillation studies with atmospheric and beam netrinos, measurement of astrophysical neutrinos and the search for the proton decay, described in the following subsections. More information, also about other planned studies, such as indirect search for Dark Matter etc., can be found in [1].

3.1 Oscillations of beam and atmospheric neutrinos

The Hyper-Kamiokande plans to detect neutrinos from the ν_μ beam produced at J-PARC. The currently used accelerator will be upgraded to reach the 1.3 MW beam power before the experiment starts. The power supplies for magnetic horns will be also improved to reach the current of 320 kA (presently 250 kA) which allows to provide 10% higher neutrino flux and better reduction of wrong-sign neutrino contamination.

The expected systematic uncertainties are expected to be at the level of 3–4% thanks to the upgrade of the existing T2K Near Detector and building a new intermediate detector in water Cherenkov technology at the distance of about 1–2 km from the neutrino target [2].

One of the most interesting questions in neutrino physics is the possible violation of CP symmetry. T2K experiment provided recently some weak indications on CP violation, preferring the value of parameter δ_{CP} close to $-\pi/2$ [3, 4], but will not be able to excess 3σ level of statistical significance even with extended data taking [2].

The information on the CP violation can be extracted from the comparison of the electron (anti)neutrinos appearance probabilities for neutrinos and antineutrinos. The expected numbers of candidate appearance events in Hyper-Kamiokande with no CP violation for 10 years of exposure and 2.7×10^{22} protons on target (POT) are presented in Table 1.

If the CP violation occurs and $\delta_{CP} \approx -\pi/2$ the oscillation probability is strongly enhanced for neutrinos and suppressed for antineutrinos. The sensitivity to δ_{CP} will be improved by using not only the total number of events but also the (anti)ν_e reconstructed energy distributions which is different for different values of δ_{CP} as shown in Fig. 2.

	signal		background		
	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ, $\bar{\nu}_\mu$	intrinsic ν_e, $\bar{\nu}_e$	NC
ν mode	2300	21	10	362	188
$\bar{\nu}$ mode	289	1565	6	444	274

Table 1: Numbers of electron (anti)neutrino candidate events in Hyper-Kamiokande for 2.7×10^{22} POT. The assumed values of oscillation parameters are: $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$, normal mass hierarchy. The ν mode and $\bar{\nu}$ mode beam running time ratio is 1:3.

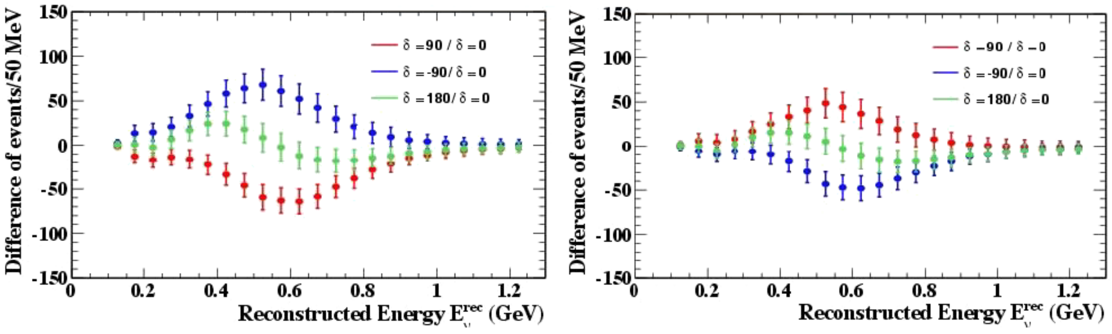

Figure 2: The difference of the recontructed (anti)ν_e energy distribution from the case with $\delta_{CP} = 0$. The error bars denote the statistical uncertainties.

In Hyper-Kamiokande the CP conservation can be excluded with 3σ (5σ) significance for 78% (62%) possible values of δ_{CP} parameter (see left plot in Fig. 3). The value of δ_{CP} can be measured with the resolution of 21° for $\delta_{CP} = \pm 90°$ and 7.2° for $\delta_{CP} = 0$ or 180° as it is shown in right plot of Fig. 3.

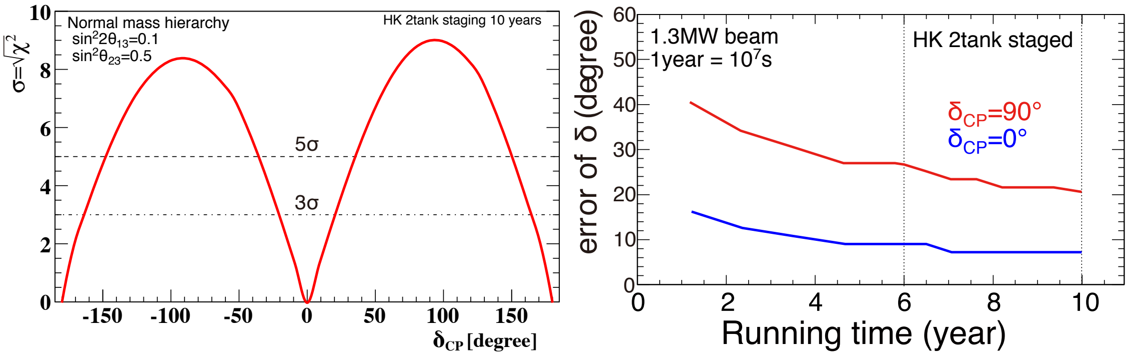

Figure 3: Expected significance to exclude $\sin \delta_{CP} = 0$ for true normal hierarchy (left). Expected uncertainty of δ_{CP} as a function of time (right).

The precise measurements of θ_{23} and Δm^2_{32} will be possible thanks to using both ν_e appearance and ν_μ disappearance channels for beam neutrinos, but also combining them with the data collected for the atmospheric neutrinos. In particular, the oscillation probability for the atmospheric neutrinos coming from below is modified by the matter effects in Earth, giving the sensitivity to the mass hierarchy. The mass hierarchy can be determined within 5 (10) years of data taking with over 3σ (5σ). The improvement is also expected for the determination of θ_{23} octant, as shown in Fig. 4.

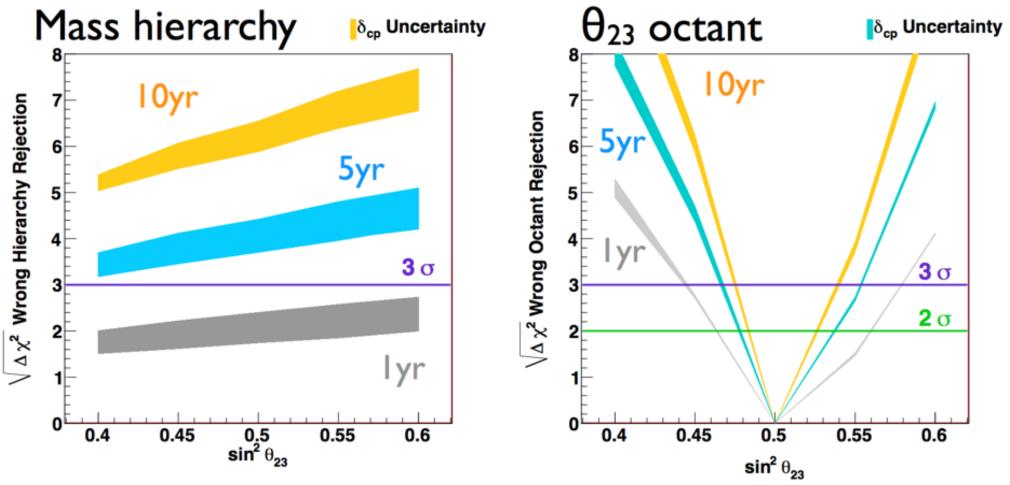

Figure 4: The expected hierarchy (left) and octant (right) sensitivity as a function of true value of $\sin^2\theta_{23}$ from combined analysis of beam and atmospheric neutrino data. The colors denote the length of exposure: 1 year (grey), 5 years (blue) and 10 years (orange).

The possibility of building the second tank in Korea is under investigation [5]. The range of possible baselines is 1000–1200 km, and the off-axis angle can be chosen in range of 1.3–3°. Such location would further enhance the sensitivity to mass hierarchy and CP violation.

The longer baseline allows to cover the second oscillation maximum in $\nu_\mu \to \nu_e$ probability. The CP asymmetry for electron (anti)neutrino appearance is there three times higher than in the first maximum, and the larger effect makes the results less sensitive to systematic errors. On the other hand, the expected number of events is much smaller because of the flux reduction.

3.2 Low energy neutrinos

The solar and supernova neutrinos are low energy events (energies of the order of few MeV), in which much smaller number of photons is emitted. Therefore the astrophysical neutrino studies will also benefit from the improved photosensors planned for Hyper-Kamiokande.

The comparison of solar and reactor neutrino oscillation measurements shows a discrepancy at the level of 2σ in the measurement of Δm^2_{21} [6] which may be caused by the regeneration of electron component inside Earth thanks to MSW effect. Although Super-Kamiokande found a 2σ indication of the day-night asymmetry in the solar ν_e flux [7], an evidence is expected to be found in Hyper-Kamiokande.

Other solar neutrinos studies planned to be performed in Hyper-Kamiokande are the short and long time variation of the ^{8}B neutrino flux, observation of *hep* component and precise measurement of the energy spectrum.

The detector will be also prepared to detect the neutrinos from possible supernova burst. With the two tanks and supernova explosion near the center of The Galaxy the expected number of events is 250 000. The elastic scattering on electrons allows to reconstruct the direction of the neutrinos and the arrival time can be precisely determined thanks to excellent timing resolution. The analysis of the neutronization peak may give the information on the mass hierarchy and the total flux of neutrinos cam be obtained from the neutral current events.

Even if the supernova explosion will not happen during the operation of Hyper-Kamiokande, the detector will still be able to detect the diffused flux of relic supernova neutrinos from past explosions.

3.3 Search for proton decay

The decay mode $p \to e^+\pi^0$ is favoured by many Grand Unified Theories. The signature of such event in Cherenkov detectors is composed of three electron-like rings coming from the positron and two photons from π^0 decay, so the final state is fully reconstructed. The planned analysis is similar to what was done in Super-Kamiokande, but with the much better reduction of atmospheric background. Such background can be tagged by the presence of neutrons, often produced in the atmospheric events, which can be detected after the capture in water with the emission of 2.2 MeV gamma: $n+p \to d+\gamma$, as it was shown by Super-Kamiokande [8]. The improved PMTs will allow to tag the prompt photon from residual nucleus deexcitation with the assumed efficiency of 70%.

Another interesting proton decay channel is $p \to \bar{\nu}K^+$, which is favoured by SUSY Grand Unified Theories. In such case, the kaon is not visible in water Cherenkov detector as it is below the Cherenkov threshold, but can be reconstructed from its decay products.

In case of the $\mu^+\nu_\mu$ decay (branching ratio 64%) the monochromatic (236 MeV) muon is accompanied by prompt photon of energy 6.3 MeV from the nucleus deexcitation. The better detection efficiency and timing resolution of Hyper-Kamiokande will allow to use such coincidence to tag the signal. Another possibility is to search for an excess in the distribution of the muon momenta.

In the $K \to \pi^0\pi^+$ decay (branching ratio 21%) the positive pion is slightly above the Cherenkov threshold. Again, the improved photosensors will allow to improve the detection of such particle.

The expected partial lifetime 90% C.L. limits after 10 years of exposure are expected to be 1.1×10^{35} years for $p \to e^+ + \pi^0$ mode and 4×10^{34} years for $p \to \bar{\nu} + K^+$ and the 3σ discovery potential as a function of time is shown in Fig. 5. For many other modes the expected improvements is basically one order of magnitude.

4. Summary

Hyper-Kamiokande, a third generation water Cherenkov detector, is based on a proven technology and plans also to gain from the newly developed photon detectors. A rich physics program covers some of the most interesting topics in particle physics and astrophysics. An international collaboration of about 300 physicists is steadily working to bring the project from idea to realization.

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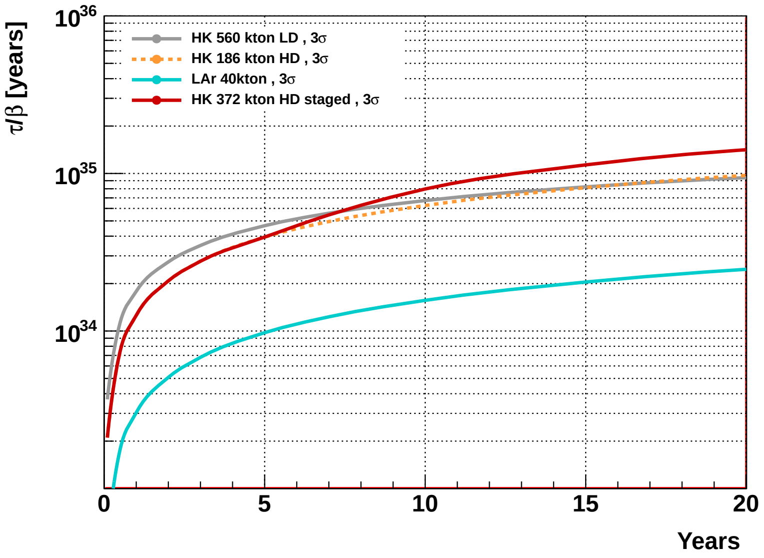

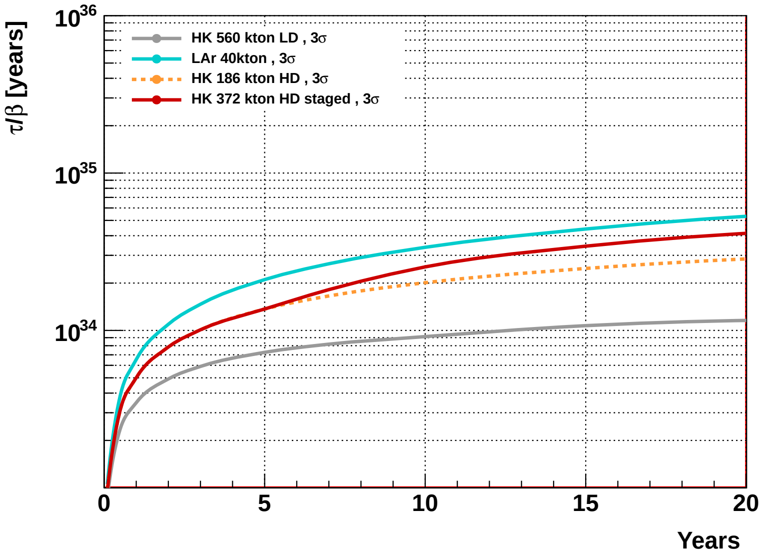

Figure 5: The 3σ discovery potential for $p \to e^+\pi^0$ (top) and $p \to \nu K^+$ (bottom) as a function of time. The red line denotes current Hyper-Kamiokande design, the grey one an other design and the cyan one a 40 kton liquid argon detector. The lines for HK include the systematic errors.

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