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The Hyper-Kamiokande Experiment

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Francesca Di Lodovico
on behalf of the Hyper-Kamiokande Collaboration

School of Physics and Astronomy
Queen Mary University of London
Mile End Road
London E1 4NS
United Kingdom

E-mail: f.di.lodovico@qmul.ac.uk

Abstract. The Hyper-Kamiokande experiment is a next generation underground water Cherenkov detector, based on the highly successful Super-Kamiokande experiment. It will serve as a far detector of a long baseline neutrino experiment for the J-PARC neutrino beam, with the main focus the determination of CP violation, and will also be a detector capable of observing - far beyond the sensitivity of the Super-Kamiokande detector - proton decay, atmospheric neutrinos, and neutrinos from astronomical sources.

1. Introduction

The Hyper-Kamiokande experiment (see Refs. [1], [2], [3]) is the next generation flagship experiment for the study of neutrino oscillations, nucleon decays, and astrophysical neutrinos. The detector is a third generation underground water Cherenkov detector. It will serve as the far detector for a long baseline neutrino oscillation experiment planned for the upgraded J-PARC (Japan Proton Accelerator Research Complex) neutrino beam as well as a detector capable of observing proton decays, atmospheric neutrinos, and neutrinos from astronomical origins enabling measurements that far exceed the current world best measurements. In the following sections, we first describe the current experimental set-up, then a description of the accelerator complex, the Hyper-Kamiokande first tank and initial proposal for a second tank, the near and far detectors, and finally the physics potential of the experiment will be described with particular focus on the sensitivity to CP violation.

2. The Experimental Set-up

The current experimental set-up of the Hyper-Kamiokande experiment foresees two cylindrical tanks with the second tank commencing operation later than the first tank. The main priority is to perform a CP violation measurement at the earliest opportunity with the first tank. The two tanks are assumed identical and at the same location for the studies presented in these proceedings. They are standing cylindrical tanks with a diameter of 74 m and height of 60 m. The total (fiducial) mass of one tank is 258 (187) kilo-tons, which is about 20 times larger than that of Super-Kamiokande and more 10 times larger than competing projects (10 times DUNE, 40 kt, or 20 times JUNO, 20 kt).

Figure 1 shows the estimated construction period of the Hyper-Kamiokande detector with the first tank. The construction for the first tank is estimated to take about 10 years including the geological survey and final design making. In parallel, a second tank should be built. The results in this proceedings assume that the second tank will become operational about 6 years after the first one. However, past studies already proposed a second tank in Korea (see e.g. [5]), and now are being revisited [6].

2.1. The J-PARC Neutrino Beam

The neutrino beam for Hyper-Kamiokande is produced at J-PARC located in Tokai Village, Ibaraki prefecture, on the east coast of Japan, 295 km from the Kamioka detector sites. The 30-GeV (kinetic energy) proton beam is extracted from the J-PARC Main Ring (MR) by single-turn fast extraction and transported to the production target after being deflected about 90° by superconducting combined function magnets to direct the beam towards Kamioka. About 80% of incoming protons interact in the target. The secondary pions (and kaons) from the target are focused by three consecutive electromagnetic horns. The focused pions and kaons enter a length decay volume (DV) filled with helium gas and decay in flight into neutrinos. The beam dump, which consists of graphite blocks followed by iron plates, is placed at the end of the DV to absorb remnant hadrons. Muon monitors (MUMONs) are placed just behind the beam dump to monitor on a spill-by-spill basis the intensity and the profile of muons > 5 GeV which pass through the beam dump.

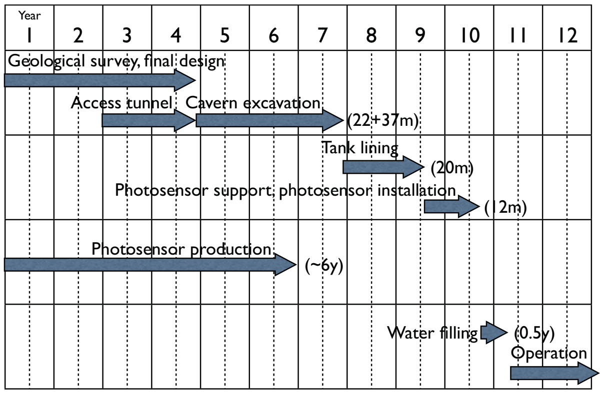

Figure 1. Construction period for the first tank.

The J-PARC neutrino beamline adopted the first ever off-axis scheme to produce a narrow energy neutrino spectrum centred at oscillation maximum to maximise the physics sensitivity. The T2K experiment is now running at a 2.5 degree off-axis angle to the Super-Kamiokande detector. The J-PARC neutrino beamline is designed to accommodate $2 \sim 2.5°$ off-axis angle at the current Super-Kamiokande and proposed Hyper-Kamiokande sites.

As of summer 2016, stable operation of the MR at 425 kW beam power has been achieved. In 2018, the design power of 750 kW will be realised by increasing the repetition rate from 1/2.48 s to 1/1.3 s by upgrading magnet power supplies, RF core and other components. Further beam power increases will require upgrades to secondary beamline components such as the beam window, target, and horns. Upgrades primarily to the RF power supply will gradually increase the number of protons/pulse (ppp) and repetition rate further to 330 Tp and 1/1.16 s, respectively, to reach > 1.3 MW by around 2025 before Hyper-Kamiokande becomes operational.

2.2. The Hyper-Kamiokande Detector

The Hyper-Kamiokande experiment employs a ring-imaging water Cherenkov detector technique to detect rare interactions of neutrinos and the possible spontaneous decay of protons and bound neutrons.

A full overview of the cavern and detector design R&D, upgraded beam and near detector suite, and expected physics sensitivities can be found in the Hyper-Kamiokande Design Report [4]. The schematic view of a tank is shown in Figure 2. The Hyper-Kamiokande detector candidate site for the first tank, located 8 km south of Super-Kamiokandeand 295 km away from J-PARC, is in the Tochibora mine, in Gifu Prefecture, Japan. The J-PARC neutrino beamline is designed so that the existing Super-Kamiokande detector in the Mozumi mine and the Hyper-Kamiokande candidate site in the Tochibora mine have the same off-axis angle. The detector will lie under the peak of Nijuugo-yama, with an overburden of 650 meters of rock or 1,750 meters-water-equivalent (m.w.e.).

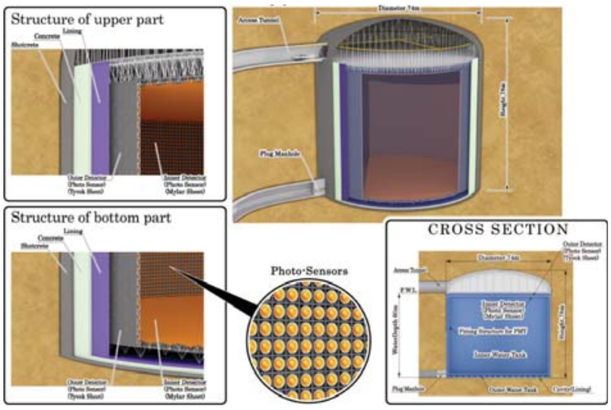

Figure 2. Schematic view for the first tank.

The Hyper-Kamiokande detector is designed to employ newly developed high-efficiency and high-resolution PMTs (Hamamatsu R12860) which will amplify faint signatures such as those of neutrons associated with neutrino interactions, nuclear de-excitation gammas and π^+ in proton decays into kaons. This increased sensitivity contributes significantly to the major goals of the Hyper-Kamiokande experiment such as clean proton decay searches via $p \rightarrow e^+ + \pi^0$ and $p \rightarrow \bar{\nu} + K^+$ decay modes and the observation of supernova electron anti-neutrinos. The inner detector region of the single tank is viewed by 40,000 PMTs, corresponding to the PMT density of 40% photo-cathode coverage (same as that of Super-K).

The detector is instrumented with front-end electronics and a readout network/computer system. The system is capable of high-efficiency data acquisition for two successive events in which Michel electron events follow muon events with a mean interval of 2 μsec. It is also able to collect the vast amount of neutrinos, which come from a nearby supernova in a nominal time period of 10 sec. Similar to Super-K, an outer detector (OD) with a layer width of 1−2 m is envisaged that, in addition to enabling additional physics, would help to constrain the external background. Sparser photo-coverage using smaller PMTs than those used for the ID is also planned.

2.3. The Second Hyper-Kamiokande Detector in Korea

The axis of the J-PARC neutrino beam emerges upwards out of the sea between Japan and Korea. The southern part of the Korean peninsula is exposed to the 1−3 degree off-axis neutrino beams with baselines of 1000−1300 km as shown in Figure 3.

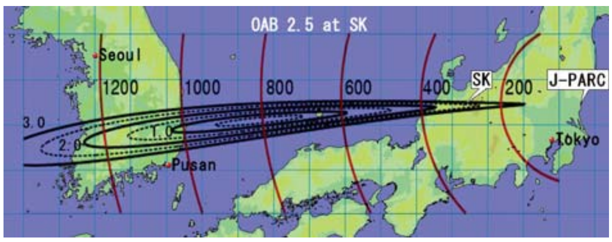

Figure 3. Contour map of the J-PARC off-axis beam to Korea.

The (anti)neutrino oscillation probabilities for a baseline of $L = 1100$ km (a typical baseline in Korea) are shown in Figure 4. In the region of the first oscillation maximum above 1.2 GeV, the matter effect has separated the oscillation probabilities for normal and inverted ordering for all values of the CP phase. In the region of the second oscillation maximum, 0.5-1.2 GeV, the CP probability differences are significant, while the matter effect also affects the height and position of the oscillation maximum. The spectra shapes for 1.5° off-axis beams are also shown for comparison. These suggest that with such a beam, it would be possible to measure the mass ordering with the high energy part of the neutrino spectrum at the first oscillation maximum, while measuring the CP phase with the second and even third oscillation maxima.

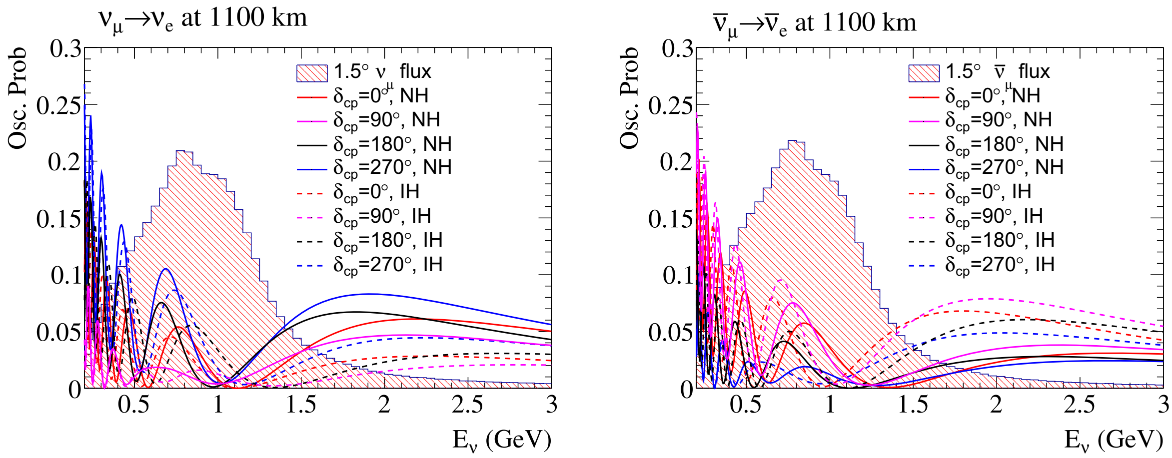

Figure 4. The oscillation probabilities for $\delta = 0, \pi/2, \pi, 3\pi/2$ and normal and inverted mass ordering are shown for neutrinos (left) and antineutrinos (right). Expected muon (anti)neutrino spectra at 1.5° off-axis with arbitrary normalisation are shown for comparison.

The two different baseline oscillation measurement at 295 km and 1100 km allows breaking the degeneracy of oscillation parameters and constrains the physics beyond PMNS paradigm. Matter effect creates a fake CP violation effect causing a difference in ν and $\bar{\nu}$ oscillations. The higher energy spectrum of the detector in Korea near the first oscillation maximum is, in particular, sensitive to the matter effect and expected to resolve the mass hierarchy better than 5σ level. Other degeneracies of δ_{CP} and θ_{23} octant or Δm^2_{31} can also be constrained. Non-standard neutrino interactions can cause additional matter effects and new physics beyond PMNS may cause distortion in the oscillation pattern. Both of these effects can be tested by the two baseline beam data.

2.4. Near and intermediate detector complex

The neutrino flux and cross-section models can be constrained by data collected at near detectors, situated close enough to the neutrino production point so that oscillation effects are negligible. Their data addresses important uncertainties in the neutrino flux or cross-section modeling.

The T2K ND280 detector suite comprises two detectors [7]: INGRID, which consists of 16 iron-scintillator modules in a cross pattern centred on the neutrino beam axis, and ND280, a multi-component detector at an angle of 2.5 degree from the beam direction. The primary purpose of the INGRID detector is to constrain the neutrino beam direction, whilst the off-axis detector is used to characterise the neutrino beam before oscillation. T2K has successfully applied a method of fitting to ND280 data with parametrised models of the neutrino flux and interaction cross-sections. Using the ND280 measurements, the systematic uncertainties on the parts of the models constrained by ND280 have been reduced to 3% on the Super-Kamiokandepredicted event rates. An upgrade of the current ND280 detector is planned before the starting of Hyper-K.

A water Cherenkov detector at about 1-2 km is proposed to be built possibly before Hyper-Kamiokande becomes operational [8], [9]. A water Cherenkov near detector can be used to measure the cross section on H_2O directly, with the same solid angle acceptance as the far

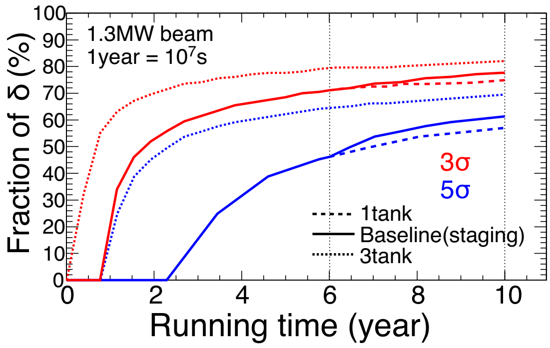

Figure 5. Fraction of δ_{CP} for which $\sin\delta_{CP} = 0$ can be excluded with more than $3\,\sigma$ (red) and $5\,\sigma$ (blue) significance as a function of the running time for the normal hierarchy case. The ratio of neutrino and anti-neutrino mode is fixed to 1:3.

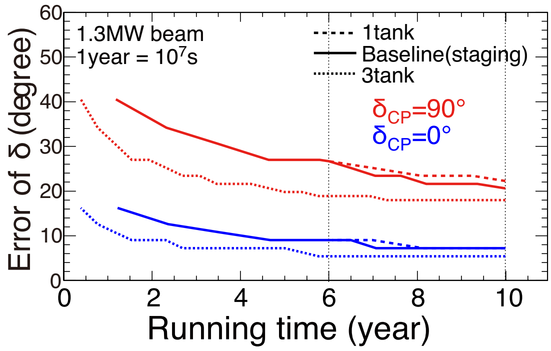

Figure 6. Expected uncertainty (half width of 68% C.L. interval) of δ_{CP} as a function of running time. For the normal hierarchy case. The ratio of neutrino and anti-neutrino mode is fixed to 1:3.

detector with no need for a subtraction analysis. Additionally, water Cherenkov detectors have shown excellent particle identification capabilities, allowing for the detection of pure ν_μ-CC, ν_e-CC and NCπ^0 samples. The CCπ^0 rate and kaon production in neutrino interactions, which are backgrounds to nucleon decay searches, can also be measured. A combination of a magnetised tracking detector such as ND280 and the water Cherenkov detector should have the largest impact to reduce systematic uncertainties.

3. Physics Potential

3.1. Accelerator-based Neutrinos

A long baseline neutrino oscillation experiment with the J-PARC neutrino beam is one of the key elements of Hyper-Kamiokande physics program. In particular, a precise study of CP asymmetry in the lepton sector is one of the major goals of Hyper-K. The existence of CP violation is one of the necessary conditions to explain the matter-antimatter asymmetry of the Universe.

For a direct and model-independent measurement of the CP asymmetry, a comparison of oscillation probabilities between neutrino and anti-neutrino will be necessary. Measurements of $\nu_\mu \rightarrow \nu_{\mathrm{e}}$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_{\mathrm{e}}$ oscillations are practically the only possible way to study the lepton CP asymmetry. Combining an intense (>MW) and high quality neutrino beam from J-PARC, the huge mass and high performance of the Hyper-Kamiokande detector, a highly capable near/intermediate detector complex, and the full expertise obtained from ongoing T2K experiment, Hyper-Kamiokande will be the best project to probe neutrino CP violation and new physics with neutrino oscillation.

The sensitivity to leptonic CP asymmetry of a long baseline experiment using a neutrino beam directed from J-PARC to the Hyper-Kamiokande detector has been studied based on a full simulation of beamline and detector.

Figure 5 shows the fraction of δ_{CP} for which $\sin\delta_{CP} = 0$ is excluded with more than $3\,\sigma$ and $5\,\sigma$ of significance as a function of the integrated beam power. The ratio of integrated beam power for the neutrino and anti-neutrino mode is fixed to 1:3. The normal mass hierarchy is assumed. The results for the inverted hierarchy are almost the same. CP violation in the lepton sector can be observed with more than $3(5)\,\sigma$ significance for 78(62)% of the possible values of δ_{CP}. Figure 6 shows the uncertainty of δ_{CP} as a function of the integrated beam power. The value of δ_{CP} can be determined with an uncertainty of 7.2° for $\delta_{CP} = 0°$ or 180°, and 21° for

$\delta_{CP} = \pm 90°$.

There will also be a variety of measurements possible with the Hyper-Kamiokande experiment with both near and far detectors, such as neutrino-nucleus interaction cross section measurements and exotic physics searches, using the well-understood neutrino beam.

3.2. Atmospheric Neutrinos

Though atmospheric neutrinos were used to make the first discovery of the neutrino oscillation phenomenon, for very large detectors like Hyper-Kamiokande, they provide excellent sensitivity to many of the remaining open questions in oscillation physics. Indeed, current neutrino telescopes have demonstrated constraints on the atmospheric mixing parameters comparable to beam measurements using atmospheric neutrinos alone. Additionally, future experiments seek to use these neutrinos to study the mass hierarchy. While both of these measurements and more are available to Hyper-Kamiokande, it offers two distinct advantages to other planned projects. First, with its exquisite ability to distinguish between charged current ν_e and ν_μ interactions, it will have improved access to the oscillation modes with the greatest hierarchy sensitivity, $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$. It is indeed the asymmetry in these two probabilities for few GeV neutrinos traversing the earth that provides the cleanest signature of the mass hierarchy. Additionally, Hyper-Kamiokande will make combined beam and atmospheric neutrino oscillation measurements to an yield increased sensitivity. Figure 7 (left panel) shows that with five years of data with one tank, the combined atmospheric neutrino and beam samples show better than 3σ ability to reject the inverted hierarchy hypothesis, assuming a true normal hierarchy. Similarly, the ability to resolve the θ_{23} octant improves with the combination (middle panel of Figure 7). While atmospheric neutrinos alone can resolve the octant at 3σ if $|\theta_{23} - 45| > 4°$, but in the combined analysis it can be resolved when this difference is only 2.5° in ten years. Moreover, for a fixed baseline uncertainty in the mass hierarchy leads to parameter degeneracies in the beam neutrino measurement that can be resolved using atmospheric neutrinos (right panel of Figure 7). Finally, atmospheric neutrinos form the basis for searches for exotic particles, such as dark matter, whose interactions may produce neutrinos that would subsequently appear atop the atmospheric neutrino spectrum. For these reasons a precise characterisation of the atmospheric neutrino flux is key to future discoveries at Hyper-Kamiokande.

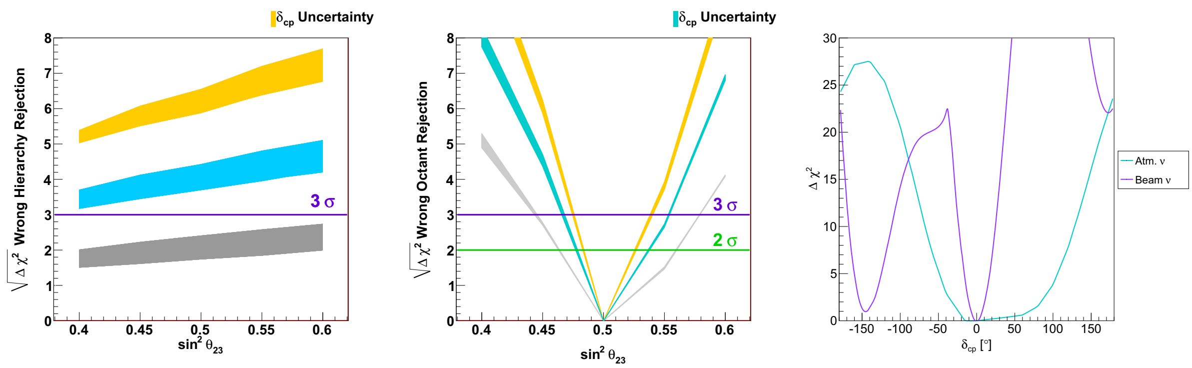

Figure 7. Neutrino oscillation sensitivities from combined analysis of atmospheric neutrino and accelerator data at Hyper-K. The left (middle) panel illustrates the expected hierarchy (octant) sensitivity as a function of true value of $\sin^2\theta_{23}$ for three exposures: 1 year (grey), 5 years (blue), 10 years (orange). Assuming a normal mass hierarchy and $\delta_{CP} = 0$ the beam (violet) and atmospheric neutrino (cyan) constraints on δ_{CP} after a 5.6 Mton·year exposure are shown in the right panel.

3.3. Proton Decay

Optimising Hyper-Kamiokande for the observation and discovery of a nucleon decay signal is one if its primary design drivers. In order to significantly extend sensitivity beyond existing limits, many of which have been set by Super-Kamiokande, Hyper-Kamiokande needs both a much larger number of nucleons than its predecessor and sufficient reconstruction ability to extract signals and suppress backgrounds. While it is possible to target specific decay channels, one of the strengths of water Cherenkov technology is its sensitivity to a wide variety of modes. Using MC and analysis techniques originally developed for Super-Kamiokande, Hyper-K's expected sensitivity after 10 years to the flagship proton decay modes, $p \to e^+\pi^0$, is 1.2×10^{35} yrs at 90% C.L. (8.0×10^{34} yrs at $3\,\sigma$) and for $p \to \overline{\nu}K^+$ is 2.8×10^{34} yrs at 90% C.L. (2.5×10^{34} yrs at $3\,\sigma$). Other $\Delta(B-L)$ conserving, $\Delta B = 2$ dinucleon, and $\Delta(B-L) = 2$ decays sensitivities can be found in Ref. [4].

3.4. Astrophysical Neutrinos

With its huge target mass, the large number of neutrino events and superior sensitivity to astrophysical neutrinos, i.e. solar neutrinos, supernova burst neutrinos and supernova relic neutrinos, is expected. One of the major motivations of solar neutrino research is the test of the solar model predictions as well as the study of neutrino properties themselves. With Hyper-Kamiokande, the day-night asymmetry can be measured with the large statistics and the result will be precise enough to separate itself from the current KamLAND best value above 3.5σ with 10 years measurement. Moreover, many precise measurements of solar neutrino would also be possible, e.g. the undiscovered Hep process neutrino, the solar neutrino energy spectrum upturn where the beyond standard model physics could be, and the seasonal variation of the flux. Hyper-Kamiokande will be possible to alert a supernova burst for other supernova observation experiments with its high directional sensitivity, ~2 degrees for a supernova at 10 kpc. Figure 8 shows the expected number of supernova neutrino events at Hyper-Kamiokande versus the distance to a supernova. The multi-messenger observation of supernova with visible light, gamma-ray, x-ray and gravity wave will also reveal the supernova explosion system in details. Another observation is the supernova relic neutrinos (SRN), produced by all the past supernova explosions since the beginning of the universe. They must fill the present universe and their flux is estimated to be a few tens/cm2/sec. SNR contains information of its origins, i.e. the star formation rate, energy spectrum of supernova burst neutrinos, and black hole formations.

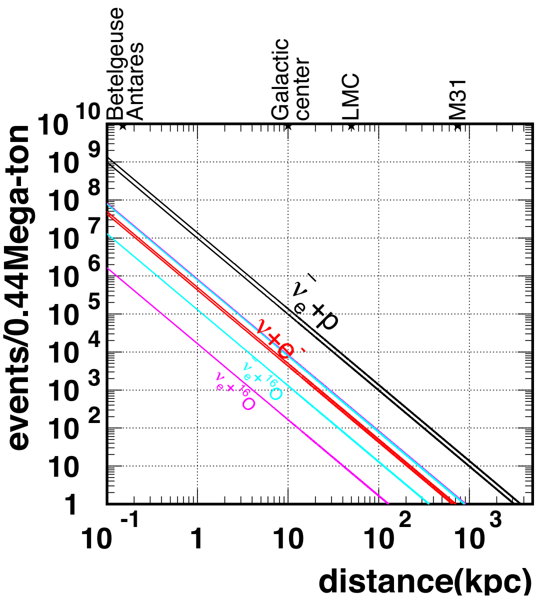

Figure 8. Expected number of supernova burst events for each interaction as a function of the distance to a supernova with 2 tank. The band of each line shows the possible variation due to the assumption of neutrino oscillations.

3.5. Physics Summary

A summary of the physics potential of the experiment as presented in these proceedings is compiled and shown in Table 3.4.

Neutrino beams	Physics Target	Sensitivity
Beam (1.3 MW × 10^7 sec)	δ_{CP} (0°,90°)	7°-21°
	CPV coverage ($3\sigma/5\sigma$)	78%/62%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.015
Atmospherics+Beam	MH determination ($\sin^2\theta_{23}$=0.40)	$> 5.3\sigma$
	Octant ($\sin^2\theta_{23}$=0.45)	5.8σ
Proton Decay (90% C.L.)	$p \to e^+ + \pi^0$	1.2×10^{35} yrs
	$p \to \bar{\nu} + K^+$	2.8×10^{34} yrs
Solar	Day/Night (from 0/ from KamLAND)	$12\sigma/6\sigma$
	Upturn	$\sim 5\sigma$
Supernova	Burst	104k-158k
	Nearby galaxies	2∼20 events
	Relic	98 events/4.8σ

Table 1. Physics targets and expected sensitivities of the Hyper-Kamiokande experiment, based on the study shown in Ref. [3] for a total of 10 years data taking with two tanks, the second starting after 6 years, with the same size and at the same location as the first. Improvement is expected with further optimisation of the detector design and development of reconstruction/analysis tools. Also, only selected values are listed; for example, other channels will be accessible for nucleon decays.

4. Conclusions

The Hyper-Kamiokande project has an extremely rich physics portfolio that spans from the study of the CP violation in the leptonic sector and neutrino mixing parameters to proton decay, atmospheric neutrinos and neutrinos from astronomical origin. It is a next generation large water Cherenkov detector that also acts as the far detector of a long baseline neutrino that uses the J-PARC neutrino beam.

References

[1] K. Abe *et al.*, arXiv:1109.3262 [hep-ex].
[2] K. Abe *et al.* [Hyper-Kamiokande Working Group Collaboration], arXiv:1412.4673 [physics.ins-det].
[3] K. Abe *et al.* [Hyper-Kamiokande Proto- Collaboration], PTEP **2015** (2015) 053C02 doi:10.1093/ptep/ptv061 [arXiv:1502.05199 [hep-ex]].
[4] [Hyper-Kamiokande Collaboration], KEK-PREPRINT-2016-21, ICRR-REPORT-701-2016-1.
[5] K. Hagiwara, Nucl. Phys. Proc. Suppl. **137** (2004) 84 doi:10.1016/j.nuclphysbps.2004.10.054 [hep-ph/0410229].
[6] K. Abe *et al.* [Hyper-Kamiokande proto- Collaboration], arXiv:1611.06118 [hep-ex].
[7] K. Abe *et al.* [T2K Collaboration], Nucl. Instrum. Meth. A **659** (2011) 106 doi:10.1016/j.nima.2011.06.067 [arXiv:1106.1238 [physics.ins-det]].
[8] S. Bhadra *et al.* [nuPRISM Collaboration], arXiv:1412.3086 [physics.ins-det].
[9] C. Andreopoulos *et al.*, arXiv:1606.08114 [physics.ins-det].