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Future neutrino physics with Hyper-Kamiokande

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Abstract. Hyper-Kamiokande, the next-generation neutrino observatory in Japan, evolves from its predecessors, Kamiokande, Super-Kamiokande and T2K, with a significant upgrade to a 258-kton water Cherenkov detector equipped with 20,000 PMTs. Hyper-Kamiokande will host an extremely rich and broad physics program, covering areas from neutrino astrophysics to nucleon decay searches and precision neutrino oscillation measurements. Positioned as the far detector for the JPARC neutrino beam, with a baseline of 295 km, and utilizing near detectors such as the upgraded ND280 detector and INGRID currently used by the T2K experiment, Hyper-Kamiokande will have excellent sensitivity to CP violation signatures in neutrino oscillations. Set to be completed in 2027, we summarize Hyper-Kamiokande's status and physics program, with an emphasis on its CP violation searches.

1 Introduction

Neutrinos are the most abundant known massive particles and participate in a wide-range of phenomena, being crucial in nuclear physics astrophysics and cosmology. Despite of their prominent role in the physics current knowledge about their behavior is still limited compared to the other Standard Model fermions due to neutrinos unusually small cross section [1]. To overcome this limitation next-generation experiments, such as DUNE [2] and Hyper-Kamiokande [3] –presented in this text– are being built employing beams of unprecedented power and detectors of unprecedented size.

The main goal of this next-generation of experiments is to shed light on the behavior of neutrino oscillations [4], and more prominently to measure with precision all parameters involved in their phenomenology and their correlations. Of particular relevance is the study of three quantities:

- The determination of the neutrino mass ordering, that indicates if the neutrino with a larger fraction of the electronic flavor is the lightest (normal ordering) or the heaviest (inverted ordering).
- The determination of the θ_{23} octant, that indicates the relation between the μ and τ flavors, and informs theorists about what flavor structure might be behind the observed flavor patterns in the quark and the lepton sectors.

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- The measurement of the amount of CP-violation in the lepton sector, often characterized by the Jarlskog invariant [5, 6], and that requires of a precision measurement of the CP-violating phase δ_{CP}. Existing measurements suggest the non conservation of the CP symmetry in the lepton sector [7], a necessary requirement to explain the observed matter-antimatter asymmetry in the Universe via leptogenesis [8].

2 The Hyper-Kamiokande Experiment

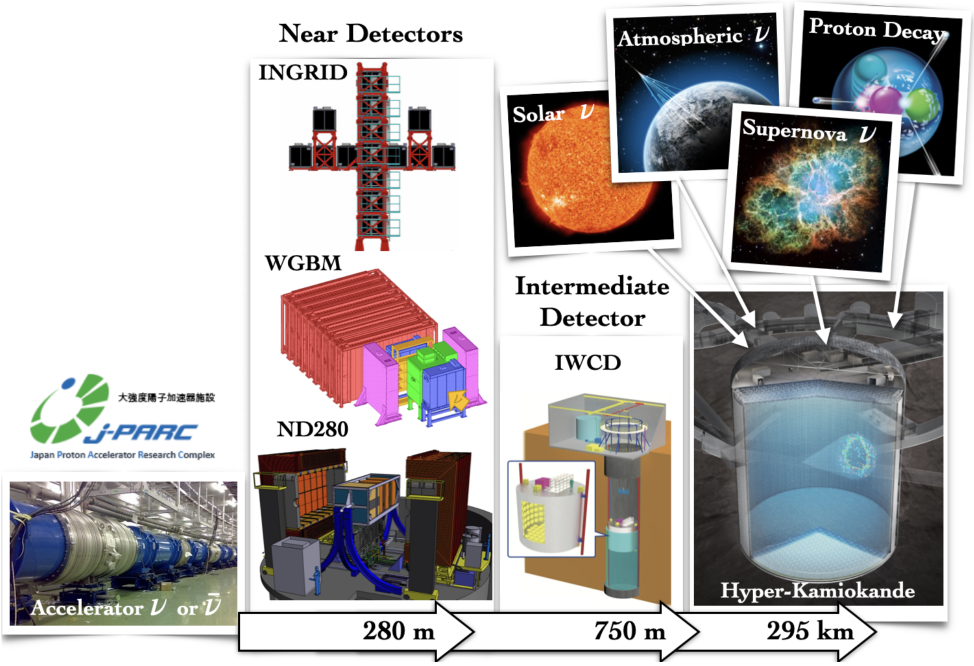

Figure 1. Sketch of the elements in the Hyper-Kamiokande Experiment.

Hyper-Kamiokande will be the next flagship neutrino experiment in Japan, starting in 2027, combining and extending the physics programs of two of the most important existing experiments in neutrino physics: T2K [9] and Super-Kamiokande [10]. A sketch presenting the different elements of the experiment is presented in Figure 1.

2.1 Hyper-Kamiokande Detector

Following on the success of previous water Cherenkov experiments KamiokaNDE [11] and Super-Kamiokande [10], with a total mass of 3 kton and 50 ktons respectively, Hyper-Kamiokande will be a the third generation experiment reaching a total mass of 258 kton. Similar to its predecessors, Hyper-Kamiokande will use Photo-Multiplier-Tubes (PMTs) because of their excellent photon detection capabilities over a large sensitive area. Relative to Super-Kamiokande, Hyper-Kamiokande PMTs will have doubled photon detection sensitivity [12]. The production of Hyper-Kamiokande PMTs, totaling 20,000 units, started in 2021, as of Summer 2024, over half of the PMTs are ready. Hyper-Kamiokande will adopt a hybrid PMT configuration using in addition a smaller number of multi-PMTs, based on a pressure vessel instrumented with 19 3-inch photosensors, each one with a different orientation, readout electronics and power supply [13, 14].

2.2 Beam and ND280

Hyper-Kamiokande will inherit the J-PARC neutrino beamline in use by the T2K experiment, and will also operate at 2.5° off-axis, exposed to a narrow energy spectra peaking at 0.6 GeV, and composed –before oscillations– mainly by ν_μ or $\bar{\nu}_\mu$ depending on the operation mode of the experiment (ν-mode or $\bar{\nu}$-mode) which is controlled by the choosing polarity of focusing horns in the neutrino beamline. The neutrino beamline has been recently upgraded, increasing the nominal power of 500 kW to 800 kW, and a future upgrade is expected to achieve a power of 1.3 MW before Hyper-Kamiokande starts taking data [15].

Hyper-Kamiokande will also inherit the near detector complex in use by T2K [16] , located at 280 meters from the beam target, that consists of INGRID, the ND280 magnetized detectors, and the Wagasci-BabyMIND detector. INGRID is utilized to study the beam stability and direction, whereas ND280 –utilizing plastic and water targets–, is crucial to characterize the neutrino interaction cross sections and the unoscillated neutrino flavor composition and energy spectra. Wagasci-BabyMIND —utilizing plastic and water targets–, is also magnetized, and exposed to a slightly different energy spectra at 1.5° off-axis, thus complementing ND280 in characterizing the unoscillated flux and systematic uncertainties related to neutrino interaction cross section, particularly in different target materials.

The ND280 detector has been recently upgraded [17], boosting its already remarkable performance, particularly extending its acceptance, enhancing its hadron detection threshold, and boosting its particle identification capabilities. For Hyper-Kamiokande, further upgrades of the detector during the operation of the experiment are under evaluation.

2.3 IWCD

The Intermediate Water Cherenkov Detector (IWCD), presented in Hyper-Kamiokande's design report [3], is a new detector to be built for the Hyper-Kamiokande experiment. It consists of a movable water Cherenkov detector of a few hundred tons, located at 750 meters from the beam target, spanning off-axis angles in the range from 1.5°-4°. This capabilities will ensure the robustness of Hyper-Kamiokande results, supported by the agreement of the neutrino interaction and flux models with data in a wide range of neutrino energy spectra. In addition, IWCD will measure neutrino cross sections for different flavors and for neutrinos and antineutrinos, including the double ratio $(\nu_e/\nu_\mu)(\bar{\nu}_e/\bar{\nu}_\mu)$, which is the dominant systematic for searches of CP-violation in Hyper-Kamiokande.

IWCD photosensors will consist exclusively of multi-PMTs [12, 13], providing greatly detailed Cherenkov images. IWCD multi-PMTs will be used for physics for the first time by the Water Chernekov Test Experiment (WCTE) [18] at CERN towards the end of 2024, helping to characterize and validate this technology for Hyper-Kamiokande.

3 Physics Program and Expected Sensitivity

The physics program of Hyper-Kamiokande is extensively covered in its design report [3]. Here a summary is presented, extended by highlights of updated sensitivity studies regarding accelerator neutrinos that will be soon presented in a dedicated article. This sensitivity

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studies are based on the same methodology employed by the T2K collaboration in its oscillation analysis studies, scaling up the far detector statistics to those expected at the time of Hyper-Kamiokande, and presenting the results under various systematic uncertainties scenarios, ranging from the conservative T2K 2020 systematics case to the ideal statistics only results. Unless otherwise specified the discussion below is based on the metrics for the *Improved systematics* case, which is the one expected to better represent the systematic uncertainties in Hyper-Kamiokande.

3.1 Accelerator and Atmospheric Neutrinos

3.1.1 CP-violation

The presence of CP-violation in neutrino oscillations, i.e. unequal oscillation in neutrinos and antineutrinos, is characterized by a δ_{CP} phase different from 0 and 180°. Maximal sensitivity to exclude CP-conservation is expected when the CP-violation is maximal, namely, for values of δ_{CP} of 90° or 270°. The expected sensitivity of Hyper-Kamiokande to identify such asymmetry is presented in Figure 2. In the most favorable scenario, Hyper-Kamiokande might claim the discovery of this asymmetry after 3 years of data taking, namely, by 2030. In intermediate scenarios, the discovery is expected in less than a decade. In 10 years of operation, Hyper-Kamiokande expects 5σ (3σ) sensitivity in this measurement for about 63% (78%) of the possible values of δ_{CP} using beam neutrinos complemented by existing knowledge form reactor neutrinos regarding θ_{13}. The δ_{CP} measurement 1σ precision is expected to be as low as below 10% for CP-conserving values, and gradually increasing to about 20% for maximally CP-violating true values of δ_{CP}.

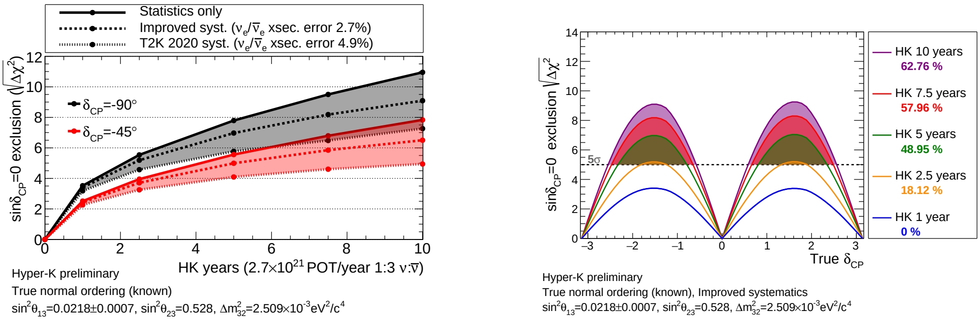

Figure 2. Left: Expected sensitivity in Hyper-Kamiokande to exclude a null value for $\sin\delta_{CP}$ over time. Right: Possible true values of δ_{CP} for which Hyper-Kamiokande would discover CP-asymmetry in neutrino oscillations.

3.1.2 Atmospheric parameters

Hyper-Kamiokande will measure with great precision the so-called atmospheric parameters θ_{23} and Δm^2_{23}, see Figure 3. Such precision will allow to reject maximal θ_{23} beyond 3σ for most values of θ_{23}. The sensitivity to identify the true octant was also studied, resulting in a 5σ confidence for $0.45 \lessapprox \sin^2\theta_{23} \lessapprox 0.57$, and 3σ confidence for $0.48 \lessapprox \sin^2\theta_{23} \lessapprox 0.54$.

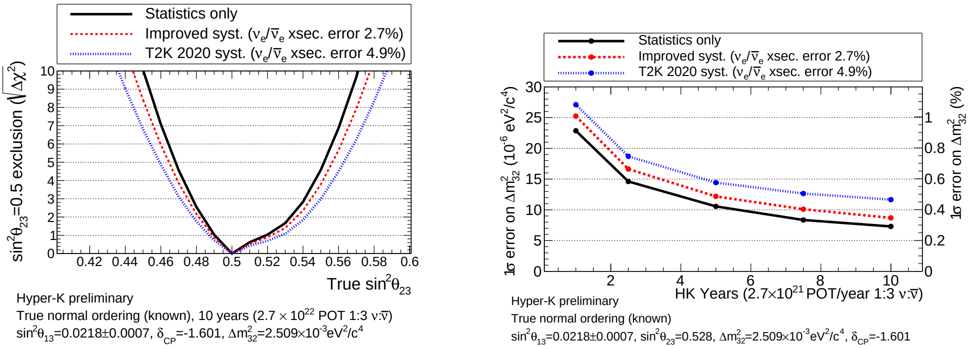

Figure 3. Left: Sensitivity to reject maximal θ_{23} mixing. Right: Expected 1 σ error for Δm^2_{23}.

3.1.3 Mass ordering

Due to the relatively short neutrino baseline of 295 km and its sub-GeV characteristic energy, Hyper-Kamiokande's accelerator program has limited sensitivity to the true mass ordering. However, Hyper-Kamiokande is expected to play a crucial role in its determination and study using atmospheric neutrinos and in combination with other experiments.

In the first place, the precise determination of Δm^2_{23}, presented above, will be essential to enable a discovery of the mass ordering in the JUNO experiment, as a precision on Δm^2_{23} better than 0.75% is expected to be necessary to reach 5σ sensitivity in JUNO [19]. As presented in Figure 3, such precision will be reached in Hyper-Kamiokande on the first years of the experiment.

In the second place, Hyper-Kamiokande vacuum-like neutrino oscillation results will complement those of DUNE, sensitive to matter effects, adding robustness to mass ordering determinations in DUNE and ruling out –or revealing– the presence of new physics effects in its determination of the mass ordering.

Lastly, Hyper-Kamiokande will complement its study of oscillations using beam neutrinos with measurements of atmospheric neutrinos, highly sensitive to matter effects. Such a combined measurement is expected to enhance the experiment sensitivity in its oscillation searches in general and its measurements of the mass ordering in particular, following a strategy similar to that recently employed by the T2K and Super-Kamiokande collaborations in a first joint study [20]. The results already disfavor the inverted mass hierarchy scenario with a posterior predictive p-value of 0.079. Sensitivity studies by the Hyper-Kamiokande collaboration extending those results based on the expected capabilities and statistics at Hyper-Kamiokande are expected in the future.

3.2 Astrophysics

The predecessor experiments Kamionade and Super-Kamiokande, have a long history of neutrino astrophysics ranging from the first ever detection of a Supernova explosion [21], to precision measurement of solar neutrinos [22]. This exploration will be extended by Hyper-Kamiokande, with capabilities described in the design report of the experiment [3] and summarized below.

Assuming a detection threshold of 4.5 MeV, 130 ^{8}B solar neutrinos are expected to be detected every day, allowing to measure the day-night asymmetry in the flux of solar neutrinos and search for the so-called solar neutrino upturn. Hyper-Kamiokande will be capable of searching hep solar neutrinos, important to refine our knowledge of the existing standard solar model.

In case of a Supernova explosion, Hyper-Kamiokande expects 50-90k interactions for a explosion at 10 kpc, the distance from Earth to the Galactic center. This number dramatically contrasts with the twelve detections achieved by Kamiokande [21], and that were crucial in validating the basic understanding of the physics describing Supernovae. The new data would allow to revolutionize that understanding, working as a unique dataset to benchmark various Supernova models, but also would allow to study a number of fundamental physics quantities [23–25].

3.3 Proton Decay

Hyper-Kamiokande will further extend existing nucleon decay searches currently lead by Super-Kamiokande [26, 27], particularly via the search of $p \to \pi^0 e^+$ and other channels involving neutral and charged kaons in the final state, improving the current boundaries by about an order of magnitude. Additional details are presented in Hyper-Kamiokande's design report [3].

4 Conclusions

Hyper-Kamiokande is the next-generation flagship neutrino experiment in Japan, and will consist of the largest water Cherenkov detector in the world, with a mass of 258 ktons and 20,000 PMTs, a 1.3MW neutrino (or antineutrino) beam from JPARC, and suit of near detectors crucial to characterize the neutrino beam flux and the neutrino interaction systematic uncertainties.

The experiment is under construction and the timeline is moving forward according to plan with the goal of starting the data taking in 2027. Hyper-Kamiokande will combine and extend the physics programs, technologies and experiences of the T2K and Super-Kamiokande experiments to create a uniquely broad physics experiment.

Sensitivity studies by the Hyper-Kamiokande collaboration show excellent capabilities to measure neutrino oscillations, and to critically contribute to our understanding of CP-violation, the mass ordering and the flavor structure of the lepton sector. Similarly, Hyper-Kamiokande boasts an impressive neutrino astrophysics program, that will continue expanding our understanding of the Sun measuring its neutrinos, and will become an exceptionally capable detector to measure Supernova neutrinos. Lastly, Hyper-Kamiokande will lead the search of nucleon decay, increasing the existing limits to new horizons, with the potential to revolutionize our modern view of particle physics.

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