PROCEEDINGS OF SCIENCE

Hyper-Kamiokande: Neutrino Astrophysics and Status

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The Hyper-Kamiokande (Hyper-K) project is a multi-purpose next generation neutrino experiment. The physics program includes accelerator neutrino, atmospheric neutrino oscillation measurement and proton decay. Neutrino astrophysics is also an important research topic. With its fruitful physics research programs, Hyper-K will play a critical role in the next neutrino physics frontier. It will also provide crucial information via astrophysical neutrino measurements, such as solar neutrino, supernova burst neutrinos and supernova relic neutrino.
The Hyper-K far detector is a double-layered cylindrical shape, with 64 m in height and 71 m in diameter. It will be located deep underground to reduce cosmic-ray backgrounds, 600 m below Mt. Tochibora at Kamioka in Japan. The inner detector will be filled with ultra-pure water and surrounded by twenty thousand photosensors of 50 cm diameter and multi-PMT modules to detect water Cherenkov radiation from charged particles from the neutrino interactions. The detector will have a fiducial volume of 188 kt. In August 2025, the excavation of the access tunnels, detector cavern and surrounding caverns was completed. After installing the photosensors and system components, the data taking will start in 2028. Here, we will discuss the physics potential of Hyper-K neutrino astrophysics and construction status.

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1. Introduction

Hyper-Kamiokande (Hyper-K) is the next generation multi-purpose neutrino project in Japan, which includes the J-PARC accelerator neutrino beamline upgrade, near and far detector constructions [1–3]. The far water Cherenkov detector is designed as a successor to the Super-Kamiokande (Super-K) experiment [4]. With the dimensions of the 71 m (D) × 60 m (H), a cylindrical water tank will have a fiducial (total) volume of 0.188 (0.258) million metric tons (figure 1); respectively 8 (5) times larger than those of Super-K. The inner detector will be surrounded by 50 cm diameter photodetectors and multi-PMT modules. The photo-coverage of 20 % will be realized with 20,000 of 50 cm PMTs (Hamamatsu R12860) and 800 multi-PMT modules. 3,600 of 7.5 cm diameter photodetectors with wavelength shifting plates will be provided for the outer veto detector, to remove cosmic-ray muon backgrounds. The detector will be located underground at Kamioka mine in Gifu prefecture, Japan, with an overburden of 600 meters or more of rock. It is equivalent to 1,620 meters or more of water. Charged particles, such as the products of neutrino interactions, are detected with the emitted Cherenkov photons. The number of photons and their arrival times on the photodetectors are used to reconstruct the energy and vertex of the particle, respectively. Hyper-K has various physics topics: search for CP violation in neutrinos, precise study of neutrino oscillations including determination of mass hierarchy and θ_{23} octant with accelerator and atmospheric neutrinos, search for nucleon decay and observations of astrophysical neutrinos.

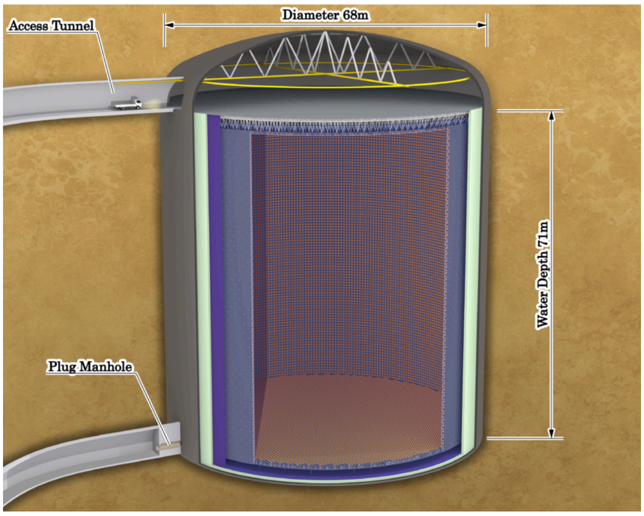

Figure 1: Schematic view of one Hyper-Kamiokande water Cherenkov detector [1]. The tank will provide the fiducial volume of 0.188 Mt ultra pure water, with the dimensions of the 71 m (D) × 60 m (H).

2. Neutrino Astrophysics

2.1 Solar Neutrino and Neutrino Oscillation Measurement

The Sun is burning and emitting neutrinos through the nuclear fusion reactions, known as the pp-chain and the CNO cycle. These processes are described by the standard solar model

(SSM) [5, 6], which provides accurate predictions of the flux and energy spectrum of solar neutrinos. Our primary observation target is the ^{8}B neutrino, which has energy above our analysis threshold of $E_{vis} > 4.5$ MeV. Here, E_{vis} is the visible energy of the neutrino event in water Cherenkov detector, which is about 1.5 MeV lower than the total neutrino energy. They are observed through neutrino-electron elastic scattering, $\nu + e \rightarrow \nu + e$. The energy, direction, and time of the original neutrinos are measured through their recoil electrons. About 130 ν-e scattering events are expected in a day for Hyper-K far detector.

The solar neutrino measurements are capable of determining the neutrino oscillation parameters between the mass eigenstates. Super-K [7], SNO [8] and several experiments [9–11] have been performed the neutrino oscillation measurement on the solar neutrinos. Figure 2 shows the latest results [12] of the allowed neutrino oscillation parameters, the mixing angle θ_{12} and the mass squared difference Δm^2_{21} from all solar neutrino experiments, as well as the reactor neutrino experiment KamLAND [13]. The Δm^2_{21} of $6.11^{+1.21}_{-0.68} \times 10^{-5}$ eV^2 is reported by Super-Kamiokande collaboration, as the results of solar oscillation analysis combining Super-K and SNO measurements. The tension

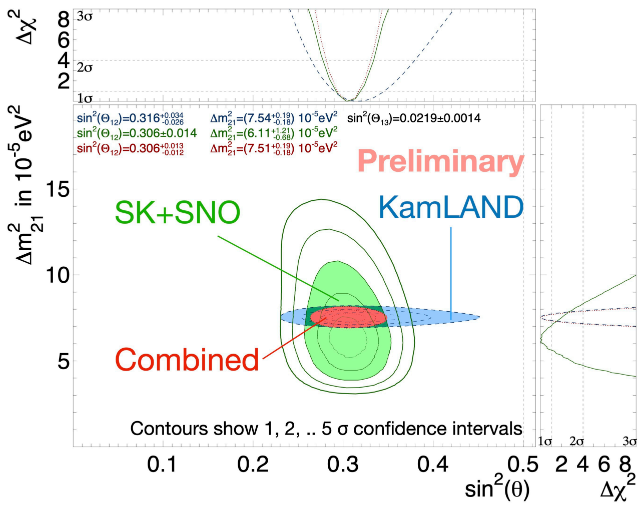

Figure 2: Neutrino oscillation parameter allowed region from all the solar experiments (green), KamLAND (blue) and Solar+KamLAND (red) from 1 to 5 σ lines and 3 σ area are shown[12]. The dashed green line is the combined results of Super-K and SNO.

between solar and reactor best fit Δm^2_{21} became rather small as ~1.4 σ, comparing to ~2 σ tension with solar best fit $\Delta m^2_{21} = 4.8^{+1.5}_{-0.8} \times 10^{-5}$ eV^2 in 2016 [7]. It is mainly derived from the asymmetry of the solar neutrino flux during day and night (day-night asymmetry), which was indicated by Super-K [14]. The asymmetry arises from the terrestrial matter effect, i.e. the regeneration of the electron neutrinos through MSW matter effect in the Earth. The effect can be seen as a few percent higher event rate in the nighttime, than that in the daytime. In the Hyper-Kamiokande far detector, the day-night asymmetry effect can be measured precisely tanks to the large detector volume. Assuming the solar best fit Δm^2_{21} parameter at 2020, at Hyper-Kamiokande it will be possible to prove the day-night asymmetry effect above 5 σ after 10 years observation. On the other hand, the sensitivity to prove the difference between solar and reactor Δm^2_{21} will stay at ~2 (3) σ, after 10 (20) years of Hyper-K operation.

The spectrum upturn is also of interest. For example, it is predicted by MSW-LMA solution and possibly affected by physics beyond the standard model, such as non-standard interaction[15], mass-varying neutrino oscillation[16] and sterile neutrino[17], for example. Even with the oscillation parameters as measured in 2020, the non-zero upturn sensitivity will be about 3σ after the 10 years of solar neutrino measurements with 4.5 MeV energy threshold.

3. Supernova Neutrinos

Core collapse supernova explosions (supernova bursts) are the last process in the evolution of massive stars (>8 $M_{\odot}$). The energy released by a supernova is estimated to be $\sim 3 \times 10^{53}$ ergs and 99% of the energy is carried out by all three types of neutrinos and anti-neutrinos. The detection of supernova neutrinos gives direct information of the energy flow during the bursts. The observation of supernova with the large neutrino detector will provide the details of the explosion and an opportunity to test the theoretical models of the burst mechanism.

The first and direct observation of supernova neutrinos comes from the supernova burst neutrinos, which are released in several seconds after its onset of a burst. About 90% of signals at Hyper-K comes from inverse beta decay reaction ($\bar{\nu}_e + p \rightarrow e^+ + n$). The following are expected for a supernova explosion at the center of our galaxy (10 kpc, figure 3): 49,000-68,000 inverse beta decay events, 2,100-2,500 ν-e scattering events, 80-4,100 ν_e+^{16}O CC events, and 650-3,900 $\bar{\nu_e}$+^{16}O CC events, in total 52,000-79,000 events. The statistical error will be small enough to test several theoretical model predictions (figure 4). In past simulation, the deceleration of the shock wave and resulting failed explosion were annoying problems. Recent simulations suggest that the shock wave is heated efficiently by neutrinos to revival, due to the physical motions in the core, Standing Accretion Shock Instability (SASI) or convection, rotation of supernova are the examples. As the results, these models predict characteristic frequency modulation of neutrino flux. The detection of these modulations will prove the new role of neutrino as the driver of supernova bursts. Other astrophysics and particle physics problems also can be examined, e.g. the direct observation of black hole formations and the mass hierarchy of neutrinos.

Another observation target is the supernova diffused neutrino background (DSNB), produced by all past supernova explosions since the beginning of the universe. They must fill the universe and the flux is estimated to be a few tens/cm^2/sec. The spectrum of DSNB contains the information of its origins, i.e. the star formation rate, energy spectrum of supernova burst neutrinos, and the fraction of strange supernova explosions like dim supernovae or black hole formations. Though no clear evidence of DSNB signals has yet been obtained so far, Super-K reported the indication of DSNB signals by 2.3 σ with its observation over 18 years, including the new detector period upgraded with Gd-loading. In the Hyper-K, 4 to 7 DSNB events/year are expected at 16-30 MeV. The large volume and statistics will allow us to overcome the Super-K sensitivity and test several theoretical models above ~22 MeV, where we are almost free from the cosmic-ray muon spallation background.

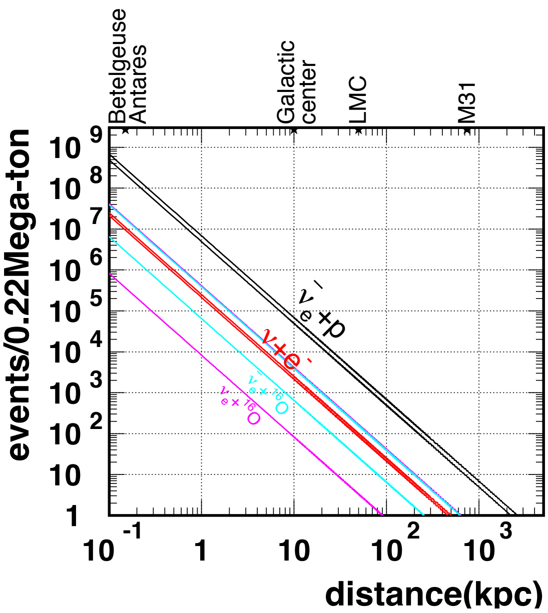

Figure 3: Expected number of supernova burst events for each interaction as a function of the distance to a supernova[3]. The band of each line shows the possible variation due to the assumption of neutrino oscillations.

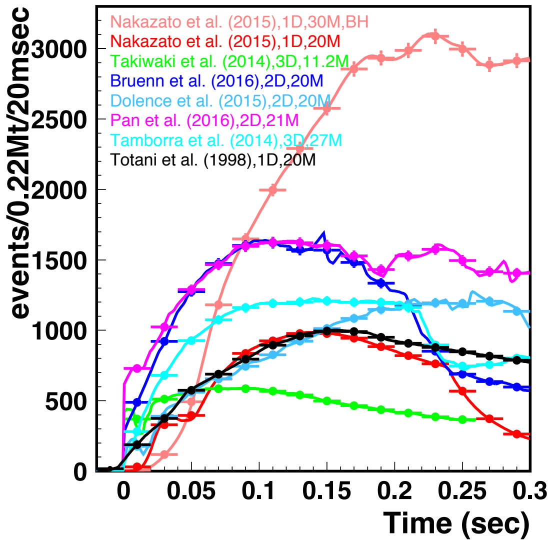

Figure 4: Inverse beta decay event rate predicted by supernova simulations for the first 0.3 seconds after the onset of a 10kpc distant burst[3]. The error bars show the statistical error.

4. Project Status

The construction project of Hyper-K far detector officially started in 2020. The excavations of the access, the approach tunnel, and the main cavern were completed by August 2025 (Fig.6). The tank construction, i.e. lining the detector cavern with stainless steel plates, is ongoing in this autumn 2025. The far detector will be constructed by installing the photosensors and underwater electronics into the tank support structures. After filling the pure-water into the detector tank, the data taking will start in 2028 (Fig.7).

5. Summary

Hyper-Kamiokande project is the next generation multi-purpose neutrino experiment in Japan. The project includes a new 258 kt large water Cherenkov detector, which will also play a pivotal role of the far detector, for its accelerator neutrino oscillation measurement. The far detector is designed as the successor of current Super-K detector and therefore the neutrino observation for natural sources and proton decay will be to be continuously studied. Astrophysical neutrinos, i.e. solar and supernova neutrinos are important physics targets for Hyper-Kamiokande. Thanks to high statistics, precision measurement of the solar neutrino oscillation, searches for physics beyond the standard model, supernova burst neutrino and diffuse supernova neutrino background can be performed. As a conclusion, Hyper-K will play a crucial role in the next neutrino physics frontier for particle physics and neutrino astrophysics.

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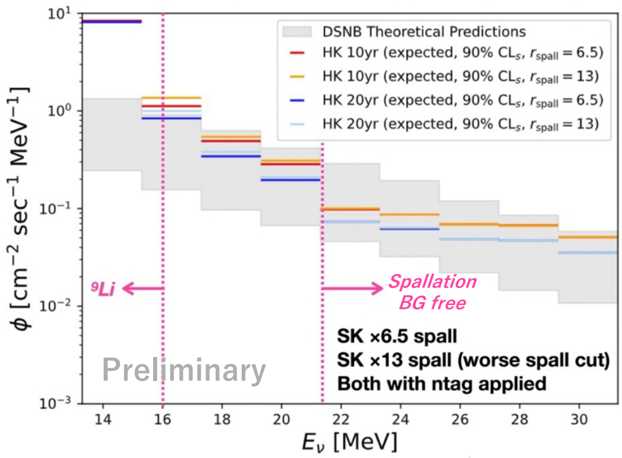

Figure 5: The flux upper limits with Hyper-K 10 (20) years observation, by spectrum-independent analysis. The cosmic-ray muon spallation products will be the dominant background for the observation. Two spallation background scenarios are considered for the shallower depth of Hyper-K, 6.5 and 13 times larger background than that of Super-K.

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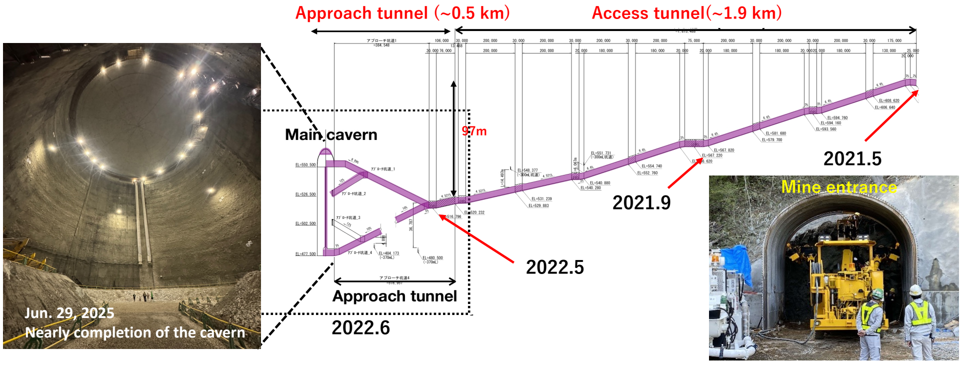

Figure 6: History of Hyper-K far detector tunnel and cavern excavations.

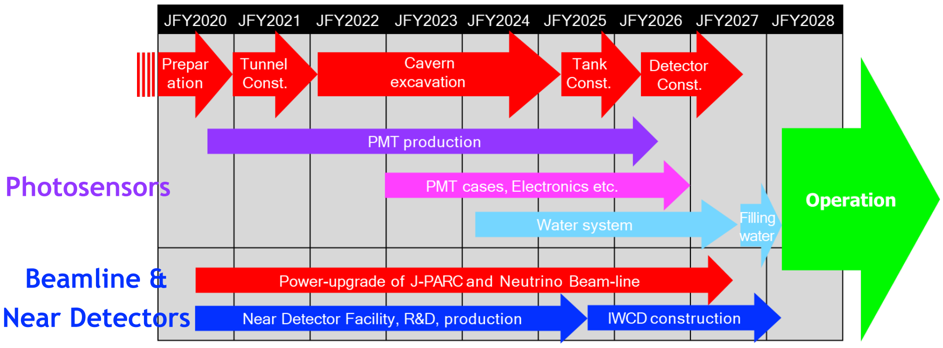

Figure 7: The construction schedule of the Hyper-K far detector. The upgrade of the neutrino beamline and the construction of our IWCD (intermediate water Cherenkov detector) will be performed in parallel.

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