Hyper-Kamiokande and Astrophysics

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Abstract. Hyper-Kamiokande (Hyper-K) is a proposed next generation underground large water Cherenkov detector. Recently a new detector design of Hyper-K is presented, as the two cylindrical pure water tanks. In the new design, each detector is surrounded by 40,000 newly developed photos sensors and provids the fiducial volume of 0.187 Mt. In total, the fiducial volume will be 0.37 Mt. Hyper-K will play the important role in several science of the next neutrino physics frontier, even in the neutrino astrophysics. The detection with large statistics of astrophysical neutrons, i.e., solar neutrino, supernova burst neutrino and supernova relic neutrino, will be remarkable information for both of particle physics and astrophysics.

1. Introduction
Hyper-Kamiokande (Hyper-K, HK) is a next generation water Cherenkov detector planned in Japan [1–3], as a successor of the Super-Kamiokande (Super-K, SK) [4]. With the dimensions of the 74 m (D) × 60 m (H) for each, two cylindrical water tanks provide the total (fiducial) volume of 0.52 (0.37) million metric tons (Figure 1). They are 10 (16) times larger than that of Super-K. The measurement with the second tank will begin 6 years after the beggining of the measurement with the first tank. An inner detectors are surrounded by 40,000 photodetectors with 50 cm diameter. 6,700 photodetectors with 20 cm diameter are also provided for an outer veto layer to reject cosmic-ray muons. The detector will be located underground at Kamioka mine in Gifu Prefecture, with an overburden of ∼650 meters or more of rock, which is equivalent to 1,750 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 the vertex of the particle, respectively. New photodetectors are being developed for HK, to achieve twice larger detection efficiency for Cherenkov photons, the superior photon counting and timing resolution compared to that used in SK. Hyper-K has various physics topics: search for CP violation in neutrinos, precise study of neutrino oscillations including determination of mass hierarchy and θ23 octant with beam and atmospheric neutrinos, search for nucleon decay and observations of astrophysical neutrinos.

2. Solar Neutrino
The Sun is burning and emitting neutrinos with the nuclear fusion reactions, that are called as the pp-chain and the CNO cycle and can be summarized: \[ 4p \rightarrow \alpha + 2e^+ + 2\nu_e. \] These processes are described with the standard solar model (SSM) [5]. The SSM provides the good prediction of flux and energy spectrum of solar neutrinos. Since the solar neutrinos with \( E_\nu > 6.5 \) MeV will be detectable with Hyper-K, our dominant observation will be boron-8 neutrinos. 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 the recoil electron. About 130 $\nu$-$e$ scattering events will be observed in a day with HK, while 15 $\nu$ events/day are observed with SK.

One of the major motivations of solar neutrino study is the test of the solar model predictions. Because of its high penetration power, neutrino is the unique probe for the current status of the center of Sun, where they are generated. Several precise measurements of solar neutrino would be possible with Hyper-K and its high statistics, e.g. the undiscovered Hep process neutrino generated in $^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e$ reaction and the seasonal variation of the flux. Another major motivation is the study of neutrino properties themselves. Super-K, SNO [6] and several experiments [7–9] have been measured the neutrino oscillation on the solar neutrino. A recent result of the oscillation analysis among solar neutrino experiments is following: $\sin^2 \theta_{12} = 0.311^{+0.014}_{-0.013}$, $\Delta m^2_{21} = 4.85^{+1.4}_{-0.59} \times 10^{-5} \text{eV}^2$ [10]. On the other hand, a reactor neutrino experiment, KamLAND, also measured these oscillation: $\tan^2 \theta_{12} = 0.436^{+0.029}_{-0.029}$, $\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5} \text{eV}^2$ [10].

Figure 2 shows the comparison of these two measurement results and these combined result. The $\sim 2 \sigma$ tension between these $\Delta m^2_{21}$ measurement could be tested by Hyper-K. The tension is mainly come from the asymmetry of the solar neutrino flux during day and night (day-night asymmetry), which is indicated by Super-K [11]. The asymmetry arises from the terrestrial matter effect, which the solar neutrinos pass through during only night period. With Hyper-K, the day-night asymmetry effect can be measured with the large statistics. Assuming the current solar best $\Delta m^2_{21}$, our measurement will be precise enough to separate itself from the current KamLAND best value above 3.5$\sigma$ with 10 years observation. The difference of $P_{\nu_e \rightarrow \nu_e}$ and $P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$ will be a test of CPT violation at neutrinos. The solar neutrino energy spectrum upturn, where the beyond standard model physics could be, is also the interested physics properties. For that, we will perform further optimization of our detector, analysis and calibrations.

**Figure 1.** Schematic view of one Hyper-Kamiokande detector [1].

**Figure 2.** Neutrino oscillation parameter allowed region from all the solar experiments (green), KamLAND (blue) and Solar+KamLAND (red) from 1 to 5 $\sigma$ lines and 3 $\sigma$ area are shown[10].
3. Supernova Neutrinos

Core collapse supernova explosions are the last process in the evolution of massive stars (>8M⊙). The energy released by a supernova is estimated to be ∼ 3 ×10^{53} ergs. 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 energy flow during the explosions. From SN1987a, the Kamiokande, IMB, and Baksan experiments observed 25 neutrino events. It proved the basic scenario of the supernova explosion was correct. However, close to three decades later the detailed mechanism of explosions is still not known. The observation of new supernova with the large neutrino detector is desired. The multi-messenger observation with visible light, gamma-ray, x-ray, gravitational wave and Hyper-K will also reveal the supernova explosion in details.

The first and direct observation of supernova neutrinos is about the supernova burst neutrinos, which are released in several seconds after its onset of a burst. About 90% of signals at Hyper-K is inverse beta reaction (\(\bar{\nu}_e + p \rightarrow e^+ + n\)). At the full volume of two inner detectors, we expect to see about 98,000–136,000 inverse beta events, 4,200–5,000 \(\nu\bar{e}\) scattering events, 160–8,200 \(\nu_e +^{16}\text{O}\) CC events, and 1,300–7,800 \(\bar{\nu}_e +^{16}\text{O}\) CC events, in total 104,000–158,000 events for a supernova explosion at halfway across our galaxy (10 kpc). The statistical error will be enough smaller to compare several SN models, and so Hyper-K should give crucial data for further model predictions. The modulation of supernova neutrino flux, which is predicted by recent computer simulations, also could be observed and proved [12]. Another observation is about the supernova relic neutrinos (SRN), produced by all past supernova explosions since the beginning of the universe and diffused. They must fill the universe and their flux is estimated to be a few tens/cm²/sec. SRN contains the information of its origins, i.e. the star formation rate, energy spectrum of supernova burst neutrinos, and black hole or neutron star formations. Although searches for SRN have been conducted at large underground detectors, no evidence of SRN signals has yet been obtained, because of the small flux of SRN. ~100 SRN events are expected at 16-30 MeV with 10 years observation. The significance will be 4.8 \(\sigma\) and enough for discovery.

4. Summary

Hyper-Kamiokande is a next generation large water Cherenkov detector. Several studies are being performed, e.g. photosensor R&D, design and physics optimization. Astrophysical neutrino measurement is one of the features of Hyper-K. We will provide the unique information for solar, supernova burst and supernova relic neutrinos. Hyper-K will play remarkable role in the next neutrino physics frontier for both of particle physics and neutrino astrophysics.

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