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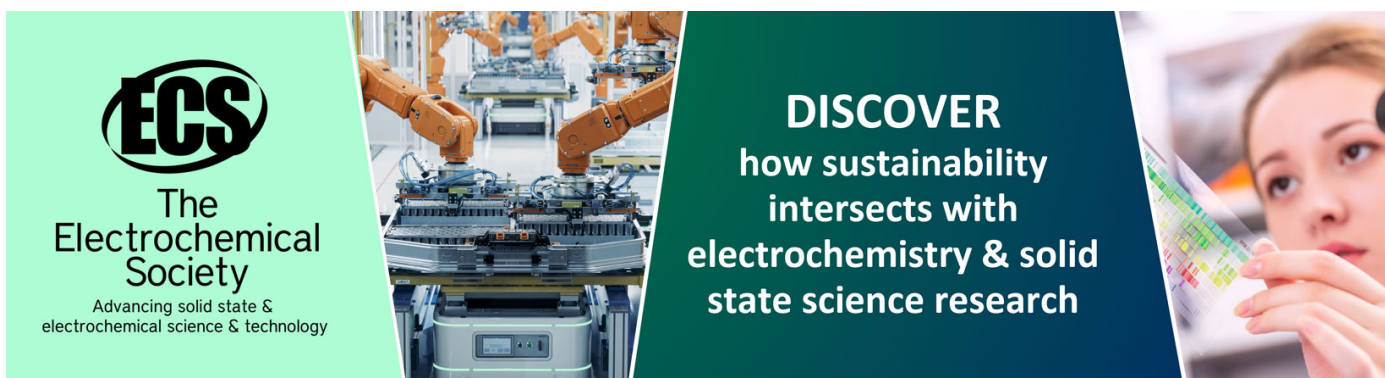
Astrophysical Neutrino in Hyper-Kamiokande

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Astrophysical Neutrino in Hyper-Kamiokande

Takatomi Yano for Hyper-Kamiokande Proto-Collaboration

Department of Physics, Kobe University 1-1 Rokko-dai, Nada, Kobe, Hyogo, 657-8501 JAPAN

E-mail: tyano@phys.sci.kobe-u.ac.jp

Abstract. Hyper-Kamiokande (Hyper-K) is a proposed next generation underground large water Cherenkov detector. We plan to build two cylindrical water tanks in our experimental period, filled with ultra pure water and surrounded with newly developed photo sensors. In total, it will provide the fiducial volume of 0.19-0.37 Mt. The energies, positions, directions and types of charged particles produced by neutrino interactions are detected using its Cherenkov light in water. Our detector will be located at deep underground to reduce the cosmic muon flux and its spallation products, which is a dominant background for the analysis of the low energy astrophysical neutrinos.

With the fruitful physics research programs planned for the accelerator neutrinos, atmospheric neutrinos and nucleon decay, Hyper-K will play an important role in the next neutrino physics frontier, even in the neutrino astrophysics. It will provide remarkable information for both of particle physics and astrophysics with its large statistics of astrophysical neutrino measurements, i.e., solar neutrino, supernova burst neutrinos and supernova relic neutrino. Here, we will discuss about physics potential of Hyper-K neutrino astrophysics and expected performance of the detector.

1. Introduction

Hyper-Kamiokande (Hyper-K, HK) is a next generation water Cherenkov detector planned in Japan [1, 2, 3], as a successor of the Super-Kamiokande (Super-K, SK) experiment [4]. With the dimensions of the 74 m (D) $\times$ 60 m (H) for each, two cylindrical water tanks provide the fiducial (total) volume of 0.19 (0.26) million metric tons per tank (Figure 1). They are 8 (5) times larger than that of Super-K. The target date for beginning the measurement with first tank is 2026. The measurement with the second tank will begin 6 years after that. Inner detectors are surrounded by 20-inch diameter 40,000 photodetectors. 8-inch diameter 6,700 photodetectors are also provided for an outer veto detector to reject cosmic-ray muons. The 20-inch photodetector, Box&Line dynode photo-multiplier tube Hamamatsu R12860, is newly developed for HK, to achieve twice larger detection efficiency for Cherenkov photons, the superior photon counting and timing resolution compared to that of SK (Hamamatsu R3600) [5]. It also has the high pressure tolerance for the usage below 60 m depth of water. The multiple-photosensor unit is also in our R&D for the outer detector [5, 6]. The detector will be located underground at Kamioka mine in Gifu Prefecture, with an overburden of $\sim$ 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 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



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with beam and atmospheric neutrinos, search for nucleon decay and observations of astrophysical neutrinos.

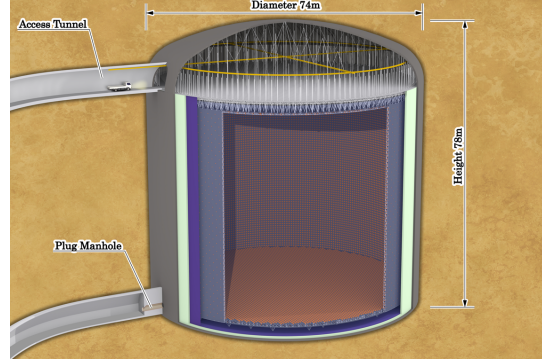


Figure 1. Schematic view of one Hyper-Kamiokande water Cherenkov detector [1]. Our proto-collaboration plans to construct two detector tanks consecutively, aiming the observations start at 2026 and 2032 respectively. Each tank will provide the fiducial volume of 0.187 Mt ultra pure water, with the dimensions of the 74 m (D) $\times$ 60 m (H).

2. Solar Neutrino

The Sun is burning and emitting neutrinos with the nuclear fusion reactions, which 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) [7]. The SSM provides good predictions of the flux and energy spectrum of solar neutrinos. Our main observation target is the boron-8 neutrino, since the analysis threshold of our detector will be $E_{vis} > 4.5$ MeV. Here, E_{vis} is the visible energy of the neutrino event in water Cherenkov detector. It is smaller than the total energy of neutrinos by ~ 1.5 MeV. 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 will be observed in a day at each HK tank, while 15 ν events/day are observed at SK-I.

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 activity of the solar core, where they are generated. Several precise measurements of solar neutrinos would be possible with Hyper-K and its high statistics, e.g. the first measurement of *hep* process neutrino generated in ${}^3\text{He} + p \rightarrow {}^4\text{He} + e^+ + \nu_e$ reaction and the seasonal variation of the ${}^8\text{B}$ neutrino flux. Another major motivation is the study of neutrino properties themselves. Super-K, SNO [8] and several experiments [9, 10, 11] have been measured the neutrino oscillation on the solar neutrinos. A recent result of the oscillation analysis among solar neutrino experiments is following: $\sin^2 \theta_{12} = 0.334^{+0.027}_{-0.023}$, $\Delta m_{21}^2 = 4.8^{+1.5}_{-0.8} \times 10^{-5} \text{ eV}^2$ [12]. On the other hand, a reactor neutrino experiment, KamLAND, also measured these oscillation: $\tan^2 \theta_{12} = 0.56^{+0.14}_{-0.09}$, $\Delta m_{21}^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5} \text{ eV}^2$ [13]. Figure 2 shows the comparison of these two measurement results and these combined result. The $\sim 2\sigma$ tension between these Δm_{21}^2 measurements could be tested by Hyper-K. The tension is 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 would arise from the terrestrial matter effect. With Hyper-K, the day-night asymmetry effect can be measured precisely with the large statistics. Assuming the current solar best Δm_{21}^2 parameter, our measurement will be precise enough to separate itself from the current KamLAND best

value about 4σ with 10 years observation (Figure 3). The difference of $P_{\nu_e \rightarrow \nu_e}$ in solar neutrino oscillation and $P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$ in reactor neutrino will be a test of CPT violation at neutrinos. The solar neutrino energy spectrum upturn is also the interesting physics properties. It is predicted by MSW-LMA hypothesis and possibly affected by physics beyond the standard model. The non-zero upturn sensitivity will be about 3σ (4σ) after the 10 years solar neutrino measurement with 4.5 MeV (3.5 MeV) threshold.

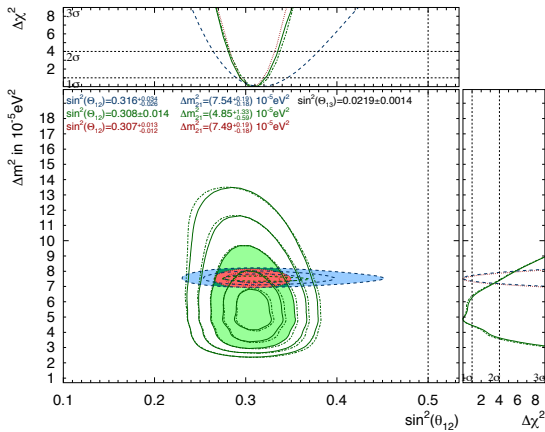


Figure 2. Neutrino oscillation parameter allowed region from all the solar experiments (green), KamLAND (blue) and Solar+KamLAND (red) from 1 to 5 σ lines and 3 σ area are shown[12]. The dashed green line is the combined results of SK and SNO.

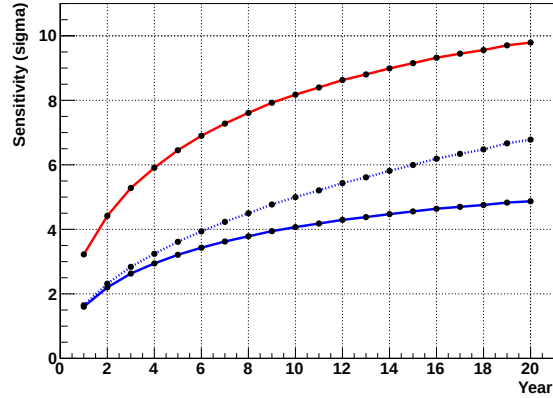


Figure 3. Day-night asymmetry observation sensitivity as a function of observation time. The red line shows the sensitivity from the no asymmetry, while the blue line shows from the asymmetry expected by the reactor neutrino oscillation. The solid line shows that the systematic uncertainty is 0.3%, while the dotted line shows the 0.1% case.

3. Supernova Neutrinos

Core collapse supernova explosions 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 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 ($\bar{\nu}_e + p \rightarrow e^+ + n$). For each full volume of two inner detectors, we expect to see about 49,000-68,000 inverse beta events, 2,100-2,500 ν -e scattering events, 80-4,100 $\nu_e + {}^{16}\text{O}$ CC events, and 650-3,900 $\bar{\nu}_e + {}^{16}\text{O}$ CC events, in total 52,000-79,000 events for a supernova explosion at halfway across our galaxy (10 kpc, Figure 4). The statistical error will be small enough to compare several SN models, and so Hyper-K should give crucial data for further model predictions (Freffig:model). A new characteristic modulation of the supernova neutrino flux also can be tested with HK, which the recent computer simulations predict. In

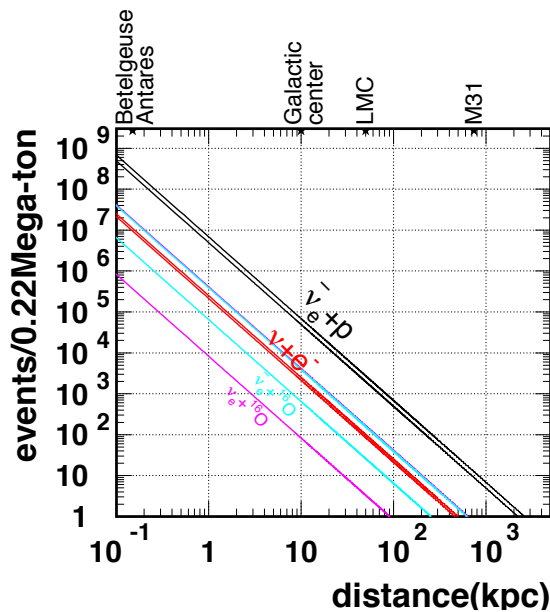


Figure 4. Expected number of supernova burst events for each interaction as a function of the distance to a supernova. The band of each line shows the possible variation due to the assumption of neutrino oscillations.

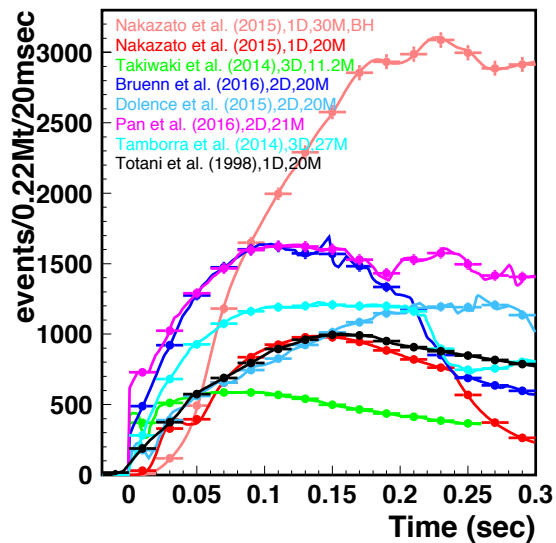


Figure 5. Inverse beta event rate predicted by supernova simulations for the first 0.3 seconds after the onset of a 10kpc distant burst. The error bars shows the statistic error.

past simulation, the deceleration of the shock wave and resulting failed explosion were annoying problems. Recent simulations suggest that the shock wave will be heated efficiently by neutrinos to revival, due to the physical motions in a supernova, Standing Accretion Shock Instability (SASI) or convection, rotation or supernova are the examples. These models also predict the characteristic frequency modulation of neutrino flux, due to the motions in supernovae. The detection of these modulation will prove the neutrino as the driver of supernova explosions. Other topics for astrophysics and particle physics also can be examined, e.g. direct observation of black hole formations and mass hierarchy of neutrinos.

Another observation target 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 the fraction of strange supernova explosions like dim supernovae or black hole formations (Figure 6). 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. With incoming detector update, Gd-loaded Super-Kamiokande (SK-Gd) can be the discoverer of SRN. The number of event in their detector will be 0.8-5 events/year above 10 MeV. Even though, it is still very interesting physics theme to measure and determine the precise flux of SRN. ~70 SRN events are expected at 16-30 MeV with 1 tank and 10 years observation. The significance will be 4.2 σ and enough for confirming the discovery (Figure 7). Further studies for astro and particle physics topics will be performed.

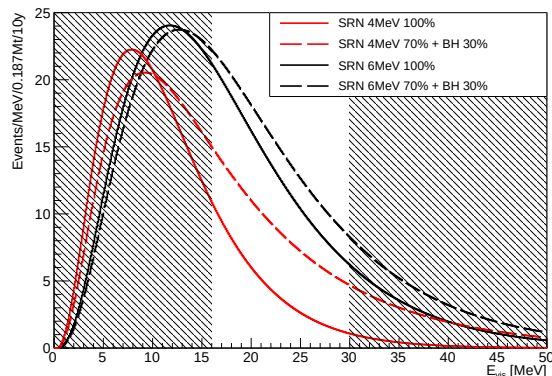


Figure 6. The expected SRN signal in 1 tank FV and 10 years observation. Black line shows the case of supernova neutrino temperature of 6 MeV, and red shows the case of 4 MeV [15, 16]. Solid (dashed) line corresponds to the case, in which all the core-collapse supernovae emits neutrinos with the particular energy (30% of them form black hole and emits higher energy neutrinos with the temperature of 8 MeV). Shaded energy region shows the range out of SRN search window at Hyper-K.

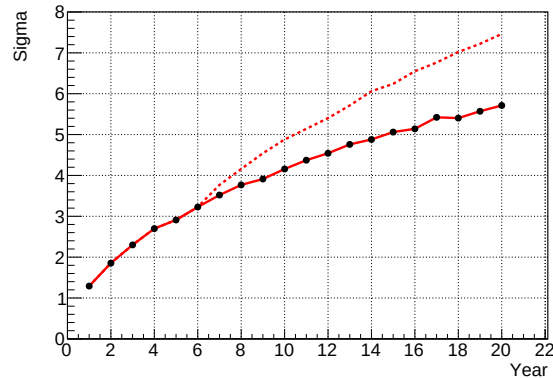


Figure 7. The figure shows the number of observed the SRN discovery sensitivity as a function of observation period. Red solid line shows the continuous measurement with 1 tank and red dashed line shows the scenario with 2 tanks after 6 years, respectively.

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 a crucial role in the next neutrino physics frontier for both of particle physics and neutrino astrophysics.

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