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Sensitivity Study for Astrophysical Neutrinos at Hyper-Kamiokande

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Hyper-Kamiokande (Hyper-K) is a next generation underground large water Cherenkov detector. The detector is filled with ultra-pure water and surrounded with newly developed photodetectors. It will provide the fiducial volume of 0.187 Mt, which is 8 times larger than preceding experiment Super-Kamiokande. The energies, positions, directions and types of charged particles produced by neutrino interactions can be identified using its Cherenkov light in water. The Hyper-K detector will be located at deep underground to reduce the cosmic muon flux and its spallation products, which is a dominant background for the low energy astrophysical neutrino measurements. With its fruitful physics research programs, Hyper-K will play a critical role in the next neutrino physics frontier. It will also provide important information via astrophysical neutrino measurements, i.e., solar neutrino, supernova burst neutrinos and supernova relic neutrino. Here, we will discuss the physics potential of Hyper-K neutrino astrophysics.

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1. Introduction

Hyper-Kamiokande (Hyper-K, HK) is a next generation water Cherenkov detector planned in Japan [1], as a successor of the Super-Kamiokande (Super-K, SK) experiment [2]. With the dimensions of the 64 m (D) × 71 m (H) for each, our cylindrical water tanks provide the fiducial (total) volume of 0.187 (0.26) million metric tons (figure 1). They are 8 (5) times larger than those of Super-K. After the budget approval from the Japanese government at 2020, the construction of Hyper-K is started toward the observation which will start at 2027. Our cylindrical detector structure will be separated to inner and outer detectors. The inner detector will be surrounded by 20-inch diameter 40,000 photodetectors. 8-inch diameter 6,700 photodetectors will be installed for the outer veto detector to remove cosmic-ray muon backgrounds. The 20-inch photodetector, Box&Line dynode photo-multiplier tube Hamamatsu R12860, is newly developed for HK. It achieved twice better photon detection efficiency, the superior photon counting and timing resolution compared to the photodetector used in SK (Hamamatsu R3600) [3]. It also has the high-pressure tolerance for the usage below 70 m depth of water. The multiple-photosensor unit is also in our R&D [3, 4]. The detector will be located underground with an overburden of ~650 meters of rock, which is equivalent to 1,750 meters 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 beam and atmospheric neutrinos, search for nucleon decay and observations of astrophysical neutrinos.

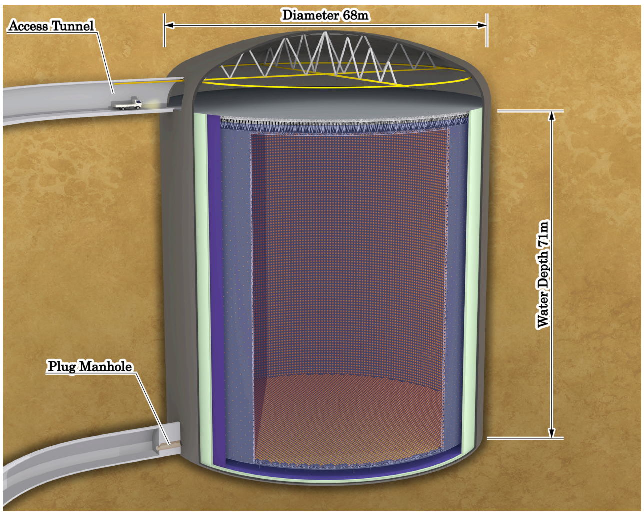

Figure 1: Schematic view of one Hyper-Kamiokande water Cherenkov detector [1].

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. They can be summarized as follows: $4p \to \alpha + 2e^{+} + 2\nu_e$. These processes are well described with the standard solar model (SSM) [5, 6]. Our main observation target is the ^{8}B neutrino, produced by $^8\mathrm{B}\rightarrow{}^8\mathrm{Be}^* + e^+ + \nu_e$, with its high energy above our analysis threshold of $E_{vis} > 4.5$ MeV. ^{8}B neutrino is observed through neutrino-electron elastic scattering, $\nu + e \rightarrow \nu + e$. E_{vis} is the visible energy of the neutrino event in water Cherenkov detector, which is equivalent to the scattered electron kinematic energy in the reaction above. About 130 ν-e scattering events will be observed with Hyper-K per day, while 21 ν events/day are observed at SK-IV.

2.1 Solar Neutrino Oscillation

The solar neutrino measurement is capable of determining the neutrino oscillation parameters between neutrino mass eigenstates. Super-K [7], SNO [8] and several experiments have been performed the neutrino oscillation measurement on the solar neutrinos. Figure 2 shows the latest results 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 [9].

- Solar combined results: $\sin^2\theta_{12} = 0.334^{+0.027}_{-0.023}$, $\Delta m^2_{21} = 4.8^{+1.5}_{-0.8} \times 10^{-5}\,\mathrm{eV}^2$ [7]
- Reactor results: $\tan^2\theta_{12} = 0.56^{+0.14}_{-0.09}$, $\Delta m^2_{21} = 7.58^{+0.21}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$ [9]

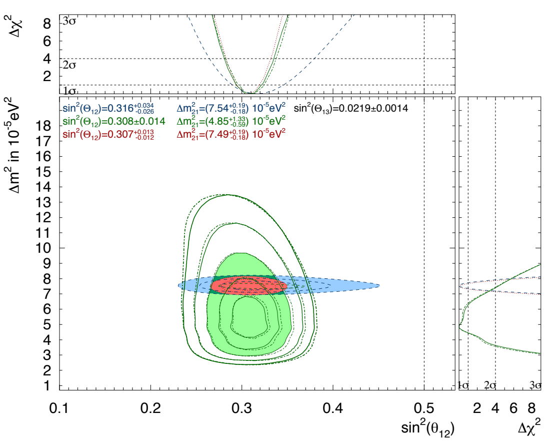

Figure 2: Neutrino oscillation parameter allowed region from all solar experiments (green), KamLAND (blue) and Solar+KamLAND (red) from 1 to 5 σ lines and 3 σ area are shown[7]. The green dashed line is the combined results of SK and SNO.

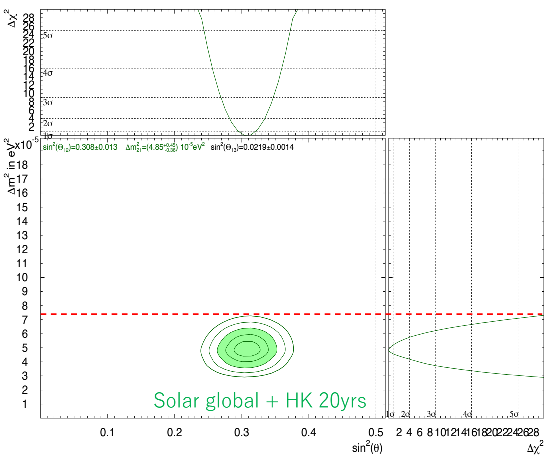

Figure 3: Neutrino oscillation parameter allowed region, with all solar neutrino experiments at 2018[10] and Hyper-K 20 years observation. 1 to 5 σ lines and 3 σ area are shown here. The red dashed line shows the best Δm^2_{21} parameter given by KamLAND.

Though θ_{12} is consistent between solar and reactor neutrinos, we see ~2 σ tension between these Δm^2_{21} results. The tension is mainly derived from the asymmetry of the solar neutrino flux during day and night (day-night asymmetry), which was indicated by Super-K [11]. The asymmetry would 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 more event rate in the nighttime, than that in the daytime [11]. With Hyper-K, the day-night asymmetry effect

can be measured precisely with our large detector volume. Assuming the current solar best Δm^2_{21} parameter, our measurement will be possible to separate itself from the current KamLAND best value about 4 (5) σ with 10 (20) years observation (figure 3). The difference of $P_{\nu_e \to \nu_e}$ in solar neutrino oscillation and $P_{\bar{\nu_e} \to \bar{\nu_e}}$ in reactor neutrino will introduce the test of new physics, e.g. CPT violation of neutrinos.
The solar neutrino energy spectrum upturn is also the interesting physics target. It is predicted by MSW-LMA hypothesis [7] and possibly affected by physics beyond the standard model, such as non-standard interaction [12], mass-varying neutrino oscillation [13] and sterile neutrino [14]. The non-zero upturn sensitivity will be about 3 (4) σ after the 10 years solar neutrino measurement with 4.5 MeV (3.5 MeV) threshold.

2.2 Hep Solar Neutrino Search

Another motivations of solar neutrino observation is the test of the SSM predictions. Hep solar neutrino, produced by ^{3}He+$p \to ^4$He+$e^+ + \nu_e$ reaction is an undiscovered solar neutrino. Though it has the highest energy in solar neutrinos, most of the energy spectrum overlaps with that of ^{8}B solar neutrinos. So far, only upper limits were reported by SNO[15].The uncertainty of the measured hep neutrino flux will be ~60% (~40%) and the non-zero significance will be 1.8 (2.3) σ after 10 (20) years observation in Hyper-K.

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 ~ 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 ($\bar{\nu}_e + p \to e^+ + n$). 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 ν_e+^{16}O CC events, and 650-3,900 $\bar{\nu}_e$+^{16}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 (figure 5). 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 of 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

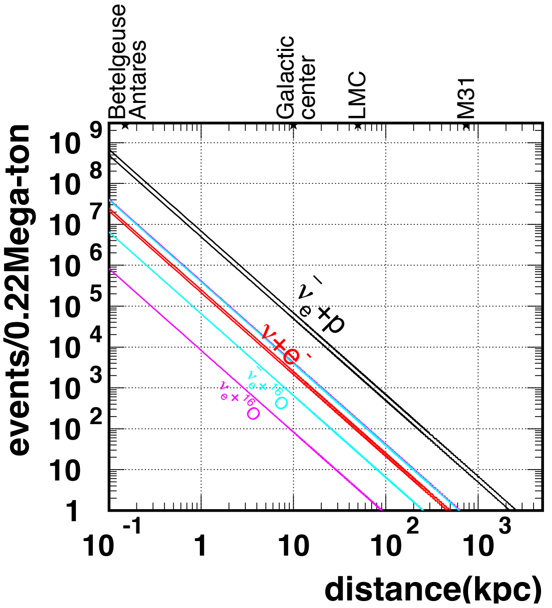

Figure 4: Expected number of supernova burst events for each interaction as a function of the distance to a supernova. The band of each color shows the variation due to the neutrino oscillation cases.

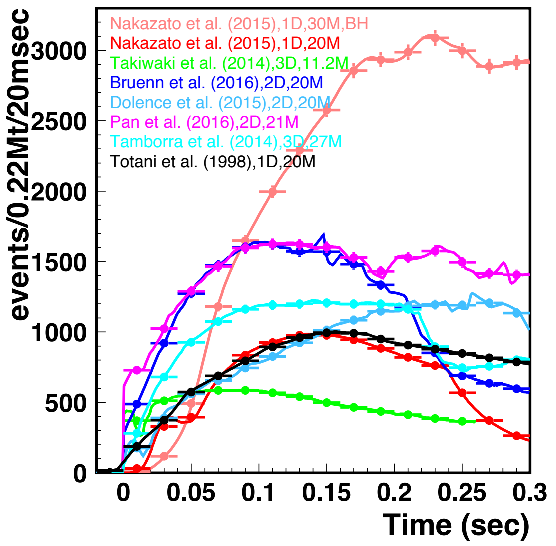

Figure 5: Inverse beta event rate predicted by supernova simulations for the first 0.3 seconds after the onset of a 10kpc distant burst. The error bars shows the statistic error.

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/cm^2/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. 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 events 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 10 years observation. The significance will be 4.2 σ and enough for confirming the discovery. Further studies for astrophysics and particle physics topics will be performed.

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. Solar neutrino measurement is one of the features of Hyper-K. Several precise measurements of solar neutrinos would be possible with Hyper-K and its high statistics, e.g. the solar neutrino oscillation, the search for physics beyond the standard model, the first measurement of hep process neutrino and also the seasonal variation measurement of the ^{8}B neutrino flux. The unique high statistics information for supernova burst and supernova relic neutrinos will be also available. As a conclusion, 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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