PROCEEDINGS OF SCIENCE

Solar neutrino physics at Hyper-Kamiokande

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Hyper-Kamiokande is a multi-purpose next generation neutrino experiment. The detector is a two-layered cylindrical shape ultra-pure water tank, with its height of 60 m and diameter of 74 m. The inner detector will be surrounded by 40,000 twenty-inch photosensors to detect water Cherenkov radiation due to the charged particles and provide our fiducial volume of 187 kt. This detection technique is established by Kamiokande and Super-Kamiokande. As the successor of these experiments, Hyper-K will be located deep underground, 650 m below Mt. Nijuugo-yama at Kamioka in Japan to reduce cosmic-ray backgrounds. Besides our physics program with accelerator neutrino, atmospheric neutrino and proton decay, neutrino astrophysics is an important research topic for Hyper-K. The sun is an important natural source of neutrinos, and neutrino is almost sole particle which can carry out the information of the solar core. Current observation of solar neutrino is well explained with standard solar model and neutrino oscillation. Though, we still see about 2 sigma discrepancy of neutrino mass squared difference between the solar and reactor experiments. Hyper-K will resolve the problem with large statistics observation. Our solar neutrino observation is also motivated by the detection of He+p neutrino or periodic modulation of the flux. In this presentation, our physics performance with solar neutrino will be discussed.

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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 those of Super-K. The target date for beginning the measurement with first tank is 2027. The inner detector will be surrounded by 20-inch diameter 40,000 photodetectors. 8-inch diameter 6,700 photodetectors are also provided 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, 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 detector [5, 6]. 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 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.

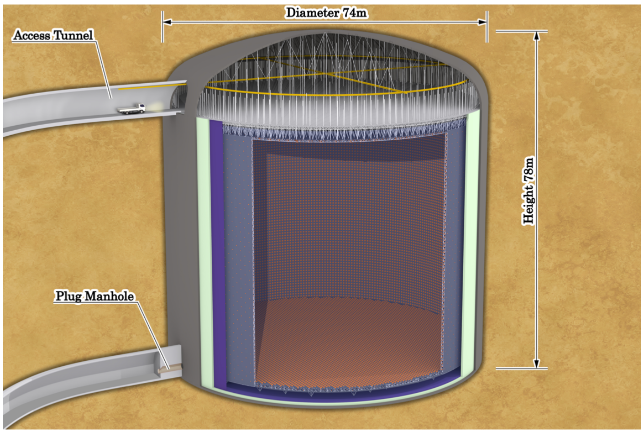

Figure 1: Schematic view of one Hyper-Kamiokande water Cherenkov detector [1]. Our proto-collaboration aims at starting the observations at 2027. The tank will provide the fiducial volume of 0.187 Mt ultra pure water, with the dimensions of the 74 m (D) $\times$ 60 m (H).

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. They can be summarized as follows: $4p \rightarrow \alpha + 2e^+ + 2\nu_e$.

These processes are described with the standard solar model (SSM) [7, 8]. The SSM provides good predictions of the flux and energy spectrum of solar neutrinos. Our main observation target is the ^{8}B neutrino, because of its 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. 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.

2.1 Solar Neutrino Oscillation

The solar neutrino measurement are capable of determining the neutrino oscillation parameters between neutrino mass eigenstates. Super-K [9], SNO [10] and several experiments [11, 12, 13] 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 [14].

- Solar combined results: $\sin^2\theta_{12} = 0.334^{+0.027}_{-0.023}$, $\Delta m^2_{21} = 4.8^{+1.5}_{-0.8} \times 10^{-5}\,\mathrm{eV}^2$ [9]
- Reactor results: $\tan^2\theta_{12} = 0.56^{+0.14}_{-0.09}$, $\Delta m^2_{21} = 7.58^{+0.21}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$ [14]

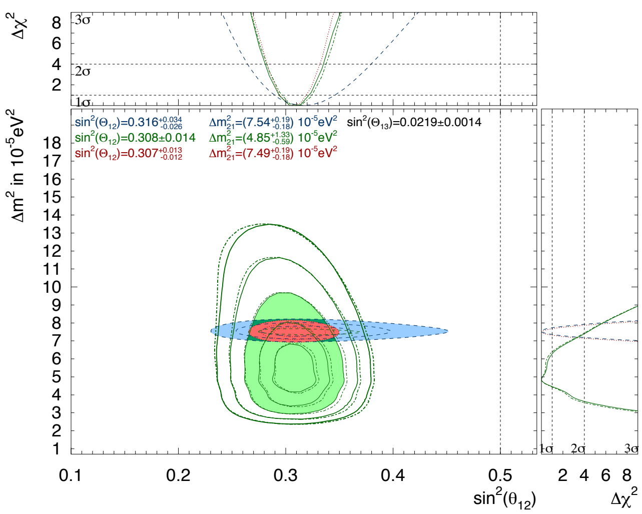

Figure 2: Neutrino oscillation parameter allowed region from all the solar experiments (green), KamLAND (blue) and Solar+KamLAND (red) from 1 to 5 σ lines and 3 σ area are shown[9]. The dashed green line is the combined results of SK and SNO.

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 [15]. 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. 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 4σ with 10 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

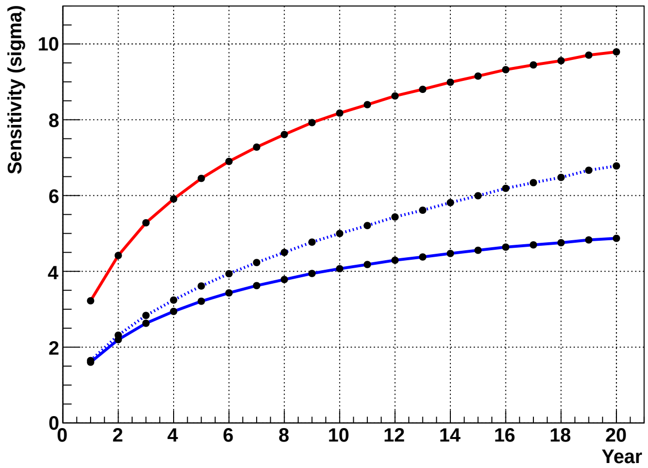

Figure 3: Day-night asymmetry observation sensitivity as a function of observation time. The red line shows the sensitivity from the no asymmetry, while the blue line shows from the asymmetry expected by the reactor neutrino oscillation. The solid line shows that the systematic uncertainty is 0.3%, while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

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 properties. It is predicted by MSW-LMA hypothesis and possibly affected by physics beyond the standard model, such as non-standard interaction[16], mass-varying neutrino oscillation[17] and sterile neutrino[18], for example. 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.

2.2 Hep Solar Neutrino Search

One of the motivations of solar neutrino observation is the test of the solar standard model predictions. Because of its high penetration power, neutrino is the unique prove for the activity of the solar core today, where they are generated. Hep solar neutrino, produced by $^3\mathrm{He}+p \to {}^4\mathrm{He}+e^+ + \nu_e$ reaction is an undiscovered solar neutrino. Though it has the highest energy in solar neutrinos, most of the energy spectrum is overlapped with that of ^{8}B solar neutrinos. So far, only upper limits were reported by SNO[19] and Super-K[20] groups. Recent SNO charged-current reaction results indicates higher hep neutrinos than the SSM prediction[21]. In figure 5, the expected hep solar neutrino events in 1.9 Mton year in Hyper-K is shown. Figure 6 shows the hep neutrino detection sensitivity. The uncertainty of the hep neutrino flux will be ~60% (~40%) and the non-zero significance will be $1.8\sigma(2.3\sigma)$ in ten (twenty) years observation in Hyper-K.

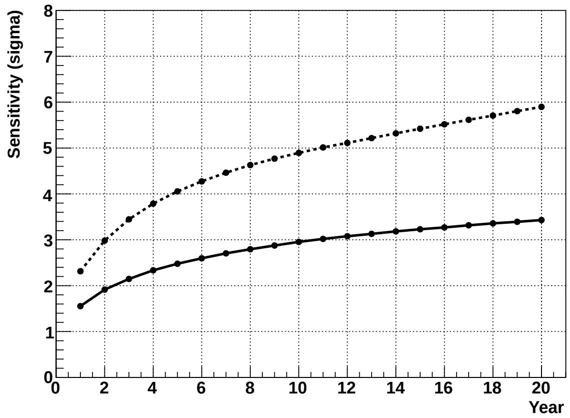

Figure 4: Discovery sensitivity for solar neutrino spectrum upturn as a function of the observation time. The solid line shows the case with the energy threshold of 4.5 MeV, while the dotted line shows the case with the energy threshold of 3.5 MeV,

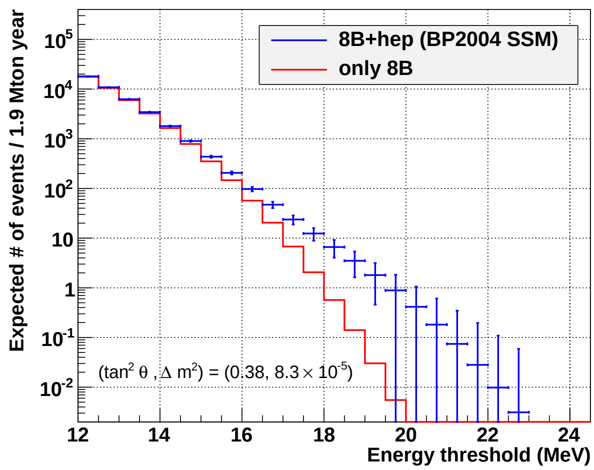

Figure 5: Expected hep solar neutrino events with neutrino oscillations in Hyper-K. The horizontal axis is the energy threshold in electron total energy and vertical axis is expected event rate in the energy range from the threshold up to 25 MeV. SSM fluxes[7] are assumed here.

3. 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 sea-

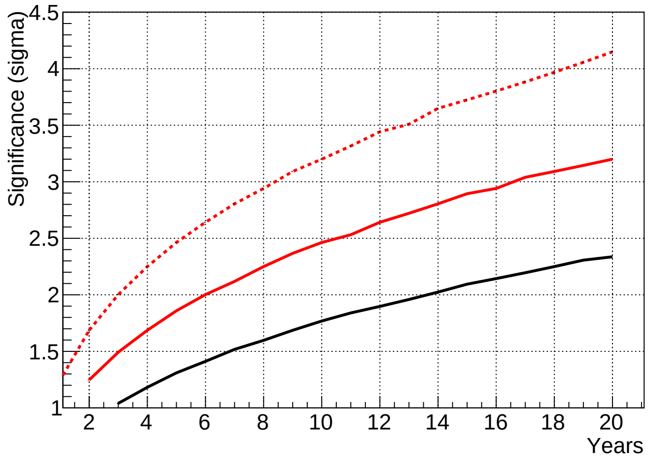

Figure 6: Expected hep solar neutrino sensitivity with Hyper-K as a function of the observation time. The vertical axis is non-zero significance of hep neutrino signal, assuming SSM fluxes[7]. The black line shows the expected sensitivity with the cosmic-ray muon spallation background at Hyper-K candidate site. The red solid and dashed lines shows the case in Super-K site and no spallation background, respectively.

sonal variation measurement of the ^{8}B neutrino flux. 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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