Neutrino astrophysics with Hyper-Kamiokande

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Abstract. Hyper-Kamiokande (Hyper-K) is a proposed next generation underground large water Cherenkov detector. The detector consists of 1 Mt pure water tank with surrounding 99,000 newly developed photo sensors, providing fiducial volume of 0.56 Mt. The energies, positions and directions 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 at the low energy analysis. Hyper-K will play a considerable role in 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) is a next generation water Cherenkov detector planned in Japan [1][2][3]. Hyper-K is a successor of the Super-Kamiokande (Super-K) [4], in which several physics topics are studied such as the nucleon decay and the properties of atmospheric, beam and astrophysical neutrinos. With their dimensions of the 48 (W) × 54 (H) × 250 (L) m³ for each, two cylindrical water tanks provide the total (fiducial) volume of 1.0 (0.56) million metric tons (Figure 1). The volume is 20 (25) times larger than that of Super-K. The inner detectors are surrounded by 99,000 photodetectors with a 50 cm diameter. 25,000 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 charged particle, respectively. The new photodetectors, with superior photon counting capability and timing resolution to conventional photomultiplier tubes used in Super-K, is being developed for Hyper-K. Hyper-K has various physics topics: search for CP violation in neutrinos, precise study of neutrino oscillations including determination of mass hierarchy and $\theta_{23}$ octant with beam and astrophysical neutrinos, search for nucleon decay and observation of astrophysical neutrinos.

In this paper, we will discuss about the observation of astrophysical neutrinos, i.e. solar neutrinos, supernova burst neutrinos and supernova relic neutrinos. With its huge target mass, the large number of neutrino events and superior sensitivity to these signals are expected with Hyper-K detector. The gamma-ray burst and dark matter annihilation in stars are also possible astrophysical neutrino sources for Hyper-Kamiokande, though they won’t be discussed here.
2. Solar Neutrino

The Sun is burning with the nuclear fusion reactions and emitting neutrinos. These series of reactions are called as the pp-chain and the CNO cycle and can be summarized: \(4p \rightarrow \alpha + 2e^+ + 2\nu_e\). These processes in the Sun are described with the standard solar model (SSM) [5]. The SSM also provides the good prediction of flux and energy spectrum of solar neutrinos.

With the Hyper-Kamiokande detector, the solar neutrinos with \(E_{\nu} > 6.5\) MeV are detectable. Because of the energy threshold, our dominant observation target will be boron-8 neutrinos (\(^8\)B). These neutrinos are observed through neutrino-electron elastic scattering, \(\nu_e + e^- \rightarrow \nu_e + e^-\). The energy, direction and time of the original neutrinos can be measured through the recoil electron.

About 200 \(\nu-e\) scattering events will be observed in a day with Hyper-K, while 15 \(\nu\) events/day are observed with Super-K.

One of the major motivations of solar neutrino research is the test of the solar model predictions. Because of its high penetration power, neutrino is the unique prove for the current status of the center of Sun, where they are generated. Another major motivation is the study of neutrino properties themselves. Super-K, SNO [6] and several experiments [7][8][9] have been measured the neutrino oscillation on the solar neutrino. A recent result of the oscillation analysis among solar neutrino experiments is follows: \(\sin^2 \theta_{12} = 0.311^{+0.014}_{-0.014}, \Delta m_{21}^2 = 4.85^{+1.4}_{-0.50} \times 10^{-5} eV^2\) [10].

On the other hand, a reactor neutrino experiment, KamLAND, also measured these oscillation parameters as follows: \(\tan^2 \theta_{12} = 0.436^{+0.029}_{-0.029}, \Delta m_{21}^2 = 7.53^{+0.18}_{-0.18} \times 10^{-3} eV^2\) [10]. Figure 2 shows the comparison of these two measurement results and these combined result. The \(\sim 2 \sigma\) tension between these \(\Delta m_{21}^2\) measurement could be tested by Hyper-Kamiokande.

The tension is mainly come from the asymmetry of the solar neutrino flux during day and night (day-night asymmetry), which is recently indicated by Super-Kamiokande [11]. The asymmetry arises from the terrestrial matter effect, which the solar neutrinos pass through during only night period. With the Hyper-Kamiokande, the day-night asymmetry can be measured with the large statistics. Assuming the current solar best \(\Delta m_{21}^2\), the result of Hyper-K will be precise enough to separate itself from the current KamLAND best value above 3.5\(\sigma\) with 10 years measurement. 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.

Because of the huge statistics with Hyper-Kamiokande, many precise measurements of solar neutrino would also be possible, e.g. the undiscovered Hep process neutrino generated in \(^3\)He\(+p \rightarrow ^4\)He\(+e^+ + \nu_e\) reaction, the solar neutrino energy spectrum upturn where the beyond standard model physics could be, and the seasonal variation of the flux. Optimization of the detector, reduction of the systematic errors and careful calibrations will be performed for these studies.
3. Supernova Neutrinos

Core collapse supernova explosions are the last process in the evolution of massive stars (>8M$_\odot$). The energy released by a supernova is estimated to be $\sim 3 \times 10^{53}$ ergs. 99% of the energy is carried out by all three types of neutrinos and anti-neutrinos, since they interact weakly with matter. 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 neutrinos with the large volume detector is desired.

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. The dominant signal at Hyper-K is inverse beta reaction ($\bar{\nu}_e + p \rightarrow e^+ + n$). Figure 3 shows the expected number of supernova neutrino events at Hyper-K versus the distance to a supernova. At the full volume of inner detector, we expect to see about 165,000 to 230,000 inverse beta events, 7,000 to 8,000 $\nu$-$e$ scattering events, 300 to 14,000 $\nu_e + ^{16}$O CC events, and 2,000 to 13,000 $\bar{\nu}_e + ^{16}$O CC events, in total 170,000 to 260,000 events for a supernova explosion at halfway across our galaxy (10 kpc). The neutrino fluxes and energies obtained by the Livermore simulation [14] is used for these estimations. Figure 4 shows inverse beta event rates predicted by various models for the first 0.3 sec after the onset of a burst. The statistical error is much smaller than the difference between the models, and so Hyper-K should give crucial data for comparing model predictions.

The recent computer simulations for supernova predict new characteristic modulation of the supernova neutrino flux. It is Standing Accretion Shock Instability (SASI), due to the motions in supernovae and the key feature of successful explosions in the simulations. The modulation can be observed as a variance of $\pm 100$ events on a 5 ms timescale for a supernova at 10 kpc [11]. The large statistics can prove the existence of SASI by performing frequency analysis. Hyper-K will be possible to alert a supernova burst for other supernova observation experiments with its high directional sensitivity, $\sim 2$ degrees for a supernova at 10 kpc. The multi-messenger observation of supernova with visible light, gamma-ray, x-ray and gravity wave will also reveal the supernova explosion system in details.

Another observation is about the supernova relic neutrinos (SRN), produced by all the past supernova explosions since the beginning of the universe and diffused. They must fill the present universe and their flux is estimated to be a few tens/cm$^2$/sec (figure 5). SRN contains the
Figure 3. 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 [1].

Figure 4. Inverse beta event rate predicted by supernova simulations for the first 0.3 seconds after the onset of a 10kpc distant burst [1, 14-18].

Figure 5. Predictions of the supernova relic neutrino (SRN) spectrum. Fluxes of reactor neutrinos and atmospheric neutrinos are also shown [1, 19-25].

information of its origins, i.e. the star formation rate, energy spectrum of supernova burst neutrinos, and black hole formations[26]. 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 the Hyper-K, ~200 SRN events are expected between 18.5 MeV and 30 MeV in 10 years. The significance will be 4.5~6 sigma for the discovery. The statistics will be enough for further studies.
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. With its huge volume and statistics, we will provide the unique information for solar neutrino, supernova burst neutrino and supernova relic neutrino. Hyper-K will play remarkable role in the next neutrino physics frontier for both of particle physics and neutrino astrophysics.

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