Results from Super-K

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Super-Kamiokande (Super-K, SK) is an underground water Cherenkov detector which consists of 50,000 tons of pure water equipped with about 13,000 photo-multipliers (PMTs). The front-end electronics and data acquisition (DAQ) system were upgraded in September 2008 and data-taking as a SK-IV phase was started. While it is a far detector of the T2K experiment, various other physics analyses are ongoing for such as atmospheric neutrino physics, solar neutrino physics, the relic supernova neutrino search, and the indirect WIMP search, etc. In this paper, the current status and results from Super-K will be presented.

1 Introduction

Super-Kamiokande is a water Cherenkov detector located in the 1000m-deep underground. Neutrinos from several different sources such as atmospheric [1], solar [2], accelerator [3] and supernova burst neutrino[4] have been observed and also searches for relic supernova neutrinos[5] and proton-decay [6 7 8] are in operation. The detector contains 50,000 tons of pure water equipped with about 11,000 of 20-inch PMTs for an inner detector and about 2,000 of 8-inch PMTs for an outer veto detector. Timing and charge information of a signal from each PMT is recorded and ring images of Cherenkov light are reconstructed from that information.

The measurement periods of SK are divided into four phases, so called SK-I, SK-II, SK-III, and SK-IV. The first phase of SK-I started in 1996 and continued until an accident destroyed half of PMTs in November 2001. After relocating the rest of the PMTs uniformly on the wall, the SK-II phase started in 2003 and lasted by October 2005. The half of PMTs were then newly installed, and the SK-III phase stated in July 2006 with the full photocathode coverage. The SK-III phase ended in August, 2008 and new electronics and online DAQ system were installed to improve the sensitivity and performance of the detector [9 10]. Since September 2008, the new phase of SK-IV has been collecting data with the new DAQ system. In this paper, we will describe the current results of the SK data analyses, and R & D work for a future project will also be explained.

2 Atmospheric Neutrino Oscillation Analysis

Since the first result of the two-flavor atmospheric neutrino oscillation was published in 1998 [11], much effort has been devoted to reduce systematic errors by the improvement of the Monte Carlo (MC) simulation and the event reconstruction tools for the sake of obtaining more precise values and better upper limits of the neutrino oscillation parameters. Recently we have analyzed

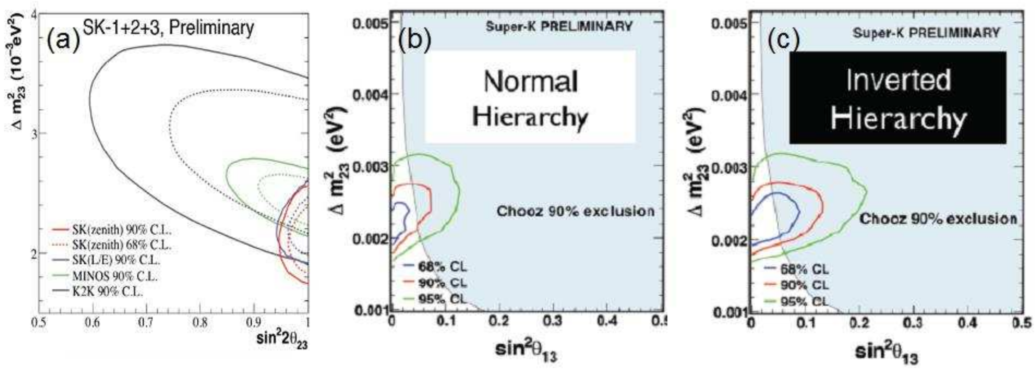

Figure 1: (a) Allowed regions of oscillation parameters for two-flavor zenith angle analysis (red) and L/E analysis (blue) using SK I+II+III data. Allowed regions by other experiments are also displayed. (b,c) Allowed regions for three-flavor zenith angle analyses using SK I+II+III data when assuming normal hierarchy (b) and inverted hierarchy (c). The shaded region shows the Chooz 90% exclusion region.

SK-III data and the result of the combined analysis for the SK-I, II, and III data is now available. The total livetime is 2,806 days.

In the atmospheric neutrino oscillation analysis, neutrino candidates are categorized into three types. They are fully contained (FC) events, partially contained (PC) events and upward-going muon (UPμ) events. The FC events have their interaction points inside the inner detector and the produced particles deposit all their energy within it. The PC events also have the interaction vertices in the inner detector, but some of the produced particles go out of the inner detector. For UPμ events, neutrinos interact in the outer surrounding rock and produced muons are detected in the SK detector. In this case, downward-going muons cannot be used for analysis because the cosmic ray muons are dominant for the downward direction. Typical neutrino energy of FC, PC and UPμ samples are 1 GeV, 10 GeV and 100 GeV, respectively.

To obtain the oscillation parameters from the SK atmospheric neutrino data, there are two types of analyses, which are zenith-angle and L/E analyses. In the zenith-angle analysis, zenith-angle distributions are prepared for many sub-samples divided by conditions of the event types (FC, PC and UPμ events) and energy, the number and types of Cherenkov rings. The least chi-square method is used with MC samples to obtain oscillation parameters. On the other hand, the L/E analysis, where L is a neutrino path length and E is neutrino energy, is sensitive to a dip in the L/E spectrum characteristic of the neutrino oscillation. The least chi-square method is also used to fit the L/E spectrum with free oscillation parameters.

Fig. 1(a) shows the results of the two-flavor oscillation analyses with both zenith-angle and L/E methods for SK-I, II and III data, together with the results from accelerator neutrino experiments[3 12]. The allowed regions of the two methods coincide well. The SK result currently gives the most stringent limit for $\sin^2 2\theta_{23}$ and a comparable limit for $|\Delta m^2_{23}|$ to the other experiments. In addition to the two-flavor analysis, we have done a three-flavor analysis with an assumption of $|\Delta m^2_{12}| \ll |\Delta m^2_{23}|$. Then the oscillation function can be described with three parameters $\sin^2\theta_{13}$, $\sin^2\theta_{23}$, $|\Delta m^2_{23}|$ and sign of Δm^2_{23}. We went through basically the same method as the 2 flavor zenith-angle analysis. The obtained results are shown in Fig. 1(b) and (c). Zero consistent $\sin^2\theta_{13}$ value was obtained[13].

3 Proton Decay Search

In the grand unification theory (GUT), there is a unique prediction that the baryon number is not conserved, which leads that a proton could decay into a lepton and a meson via an exchange

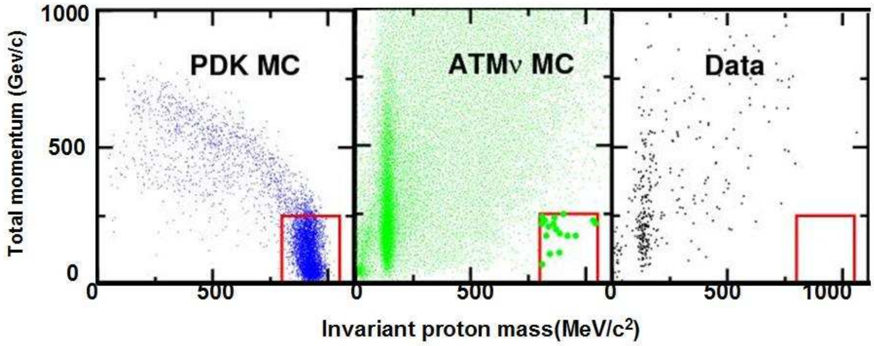

Figure 2: Total momentum versus total invariant proton mass distributions of proton decay MC (left), atmospheric neutrino MC (middle) and SK-III data (right).

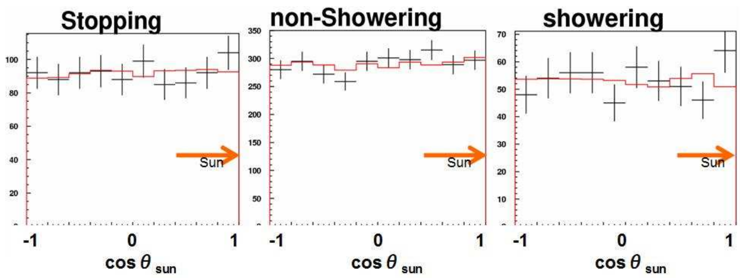

Figure 3: solar angle distributions for stopping (left), non-showeing (middle) and showering(right) muons. A red line in each figure indicates the atmospheric neutrino MC.

of a heavy gauge boson between two quarks. Among possible decay modes, $p \rightarrow e^+ + \pi_0$ is favored by many GUT models including the minimal SU(5) theory, while GUT models including supersymmetry favor the mode of $p \rightarrow \bar{\nu} + K^+$. In the $e^+ + \pi_0$ mode, the proton decays into two bodies and then the produced pion immediately decays into two gammas. From the SK data, we may reconstruct two or three Cherenkov rings with an electromagnetic shower (e-like rings). The event selection for the $e^+ + \pi_0$ mode is as follows. Firstly, FC events are selected, and two or three e-like Cherenkov rings not followed by Michel electrons are required for the events. Then we require that the reconstructed π_0 invariant mass should be between 85 and 185 MeV for events with three Cherenkov rings. For all events, we require that the total invariant mass and total momentum should be between 800 and 1050 MeV and less than 250 MeV/c, respectively.

Fig. 2 shows plots of the total momentum versus total invariant mass distributions for proton-decay MC, atmospheric MC which is a main background of the proton-decay search and the data of the SK-III phase. The exposure of SK-III data is 31.9 kton year. We have not found any events in the region of interest. From the combined results in SK-I, II and III, we set a new lower limit for the $e^+ + \pi_0$ mode, which is 1.0×10^{34} year with the exposure of 172.8 kton year. We have also obtained a new lower limit of 3.3×10^{33} years for the $\bar{\nu} + K^+$ mode from SK-I, II and III data.

4 Indirect WIMP Search

From several astrophysical and cosmological stuffs, a large amount of the matter in the universe should consist of invisible "dark matter". One of the main candidates for the cold dark matter

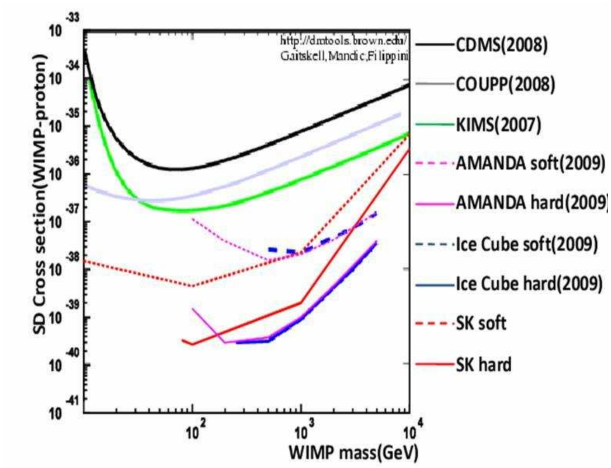

Figure 4: Limits of spin-dependent cross section of WIMPs for SK(red) and other experiments. The SK limits are calculated for both a soft channel (dotted line) and a hard channel (solid line).

is a weakly interacting massive particle (WIMP) and a number of experiments to discover it are ongoing. Since WIMPs have low kinetic energy, they are expected to accumulate near gravitational sources such as the sun and the galactic center. The density of WIMPs becomes high around the center of a gravitational source and a higher annihilation rate of WIMPs is expected. In the SK experiment, we are doing an indirect WIMP search by detecting high energy neutrinos from annihilation of WIMPs at the central region of the sun. To detect high energy neutrinos (GeV range), we measure upward-going muons which are produced from interactions between neutrinos and surrounding rock. By using these UPμ events, a larger effective volume can be used to detect neutrinos.

Fig. 3 shows solar angle distributions of the UPμ events observed by the SK detector together with the background atmospheric MC. The livetime for this analysis is 3149.2 days. Three figures correspond to three different types of UPμ events; muons which stop inside the detector (stopping muons), muons which go through the detector with (showering muons) and without (non-showering muons) an electromagnetic shower inside the tank. Each category covers a different energy region. There is no significant difference between the data and atomospheric MC and we have set a limit for the cross section of WIMPs from this result, which is shown in Fig. 4. When comparing with other experiments, the SK result gives a better limit in the lower energy region.

5 Solar Neutrino Analysis

In the solar neutrino measurement by the SK detector, the main contribution is ^8B neutrino whose energy ranges up to near 20 MeV. As neutrino energy becomes smaller than around 6 MeV, the background from radioactivity of materials around PMTs and water becomes dominant and increases steeply. The one of this low energy background sources is Rn in the water. Although we make a pre-treatment for the inlet water to remove Rn, the inlet water still includes remnants of Rn. In the SK-III period, we succeeded to lower the background level from Rn in the water by controlling a water flow inside the tank to keep the water with rich radioactivity from entering the fiducial volume in the tank. In Fig.5, a solar angle distribution for 5.0-5.5 MeV events is shown. A peak around $\cos\theta_{sun} = 1$ is due to solar neutrinos and a flat baseline is due to background events. It shows that a background rate of SK-III data is clearly reduced from SK-I inside the fiducial volume.

We have also improved detector simulation and event reconstruction tools, which give lower

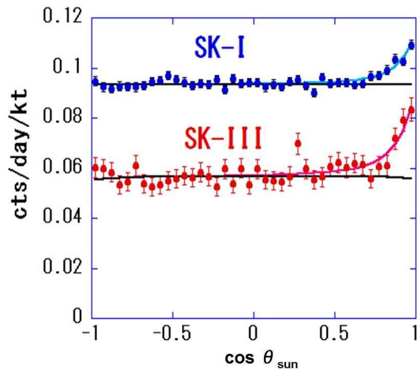

Figure 5: Solar angle distribution of 5.0-5.5 MeV solar neutrino candidates for SK-I (blue) and SK-III (red).

systematic errors. In the improvements of the detector simulation, the position dependence of the water transparency inside the tank was measured and newly implemented. The reflectivity of a sheet which optically separates between the inner and outer detectors was precisely measured and updated for the simulation. As for the event reconstruction tools, a fitter for determining a direction of a charged particle was modified and the angular resolution is improved by 10 %. With those improvements, solar neutrino data in the SK-III phase was analyzed, whose livetime is 548 days. We obtained a consistent value of the ^8B neutrino flux with the SK-I and SK-II value.

6 R & D Work for Future Relic Supernova Neutrino Search

Since the star formation started in the universe, neutrinos emitted from supernova bursts have suffused and formed a diffused neutrino background, which is so called a relic supernova neutrino. This neutrino flux has not yet been observed but the SK data analysis [5] set an upper limit for the flux of $1.2\bar{\nu_e}cm^{-2}s^{-1}$, which is now approaching to the theoretical predictions.

However, there is an inevitable and dominant background in the current SK analysis. That is a charged-current reaction of atmospheric ν_μ, where produced muon energy is below the threshold of the Cherenkov light production. In this case, the muon stops inside the tank and only decayed electron is observed by the detector. That event cannot be separated with an electron scattered event by an electron neutrino. To reduce this background, we are considering the addition of Gd compound into the SK water tank to tag neutrons which are produced from $\bar{\nu_e} + p \rightarrow e^+ + n$ reaction [14]. Neutrons from the reaction are thermalized and then absorbed by Gd, which has a large absorption cross section for low energy neutons. After Gd absorbs a neutron, it emits gamma rays immediately. The total amount of the energy of the gamma rays is about 8 MeV, which can be detectable in the SK detector. By using this method, this decay-e background is expected to be largely reduced.

Although adding Gd to the pure water in the SK tank is effective for the relic supernova neutrino search, there are several technical problems to solve beforehand. Therefore, we are now constructing a prototype detector, which is called as Evaluating Gadolinium's Action on Detector Systems (EGADS). The R & D menu of EGADS is as follows;

- Water transparency in the case of 0.2% Gd loaded
- Development of the water purification system to remove all the ions except for Gd compound
- To establish methods to add and remove Gd compound

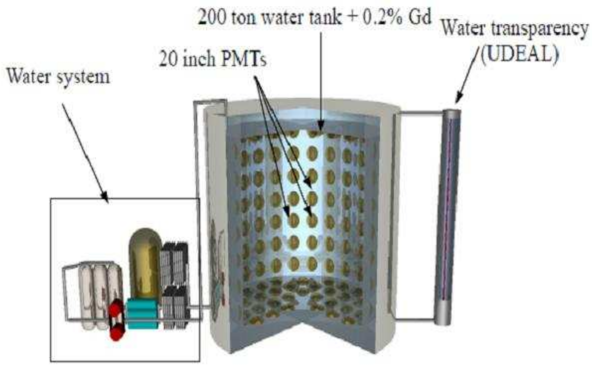

Figure 6: The total system of EGADs including a water system, a water tank with PMTs and a water transparency measurement system.

- To study the effect of adding Gd on SK material
- Measurement of neutron background rate
- Study of the effect on the trigger rate of SK

For this detector, a new site near the SK tank in the Kamioka mine was excavated. The water tank has already been constructed and several tests and preparation for other facilities such as a Gd purification system and a water transparency measurement system are on-going. In the current plan, a test of water circulation and the measurement of the water transparency will be taken place in the 2nd half of 2010 and main results will arrive in 2011.

7 Summary

There are several physics measurement and analyses ongoing in the SK experiment. We are trying to improve a data quality by reducing systematic errors and increasing statistics. Currently we have almost finished the SK-III data analysis, and move onto SK-IV data with new electronics and online system. In addition to that, to check the feasibility of the future project, a prototype detector is under construction and the test will be started next year.

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