New atmospheric and solar results from Super-Kamiokande

S Moriyama on behalf of the Super-Kamiokande Collaboration
456 Higashi Mozumi, Kamioka cho, Hida city, Gifu prefecture, JAPAN
moriyama@icrr.u-tokyo.ac.jp

Abstract. The Super-Kamiokande (SK) experiment has accumulated data on atmospheric neutrino and solar neutrino events and has made improvements in their measurements over the last 20 years. A three-flavor oscillation analysis was conducted with the atmospheric neutrino data in order to study the mass hierarchy, the leptonic CP violation term, and other oscillation parameters. A stronger preference for the normal mass hierarchy was obtained with SK + T2K external data: $\Delta \chi^2 = \chi^2_{\text{NH}} - \chi^2_{\text{IH}} = -5.2$ ($-3.1$ was expected when assuming the best fit parameters of the SK + T2K). The analysis of the appearance of $\tau$ neutrinos has been updated and a significance of $4.6\sigma$ was observed. The observation of $\sim84,000$ solar neutrinos give precise measurements of the energy spectrum and time variation testing terrestrial and solar matter effects. This data favor a lower $\Delta m^2_{21}$ value than that measured with reactor antineutrinos by KamLAND by more than $2\sigma$, and they determine this parameter in the solar neutrino oscillation fit.

1. The Super-Kamiokande experiment
Since the discovery that neutrinos have a finite mass, extensive efforts have been made to measure their differences of squared mass, mixing angles, and CP violating term as well as to identify their structure of mass hierarchy. Although experiments using manmade neutrino beams are able to maximize the sensitivities on these parameters, there are advantages to studying neutrino oscillations using naturally produced neutrinos, such as atmospheric and solar neutrinos, as they have a broader range of energies, path lengths, and flavors. The Super-Kamiokande (SK) experiment aims to identify the properties of neutrinos; furthermore, SK is expected to constrain dark matter particles and new neutrino species by combining other experimental results. In addition, by observing neutrinos from supernovae, a deeper understanding of the mechanisms behind supernova explosions is expected.

The SK is a water Cherenkov detector [1] located 1,000 m (2,700 m water equivalent) beneath the Ikenoyama mountain in Gifu prefecture, Japan. It has a cylindrical design and contains 50 kilotons of pure water. There is a 60 cm thick structure holding photomultiplier tubes (PMTs) at a distance of two meters from the wall of the tank. The inner detector (ID) inside the structure is equipped with 11,129 50 cm PMTs looking inward, and the outer detector (OD) outside the structure has 1,885 20 cm PMTs. The two detector parts are optically separated and triggered independently. The boundary of the fiducial volume for neutrino observation is two meters inside the structure, in which a target mass of
22.5 kilotons of pure water exists. The charged particles generated in the ID create Cherenkov cones, which provide information on their energies, directions, and particle types. The OD is mainly used for tagging cosmic ray muons that may cause background events in neutrino observations.

The SK has had four experimental phases. SK-I started on April 1st 1996 and continued until June 2001. Following the replacement of electrically malfunctioning PMTs, many PMTs broke due to a chain reaction of imploding PMTs. From December 2002, SK-II started with half of the regular density of inner PMTs (20% of the inner wall in this phase was covered by 50 cm PMTs, whereas the coverage for the SK-I/III/IV phases was 40%), and it continued until October 2005. During SK-II and later phases, each inner PMT was encapsulated by an anti-implosion plastic case. An improvement in the outer detector was also implemented at this time. After installing the remaining half of the inner PMTs, SK-III started in October 2006. In order to ensure the stable operation of the front-end electronics, new electronics, called QBEE boards, were developed and installed in September 2008. In SK-IV, the stability of the water quality was improved through the installation of an improved water temperature control system. This phase is currently ongoing. In total, almost 5,000 days of data obtained over 20 years have been utilized for the analyses presented in this paper.

2. Atmospheric neutrino data analyses

Atmospheric neutrinos are produced through interactions between primary cosmic ray protons and nuclei in the atmosphere; their interactions produce π and K as well as neutrinos in the final states. Recently, a flux measurement of atmospheric neutrinos was conducted and summarized in a paper [2]. The east–west asymmetry and possible solar modulation were also reported in it. Utilizing a wide range of neutrino energies spanning over five orders of magnitude as well as path lengths from all over the surface of the Earth (minimum 10 km and maximum 13,000 km), various studies on the properties of neutrinos have been conducted. In this paper, the latest results of neutrino oscillation analyses and searches are reported. These analyses and searches use data from all of the phases that the SK has been through, including SK-I/II/III and SK-IV until March 2016.

2.1. Tau neutrino appearance update

The leading term in the three-flavor neutrino oscillation framework of atmospheric neutrinos is the oscillation between ν, and ν. This causes a large deficit of ν, in the upward direction in the Multi-GeV and partially contained event samples. It is, however, difficult to identify the appearance of ν in standard oscillation analyses since the production of τ neutrinos requires high energy neutrinos where the flux is small and the majority of the decay products of τ are hadrons. Nevertheless, confirming the appearance of τ neutrinos is important in checking the three-flavor oscillation framework.

![Fig. 1](image)

**Fig. 1** Probability distribution functions for the τ neutrino (left) and non-τ neutrino events (center). The zenith angle distribution of data and Monte Carlo events are also shown (right).
We published two papers [3, 4] aiming to identify the appearance of $\tau$ neutrinos. A neural network was used to search for the hadronic decay of $\tau$. The neural network was trained by non-$\tau$ and $\tau$ Monte Carlo (MC) events, and a likelihood ranging from 0 to 1 was provided for each event. Figure 1 shows the two-dimensional histogram of $\tau$ (left) and non-$\tau$ MC (center) events. It can be seen that the $\tau$-like events are concentrated at the upward direction for the $\tau$ MC events. The analysis was conducted by fitting real data to a linear combination of two-dimensional histograms, which included a systematic error term:

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\Delta \chi^2 = \chi^2_{\text{MC}} - \chi^2_{\text{BG}} - \chi^2_{\text{PDF}} + \sum_i \epsilon_i \text{PDF}_i,$$

where $\chi^2_{\text{MC}}$ is the parameter to be fitted, and $\alpha$ is the parameter to be fitted, and it was expected to be 1 in the standard three-flavor oscillation analysis and standard cross section of $\nu$. $\text{PDF}_i$ is the PDF of the $i$th systematic error caused by shifting it by $1\sigma$, and $\epsilon_i$ is the magnitude of a nuisance parameter in the fit. The fitting was performed by an unbinned likelihood. The third term is a new one for this analysis, and it enables us to vary the systematic errors during the fit. The fitted result of $\alpha$, with a normal hierarchy of neutrino masses assumed, is $1.47 \pm 0.32$ (4.6$\sigma$ from 0, whereas 3.3$\sigma$ was expected). Figure 1 (right) shows the zenith angle distribution of $\tau$-like events overlaid by the fitted MC distributions; the red parts show the contribution of $\tau$ events. Note that the fit is not conducted with this histogram. This is evidence for the appearance of $\tau$ neutrinos, and it is consistent with the standard three-flavor oscillation scenario.

2.2. Results of the standard three-flavor oscillation analysis

Since all three of the neutrinos have masses, and the mixing angle $\theta_{13}$ is large enough, an accurate understanding of the neutrino oscillation phenomena requires a standard three-flavor oscillation analysis. With this analysis, all the sub-leading effects are taken into account [5]. Since the sub-leading effects are subject to information not yet determined, such as the mass hierarchy, octant of $\theta_{23}$, and the CP violating term $\delta_{\text{CP}}$, we are able to obtain information about them from the atmospheric neutrino data. In particular, the matter effect is useful in determining the mass hierarchy since the $\nu_{\mu}\rightarrow\nu_{\tau}$ conversion around 5–10 GeV is enhanced by the Earth for the case of a normal hierarchy but anti-$\nu_{\mu}\rightarrow$anti-$\nu_{\tau}$ is enhanced for the case of an inverted hierarchy.

In the SK, events caused by $\nu_e$ and anti-$\nu_e$ are statistically enhanced since they give a different number of associated decay electrons, number of rings, transverse momentum, and momentum fraction of the most energetic rings. Event categories with enhanced $\nu_e$ and anti-$\nu_e$ were therefore used to fit the atmospheric neutrino data with Monte Carlo simulations. In this fitting, $\sin^2\theta_{13}$ is constrained by the reactor experimental results, $0.0219 \pm 0.0012$ (PDG2015 [6]), and $\sin^2\theta_{12}$ and $\Delta m^2_{21}$ are constrained by the solar neutrino analysis and KamLAND experimental results.

Figure 2 shows the preliminary results with an SK-only parameter determination. From left to right, $\Delta \chi^2$ is determined as a function of $|\Delta m^2_{32}|$ or $|\Delta m^2_{13}|$, $\sin^2\theta_{23}$, and $\delta_{\text{CP}}$. As shown in Table 1, $\Delta \chi^2 = \chi^2_{\text{NH}} - \chi^2_{\text{IH}} = -4.3$ ($-3.1$ is expected when a normal hierarchy is assumed). To check this significance, Monte Carlo samples were generated by assuming an inverted hierarchy and analyzed as real data. For the case where $\sin^2\theta_{23} = 0.6$, the probability of having $\Delta \chi^2$ being smaller than $-4.3$ is 0.031; for the case where $\sin^2\theta_{23} = 0.4$, it is 0.007. The same was done by assuming a normal hierarchy and 0.446 was obtained ($\sin^2\theta_{23} = 0.6$).

Figure 3 shows the preliminary results of SK+T2K $\nu_e$, $\nu_\mu$ external data. As shown in Table 2, $\Delta \chi^2 = \chi^2_{\text{NH}} - \chi^2_{\text{IH}} = -5.2$ ($-3.8$ was expected when assuming the best parameters for SK and $-3.1$ was expected for the best combined values of SK+T2K). With a toy Monte Carlo study assuming an inverted hierarchy, the probability of having $\Delta \chi^2$ smaller than $-5.2$ is 0.024 for the case where $\sin^2\theta_{23} = 0.6$. For the case where $\sin^2\theta_{23} = 0.4$, it is 0.001.

Both of the results show a strong preference for the normal hierarchy.
2.3. Other related results and future improvements

Other than the oscillation analyses above, there are studies on finding the unidentified/unknown properties of neutrinos as well as searches for dark matter particles. Efforts on making future improvements are also ongoing.

2.3.1. Matter effect

The matter effect caused by the presence of electrons in the Earth has so far not been observed. For the mass hierarchy determination, discrimination of the matter effect between νe and anti-νe is important. No distinction is necessary, however, for observing the matter effect. To evaluate the strength of the

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**Fig. 2** $\Delta \chi^2$ as a function of $|\Delta m^2_{32}|$ and $|\Delta m^2_{13}|$ (left), $\sin^2\theta_{23}$ (center), and $\delta_{CP}$ (right) with SK data only. The blue and orange lines show $\Delta \chi^2$ for a normal and inverted hierarchy, respectively.

**Tab. 1** Best-fit values for the three-flavor oscillation analysis with SK data only.

| Fit (517 dof) | $\chi^2$ | $\sin^2\theta_{23}$ | $\delta_{CP}$ | $\sin^2\theta_{23}$ | $|\Delta m^2_{32}|$ | $|\Delta m^2_{13}|$ | $eV^2$ |
|---------------|---------|---------------------|---------------|---------------------|----------------------|----------------------|--------|
| SK (NH)       | 571.74  | 0.0219 (fix)        | 4.189         | 0.587               | 2.5x10^{-3}          |                      |        |
| SK (IH)       | 576.08  | 0.0219 (fix)        | 4.189         | 0.575               | 2.5x10^{-3}          |                      |        |

**Fig. 3** $\Delta \chi^2$ as a function of $|\Delta m^2_{32}|$ and $|\Delta m^2_{13}|$ (left), $\sin^2\theta_{23}$ (center), and $\delta_{CP}$ (right) with SK+T2K νµ, νe external data.

**Tab. 2** Best-fit values for the three-flavor oscillation analysis with SK+T2K νµ, νe external data.

| Fit (585 dof) | $\chi^2$ | $\sin^2\theta_{23}$ | $\delta_{CP}$ | $\sin^2\theta_{23}$ | $|\Delta m^2_{32}|$ | $|\Delta m^2_{13}|$ | $eV^2$ |
|---------------|---------|---------------------|---------------|---------------------|----------------------|----------------------|--------|
| SK+T2K (NH)   | 639.61  | 0.0219 (fix)        | 4.887         | 0.55                | 2.4x10^{-3}          |                      |        |
| SK+T2K (IH)   | 644.82  | 0.0219 (fix)        | 4.538         | 0.55                | 2.5x10^{-3}          |                      |        |
effect observed in the data, a parameter $\alpha$ that linearly scales with the matter effect was introduced: $\alpha = 0$ indicates no matter effect and $\alpha = 1$ is the matter effect expected in the standard model. Figure 4 shows $\Delta \chi^2$ as a function of $\alpha$. The orange and blue lines show the results when a normal and inverted hierarchy are respectively assumed. The $\chi^2$ minimum is consistent with the prediction produced by the standard model when a normal hierarchy is assumed, and $\Delta \chi^2$ for the vacuum ($\alpha = 0$) is 3.5. Based on the toy Monte Carlo samples, $\alpha = 0$ is excluded with an 82% confidence level in this preliminary analysis.

2.3.2. Dark matter from the Sun/Earth/Galaxy
Identification of the nature of dark matter is an important issue in astroparticle physics. Searches for neutrino signals resulting from the annihilation of dark matter particles accumulated in astrophysical objects are ongoing in the Super-K. Recently, weakly interacting massive particles (WIMPs) with a light mass (~10 GeV) generated interest in direct dark matter search experiments. Since the Super-K is sensitive to low-energy neutrinos, with energy down to a few GeV, it has a large advantage in searching for light WIMPs. In addition, the Sun is large enough to believe the accumulation rate of dark matter particles and the annihilation rate reached equilibrium. This enables us to interpret the result of the search as an interaction cross section of WIMPs to nucleons. Figure 5 shows the result of a search made in [7]. There were no significant signals but stringent limits were set. New limits lower than 200 GeV for the spin-dependent interaction, and lower than 6 GeV for the spin-independent cross section, were obtained.

Searches for neutrino signals from the Earth and the Galaxy are currently ongoing.

2.3.3. Future improvements
Extensive efforts have been made to improve the tools used for analysis, and ongoing studies include the following:
- Neutrino oscillation analysis using a new reconstruction method and a Markov Chain Monte Carlo.
- Improved usage of $\tau$ neural network including neutron tagging information
- Energy correction based on the number of tagged neutrons
- Improvement of particle identification by using timing information

3. Solar neutrino data analyses
SK and SNO solar neutrino data demonstrated solar neutrino flavor conversion. Both experiments are consistent with neutrino oscillations and the Mikheyev-Smirnov-Wolfenstein (MSW) effect [8] in the Sun. Solar neutrinos also directly probe terrestrial matter effects on neutrino oscillations. SK is sensitive to $^8$B neutrinos in the energy range 4-15 MeV. Spectral distortions from the MSW effect are largest at ~3 MeV, while terrestrial matter effects start at ~10 MeV and increase with energy. Both effects depend on the oscillation parameters, so spectral and time-variation data measure the oscillation parameters. The $\Delta m^2_{21}$ obtained by SK using solar neutrinos differs from the reactor anti-
neutrino measurement of KamLAND, and a combined fit to all solar neutrino data results in the same value of $\Delta m^2_{32}$, as the one preferred by SK. The sensitivity of the spectral measurement depends critically on the analysis energy threshold: SK has achieved a 3.5 MeV threshold for the kinetic energy of the recoil electrons. A new online software trigger which allows a threshold as low as 2.5 MeV of kinetic energy is currently commissioned. In the following subsections, a summary of recent improvements and data sets as well as observed solar neutrino signals, energy spectra, and results of oscillation analyses are presented.

3.1. Recent improvements and data sets
The most important change recently made for observing solar neutrinos was the lowering of the trigger threshold. After this change in May 2015, the trigger efficiency for the lowest energy bin, which was 2.5–4.0 MeV kinetic energy of electron, increased from approximately 84% to 99%. This is useful for reducing systematic errors at that energy bin.

Recently we released a paper [9] on solar neutrino analysis. This time we added two years of data until March 2016 (SKI + II + III + 2,365 days of SK-IV in this study, while 1,664 days of SK-IV were used for the previous paper [9]). With two more years of data, the energy spectrum and flux were updated. Since the systematic errors on the day–night analysis are currently being updated, the oscillation analysis in this paper used the updated spectrum and flux and the previous result of day–night analysis. Note that the previous result of the day–night analysis is shown in the paper [9], and the asymmetry is $-3.3 \pm 0.1$(stat) $\pm 0.5$(syst)%.

3.2. Observed solar neutrino signal
More than 84,000 solar neutrino events have been accumulated over 5,200 days when data from SK-I, II, III, and IV are combined. Figure 6 (left) shows a distribution of the cosine between the direction of the Sun and the reconstructed direction of electrons. From this data, the $^8$B neutrino flux is determined as being $2.355 \pm 0.033 \times 10^{10}$ /cm$^2$/sec in this preliminary study. The ratio between the observed flux and the Monte Carlo simulation assuming no neutrino oscillations based on the standard solar model is $0.4484 \pm 0.0062$. Figure 6 (right) shows the time variation of the ratio overlaid by the number of sunspots [9]. The black horizontal line and the red band show the SK-combined flux and its uncertainty, respectively, and the gray band corresponds to the size of the systematic error for that period. The $\chi^2$ for a flat distribution is 15.52/19 degrees of freedom, and the corresponding confidence level is 68.9%. From these numbers, we can conclude that the SK solar rate measurements are fully consistent with that of a constant solar neutrino flux emitted by the Sun.

![Fig. 6](image_url)

**Fig. 6** (left) Distribution of the cosine between the direction of the Sun and the reconstructed direction of electrons. (right) Solar neutrino event rates relative to the prediction (red points) overlaid by the number of sunspots (black points) [10].
3.3. Energy spectrum

The details of the analysis method are described in the previous paper [9]. After applying an event selection, an energy spectrum for each SK phase was extracted by an extended maximum likelihood fit. The energy spectrum for each SK phase was then compared with the expectations when assuming neutrino oscillations with MSW effect and functions with some parameters. Figure 7 shows the energy spectrum combining SK-I+II+III+IV (red points) and best-fit expectations. By comparing $\chi^2$ between the data and models, it was found that the MSW prediction with $\Delta m^2_{21}$ based on KamLAND anti-neutrino data was disfavored by $\sim 2\sigma$ but the solar neutrino data best fit $\Delta m^2_{21}$ is consistent within about $1\sigma$. Note that all SK phases are combined without regard to energy resolution or systematic error in this figure but the shown $\chi^2$ values are from the combined fit to all SK phases with all systematic and statistical errors taken into account.

**Fig. 7 Combined energy spectrum of solar neutrinos (red), fitted results with MSW solutions (green: the global solar best fit parameters, blue: global solar + KamLAND, and black: quadratic fit)**

**Fig. 8 Results of the oscillation analysis**
3.4. Result of the oscillation analysis

The oscillation analysis was conducted using the SK, SNO, radiochemical experiments, Borexino, KamLAND, and the theoretical energy spectrum of $^8\text{B}$. Their references can be found in [9]. Here, we added the updated SK-IV data that includes the low energy threshold period after May 2015. Figure 8 (top left) shows a comparison between the SK (green), KamLAND (blue), and the two combined (red). SK data determine both $\theta_{12}$ and $\Delta m^2_{31}$. The top right figure shows a comparison between the SK (green), SNO (blue), and the two combined (red). SK has the better constraint on $\Delta m^2_{31}$. The bottom left figure shows a comparison between the SK+SNO (green), KamLAND (blue), and the two combined (red). The bottom right figure shows a comparison between SK+SNO (dashed green) and all solar data combined (green). The SK spectrum and D/N data favor a lower $\Delta m^2_{31}$ value than that given by KamLAND by more than 2$\sigma$, and they mostly determine this parameter in the solar neutrino oscillation fit.

4. Summary

The SK experiment has accumulated data on atmospheric neutrino and solar neutrino events and has made improvements in their measurements over the last 20 years. A three-flavor oscillation analysis was conducted with the atmospheric neutrino data in order to study the mass hierarchy, the leptonic CP violation term, and other oscillation parameters. A stronger preference for the normal mass hierarchy was obtained with SK only data: $\Delta \chi^2 = \chi^2_{\text{NH}} - \chi^2_{\text{IH}} = -4.3$ ($-3.1$ was expected when assuming the best fit parameter of the SK) and SK+T2K external data: $\Delta \chi^2 = \chi^2_{\text{NH}} - \chi^2_{\text{IH}} = -5.2$ ($-3.8$ was expected when assuming best fit parameters for SK and $-3.1$ assuming best fit parameters for SK + T2K). The analysis of the appearance of $\tau$ neutrinos was updated, and a significance of 4.6$\sigma$ was observed. The observation of solar neutrinos gives precise measurements of the energy spectrum and time variation testing terrestrial and solar matter effects. The data favor a lower $\Delta m^2_{31}$ value than that measured by KamLAND by more than 2$\sigma$, and they determine this parameter in the solar neutrino oscillation fit.

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