Latest result of solar neutrino analysis in Super-Kamiokande

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Abstract. Super-Kamiokande (SK), a 50 kton water Cherenkov detector in Japan, is observing neutrinos and searching for proton decay and neutrino produced by dark matter. In solar neutrino analysis, SK studies the effects of both the solar and terrestrial matter density on neutrino oscillations: a distortion of the solar neutrino energy spectrum would be caused by the edge of the Mikheyev-Smirnov-Wolfenstein resonance in the solar core, and terrestrial matter effects would induce a day/night solar neutrino flux asymmetry. The installation of new front-end electronics in 2008 marks the beginning of the 4th phase of SK (SK-IV). On 2018 May, we finished taking data of SK-IV and started the refurbishment work in order to clean the inside of the detector and to seal the water tank to prevent water tank toward SK-Gd. In this proceedings, we overview the latest solar neutrino results in SK-IV, for example, the precise measurement of $^8\text{B}$ solar neutrino flux, its energy spectrum and oscillation parameters. In addition, we discuss the future prospect of the new phase of SK-V.

1. Introduction
Solar neutrinos are produced by the nuclear fusion reaction, $4p \rightarrow \alpha + 2e^+ + 2\nu_e$, in the core of the Sun. Electron neutrinos ($\nu_e$) produced in the Sun are so called $pp$, $\nu_{\text{pep}}$, $\nu_{\text{7Be}}$, $\nu_{\text{8B}}$ and $\nu_{\text{hep}}$ neutrinos, whose fluxes are predicted by the standard solar model [1].

The current physics motivation of the solar neutrino observation with the Super-Kamiokande (SK) detector [2] is to search for the Mikheyev-Smirnov-Wolfenstein (MSW) effect [3, 4]. The MSW effect leads to a resonant conversion of the solar neutrinos within the Sun and results in an about 30% level of the survival probability above a few MeV, which is so called “Up-turn”. Since the energy spectrum reflects the survival probability of the electron neutrinos, the SK searches for the “Spectrum up-turn” by measuring the recoil electron energy spectrum.

2. Super-Kamiokande detector and data set for analysis
SK is a water Cherenkov detector located at 1,000 m (2,700 m water equivalent) below the top of Mt. Ikenoyama in Gifu prefecture, Japan [2]. It is a cylindrical stainless tank structure and contains 50 ktons of ultra pure water. The detector contains an inner detector and an optically separated outer detector which is used to veto cosmic muons.

In this proceedings, we present the analysis result based on the data set until the end of SK-IV (until end of May 2018 before the refurbishment work toward SK-Gd. The livetime of this data set is 2,970 days). This data set contains about 1300 days of additional data since the
last publication [5]. The total livetime combining with different phases of SK (SK-I [6], SK-II [7] and SK-III [8]) is 5,805 days.

3. $^8$B solar neutrino flux measurement
The SK detector observes solar neutrino via the elastic scattering with electrons in pure water. In the case of $\nu-e$ interaction, the direction of the recoil electron is highly correlated with the direction of the incident neutrino. Using 5,805 days data, more than 95,000 events are observed so far. The $^8$B solar neutrino flux is measured \( (2.332 \pm 0.044) \times 10^6 \text{ } /\text{cm}^2/\text{sec} \) assuming a pure electron neutrino flavor content. Figure 1 shows the results of $^8$B solar neutrino flux measurement among solar neutrino experiments [9, 10, 11, 12, 13, 14, 16]. The SK result is the most precise flux measurement in elastic scattering channel. The ratio of the SK’s measurement to the SNO’s neutral current measurement is $0.4441 \pm 0.0084$, where the neutral current channel measures the total flux of all active neutrino flavors.

![Figure 1.](image1)

**Figure 1.** The measurement results of $^8$B solar neutrinos from solar neutrino experiments. The left (right) vertical axis shows the flux in unit of $\times 10^6$/cm$^2$/sec (the ratio of each flux result to the SNO NC flux).

![Figure 2.](image2)

**Figure 2.** The yearly flux measured by SK. The horizontal axis shows the year and the left (right) vertical axis shows the ratio of SK result to SNO NC flux (the number of sunspot number [17]).

The solar activity cycle is the 11 years periodic change of sun spots releasing the magnetic flux at the surface of the Sun. The number of the sun spots strongly correlated with the solar activity cycle. When a periodic signal of solar neutrinos is observed, this leads to an improvement of the standard solar model and gives some hints beyond the standard model of particle physics.

Since SK has observed solar neutrinos for more than 20 years, this long term observation covers nearly two solar activity cycles. Figure 2 shows the SK yearly flux measured throughout the different phases of SK together with the corresponding sun spot number (Source: WDC–SILSO, Royal Observatory of Belgium, Brussels [17]). Using the present data, the $\chi^2$ is calculated with the total experimental uncertainties as $\chi^2 = 19.28/22$ d.o.f., which corresponds to a probability of 62.8%. The SK solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.

4. Energy spectrum measurement
Although an energy of the incident neutrinos is not directly measured in the SK detector, the neutrino energy spectrum can be extracted from the recoil electron energy spectrum. We extracted the energy spectrum of recoil electrons using an extended maximum likelihood fit [5]. Figure 3 shows the combined energy spectrum from SK-I to SK-IV, where the measured energy
spectrum is divided by the expectation assuming no neutrino oscillations with the total flux of $5.25 \times 10^6 \text{/cm}^2\text{/sec}$ measured by SNO’s neutral current.

According to neutrino oscillation parameters discussed in the next section, the expected curves of the MSW effect (green curve for solar global and blue curve for solar plus KamLAND) are also shown in Figure 3. Comparing $\chi^2$ between the quadratic best-fit of the data (black) and the predictions (green and blue), the SK recoil electron spectrum is consistent within 1.0σ with the MSW up-turn for the solar global best-fit parameters. On the other hand, it disfavors the MSW up-turn for the solar plus KamLAND best-fit parameters by 1.9σ.

![Figure 3](image1.png)

**Figure 3.** The combined energy spectrum of recoil electron measured in SK-I, SK-II, SK-III, and SK-IV. The horizontal (vertical) axis shows the recoil electron kinetic energy in MeV (the ratio of the SK data to the SNO NC flux).

![Figure 4](image2.png)

**Figure 4.** Allowed region of oscillation parameters of $\Delta m^2_{21}$ and $\sin^2 \theta_{12}$. Green, blue and red contours show the region determined by the solar global, KamLAND, and solar+KamLAND (combined), respectively.

### 5. Oscillation analysis

The oscillation analysis was performed using the results from SK [6, 7, 8, 5], SNO [13], radiochemical solar neutrino experiments [18, 19, 20] and Borexino [21] as well as the antineutrino measurement by KamLAND [22]. For the mixing angle of $\theta_{13}$, we used the particle data group (PDG) average of $\sin^2 \theta_{13} = 0.0219 \pm 0.0014$ based on the measurement from short baseline reactor experiments [23]. When combining with results from the other solar neutrino experiments, the mixing angle is determined to be $\sin^2 \theta_{12} = 0.309 \pm 0.014$ and the mass difference is determined to be $\Delta m^2_{21} = 4.83^{+1.25}_{-0.60} \times 10^{-5}$ eV$^2$ as shown in Figure 4. When the KamLAND result is added, the oscillation parameters are determined as $\sin^2 \theta_{12} = 0.310^{+0.013}_{-0.012}$, $\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5}$ eV$^2$. The SK spectrum and day/night data favors a lower $\Delta m^2_{21}$ value than that measured by KamLAND by more than $\sim 2\sigma$. Further precise measurements are required to confirm this tension in future.

### 6. Progress of data analysis in SK-V

We started taking data of the fifth phase of SK (SK-V) on January 2019 and analyzed the first 62.84 days data to check the data quality in SK-V. Figure 5 shows the $\cos \theta_{\text{Sun}}$ distribution of SK-V and SK-IV, where the events above 6.49 MeV are used because event below that energy threshold is contaminated by radioactive background, such as radon.

As exampled in Figure 5, the $\cos \theta_{\text{Sun}}$ distribution of SK-V is almost same as that of SK-IV and this demonstrates the clear peak of solar neutrinos is observed in the SK-V data. In the summer of 2019, we performed the calibration campaign for SK-V. We started analyzing the data of SK-V with new calibration constants obtained by this campaign.
7. Summary

The Super-Kamiokande detector has precisely measured the $^8$B solar neutrino flux, its time variation and recoil electron spectrum. The $^8$B solar neutrino flux is measured to be $(2.332 \pm 0.044) \times 10^6 /\text{cm}^2/\text{sec}$. No significant correlation between the observed solar neutrino flux and the sun spot number is found. The energy spectrum of recoil electrons is consistent with the MSW prediction by 1.0$\sigma$ level for the solar global parameters but it disfavors the MSW prediction based on solar global plus KamLAND parameters by 1.9$\sigma$. On January 2019, SK-V has started taking data and results including SK-V is being prepared near future.

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