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Solar Neutrino Results from Super-Kamiokande

Takatomi Yano[*†]
Department of Physics, Kobe University
1-1 Rokko-dai, Nada, Kobe, Hyogo, 657-8501 JAPAN E-mail:
tyano@phys.sci.kobe-u.ac.jp

Super-Kamiokande is the world-largest water Cherenkov detector, running for neutrino observations and proton decay search over 20 years. Because of its high statistics due to the large fiducial volume of 22.5 kt, lower cosmic-ray background environment in a mine at 1000m underground and well-calibrated detector itself, Super-K has been making the world-leading results of the Boron-8 solar neutrino measurement. We measure these solar neutrino events via neutrino-electron scattering, with the sensitivity to the neutrino event direction. Recently, our constant efforts to improve the detector enabled to lower the analysis energy threshold down to 3.5 MeV in recoil electron kinetic energy. It contributes to the search for the solar spectrum distortion and the flux measurement.

In this presentation, we will show the recent status and results of ^{8}B solar neutrino measurement at Super-K IV over 2600 days. Then we will discuss about the measurements of solar mixing angle, the neutrino mass squared difference, day-night asymmetry of the flux and the solar spectrum distortions, referring whole SK-I to SK-IV data sets.

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[*] Speaker.
[†] for the Super-Kamiokande Collaboration

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1. The Super-Kamiokande Detector

Super-Kamiokande (Super-K, SK) [1] is the world-largest water Cherekov detector, located at 1,000 m underground (2,700 m water equivalent) in Ikenoyama mountain, Gifu-prefecture, Japan. The Cylindrical detector tank with the dimension of 39.3 (33.8) m in diameter and 41.4 (36.2) m in height provides 50 (22.5) kton full (fiducial) volume of ultra-pure water. THe detector tank is optically and physically separated into inner detector (ID) and outer detector (OD), which have the 11,129 20-inch-diameter photomultipliers (PMTs) and 1,885 8-inch-PMTs respectively. The Cherenkov light ring patterns are detected by these photo sensors and provide the information about the original charged particles, on their energies, directions, time and particle types. In the case of neutrino interactions, these information of neutrinos also could be extracted from the generated charged particles. The energy range from a few MeV to tens of GeV is covered by the SK detector.

The measurement of solar neutrinos has been one of the most important target of Super-K [2]. The solar neutrinos are generated by the nuclear fusion reactions, which make the Sun burning. These series of reactions are called as the pp-chain and the CNO cycle and can be summarized as $4p \to \alpha + 2e^+ + 2\nu_e$. These processes in the Sun are described with the standard solar model (SSM) [3]. The SSM also provides the good prediction of flux and energy spectrum of solar neutrinos. Their energies distributes from about 0.1 to 20 MeV. The dominant solar neutrino signals at SK is so called ^{8}B neutrinos in pp-chain. These neutrinos are observed through neutrino electron elastic scattering, $\nu + e^- \to \nu + e^-$. The observed event rate is about 20 events/day in the fiducial volume. With the high statistics data, we performed searches for time variation of the solar neutrino flux, energy spectrum distortion due to the solar MSW effect, flux variation due to the terrestrial MSW effect as well as precise measurement of the oscillation parameters Δm^2_{21} and $\sin^2\theta_{12}$.

2. Neutrino Oscillation Analysis

The recent results for Super-Kamiokande solar neutrino oscillation analysis and an indication of the terrestrial MSW effects, as a flux variation between in the day time and night time, can be found found as ref. [4, 5]. In these analysis, we used the SK-I, II, III (1496, 791 and 548 days, respectively) and SK-IV data of 1664 days, until February 2014. The analysis threshold was set to $E_{kin} = 3.5$ MeV at kinetic energy of electrons by applying tightened fiducial volumes below $E_{kin} = 5$ MeV.

In the following, the status of the solar neutrino oscillation analyses using new data sets will be discussed. For obtaining the neutrino oscillation parameters, we newly adopted the data sets in 701 days until March 2016 (in total 2365 days) of SK-IV. The analysis is conducted by constraining $\sin^2\theta_{13}$ as 0.0219±0.0014, referring the result of reactor neutrino experiments [6]. The results from SNO [7], radiochemical solar neutrino experiments [8, 9, 10] and Borexino [11, 12, 13] as well as the anti-neutrino measurement by KamLAND [14, 15] are also used.

As the result of solar global analysis with SK, SNO and all solar experiments, we got the value of $\sin^2\theta_{12} = 0.308 \pm 0.014$ and $\Delta m^2_{21} = 4.84^{+1.26}_{-0.60} \times 10^{-5}$ eV ^{2}. When we include the KamLAND result into the analysis (solar+KamLAND), these values are $\sin^2\theta_{12} = 0.316 \pm 0.012$ and $\Delta m^2_{21} = 7.49^{+0.19}_{-0.18} \times 10^{-5}$ eV ^{2}. An interesting $\sim 2\sigma$ tension in Δm^2_{21} values can be seen between these analysis. Another three-flavor oscillation analysis is also performed, without the constraint on

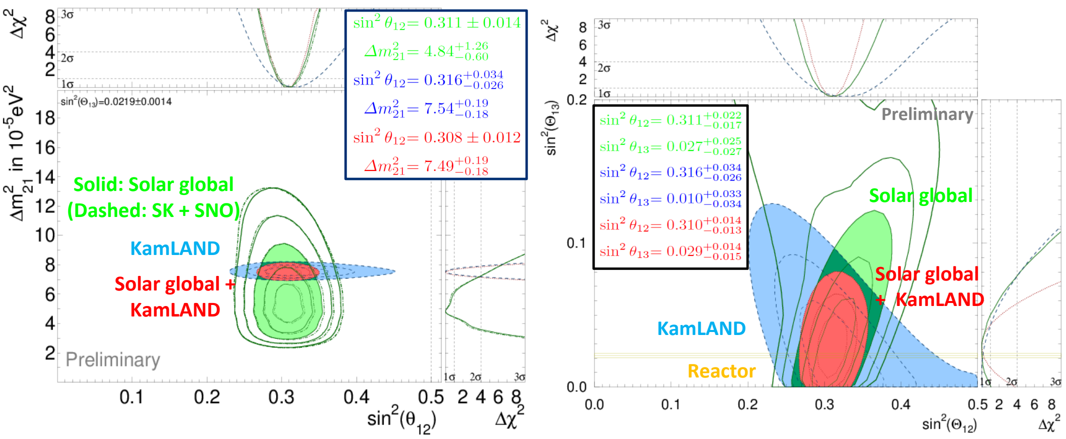

Figure 1: Allowed regions for solar neutrino oscillation parameters $\sin^2\theta_{12}$ and Δm^2_{21}, obtained by the three-flavor oscillation analyses with the Super-Kamiokande data set until March 2016 and other solar and reactor experiments. The value of $\sin^2\theta_{13}$ is constrained as 0.0219±0.0014 in the left contour plot and freed in the right plot. The green lines and areas shows the result from the solar analyses, showing the N-σ contour and 3σ area. Solid green lines show the combined result of Super-K and other all solar experiments, and dashed green lines show the combined result of Super-K and SNO. The blue lines and areas are for KamLAND reactor experiment, and the red lines and areas are for solar+ KamLAND result. Recent result of reactor experiments ($\sin^2\theta_{13} = 0.0219\pm0.0014$) are also shown as yellow lines in the right figure.

$\sin^2\theta_{13}$. These results are shown in figure 1. By combining the measurement of SK, other solar neutrino experiments and KamLAND, the value of $\sin^2\theta_{13} = 0.029^{+0.014}_{-0.015}$ was obtained. The result shows the non-zero θ_{13} at 2σ level and the value is consistent with that of reactor experiments [16, 17, 18].

More recent observation data of SK-IV 280 days (SK-IV 2645 days in total) until March 2017 is being ready and provided for a spectrum analysis. In the data set, 89,295 events are seen and $52,521^{+349}_{-347}$ solar signal events are extracted figure 2 on the next page. In the previous analysis with the data set until March 2016, about 84,000 events in total and about 4,6000 solar signal events were extracted. The data until March 2016 preliminarily resulted as ^{8}B solar neutrino flux of $2.355\pm0.033\times10^6$ [cm^2/sec] and the ratio to the standard solar model as DATA/MC (un-oscillated, from MC)$= 0.4486\pm0.0062$. Now new data set have above 10% more statistics of solar neutrino events and will be served for further analysis.

A preliminary result of spectral analysis with the data set until March 2017 is shown in figure 3 on the following page. The SK spectrum with new data set is consistent within $\sim 1\sigma$ with the MSW upturn for the solar best fit parameters. It is also marginally consistent with $\sim 2\sigma$ tension with the MSW upturn for the solar+KamLAND best fit parameters.

3. Periodic Modulation Analysis

A periodic modulation of solar neutrino is an interest, for the search of neutrino non-0 magnetic moments and the direct observation of solar inner activity variance. The past publication can be found in [19], where we applied SK-I 1496 days data for the analysis. In the past analysis, 5 days binning with the energy range of $E_{kin} = 4.5$-19.5 MeV and Lomb-Scargle (LS) method

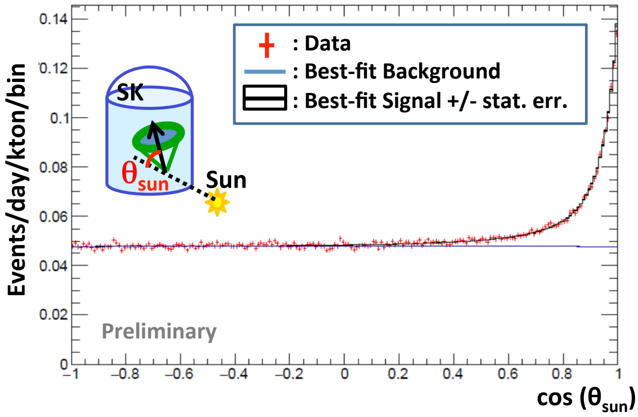

Figure 2: The angular distribution between the direction of the Sun and the reconstructed electron event directions in cosine. In total of 89285 events are recorded by Super-Kamiokande until March 2017, with extracted 51521 solar neutrino signal events (SK-I 22404 events, SK-II 7121 events, SK-III 8148 events and SK-IV 13757 events).

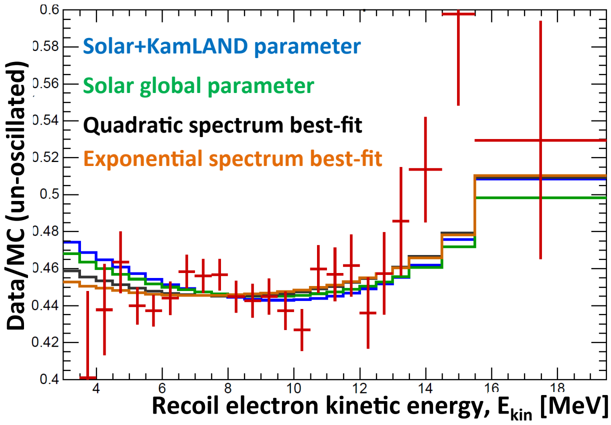

Figure 3: The energy spectrum combining SK-I to SK-IV until March 2017, as the ratio between data and un-oscillated MC. Only statistical errors are regarded to sum up the all SK spectrums, without considering the difference of energy resolution or systematics. Solar+KamLAND (blue), Solar global (green), quadratic spectrum (black) and exponential spectrum best-fit (orange) results are overlaied.

are used. With the published data sets, several researchers pointed out the periodic modulation peak at around 9.4 /year [20]. Here we performed an re-analysis of the SK-I data set with generalized Lomb-Scargle method, which can deal the measurement errors [21]. The data set of SK-IV with 1664 days is also provided for the same analysis, with 5-days binning, the energy range of $E_{kin} = 4.5$-19.5 MeV and symmetric errors. The result is shown as Fig. figure 4 on the next page. In the SK-I data, we still see the maximum peak at around 9.43 /year. Though, it vanishes in the SK-IV data analysis.

4. Conclusions

Solar neutrinos are an important research target of Super-Kamiokande. Using the large data

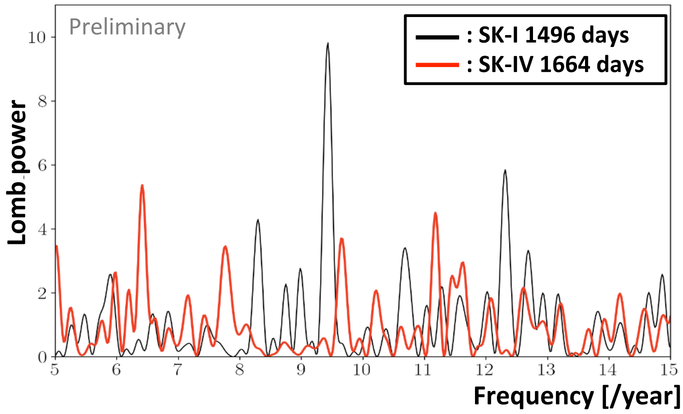

Figure 4: The result of SK-I (black) and SK-IV (red) periodic analysis applying generalized Lomb-Scargle method for the search frequency range of 5-15 [/year]. There is no significant periodic signal in the result of SK-IV, whereas a maximum peak ~9.43 /year is seen in the SK-I data set.

samples at SK, solar neutrino oscillation have been performed. The recent data sets of 2645 days are provided for the spectrum analysis. In the partial preliminary results, we still see an interesting tension of $\sim 2\sigma$ between the Solar+KamLAND analysis and global Solar analysis. The periodic modulation analysis is performed for SK-I 1496 days and SK-IV 1664 days, with generalized LS method. In SK-IV data, we haven't observed the maximum peak at around 9.43/years. More analysis updates will be performed soon.

For the low energy neutrino observation, including solar neutrinos, several improvements are also ongoing. These improvements, i.e. PMT gain correction in the energy scale and reduction of the spallation backgrounds, will result the further physics sensitivities at SK. SK collaboration also plans to upgrade the detector in 2018 to load Gadolinium sulfate, for very effective neutron tagging [22]. It will contribute to reduce the background for observing several neutrino sources, especially for low energy neutrinos.

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