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Recent oscillation results and future prospects of Super-Kamiokande

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Super-Kamiokande (SK) is a 50 kton water Cherenkov detector located 1000 m underground in Kamioka Japan. Observations at SK began in 1996 with purified water. The main physics targets at SK on neutrino oscillation are atmospheric neutrino oscillation and solar neutrino oscillation. In this article, the recent preliminary oscillation analysis results are reported. In August 2020, we added gadolinium (Gd) and moved to the SK-Gd phase. SK-Gd is expected to improve the detection efficiency of neutrons. In this article, the current status of SK-Gd and future prospects on the neutrino oscillation measurements are reported also.

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1. Introduction

Super-Kamiokande (SK) detector is a 50 kton water Cherenkov detector located 1000 m underground in Kamioka Japan [1]. The detector is a stainless-steel cylinder, 41.4 m high and 39.3 m in diameter. The inside is optically separated into two layers: an inner detector (ID) and an outer detector (OD). The conventional fiducial volume of ID is 22.5 kton (2 m from the wall) and is covered by approximately 11100 20-inch PMTs. The OD is 2 m thick and has 1885 8-inch PMTs installed for veto of cosmic ray muons etc. Observations at SK began in 1996. In August 2020, we added 0.011% gadolinium (Gd) and moved to the SK-Gd phase [2]. In July 2022, we increased the Gd addition to 0.033% and are now operating as SK-VII. The main physics targets at SK are the search for nucleon decay, observations of atmospheric neutrino oscillations, observations of solar neutrino oscillations, and observations of astronomical neutrinos. Recent publications can be found here [3-12].

2. Atmospheric neutrino oscillation results

Atmospheric neutrinos are produced by cosmic rays in Earth's atmosphere. SK measures the flavor, energy, and zenith angle distribution of atmospheric neutrinos, and is particularly sensitive to the ϑ_{23} and Δm^2_{32} parameters. In addition, electron neutrinos with energies of a few GeV are enhanced around the Earth's core due to the Earth's matter effect. This effect allows the study of ϑ_{13} and mass hierarchy (or mass ordering). Electron neutrinos in the sub-GeV region are also enhanced by the effect of the solar term of neutrino oscillations. This effect allows us to study the degeneracy of ϑ_{23} octant. In addition, in the area of interference with these two enhancements, it is possible to study CP phase (δ_{CP}). In SK-Gd, the purity of electron-neutrino-like events is improved.

Since the last paper [6], the following improvements were made: in May 2020, the exposure was increased to 364.8 kton·year and neutron tags were employed in the analysis in SK-IV to improve the separation performance between neutrino and antineutrino events. In addition, BDT was newly used to determine multi-ring events. Furthermore, we incorporated the restriction by $\sin^2\vartheta_{13}$ into the analysis and made other improvements. In May 2022, data from SK-V was added to the analysis. The effective volume was increased to 27.2 kton in some analyses. Then the total exposure becomes 484.2 kton·year. In addition, we adopted the improved T2K model constraint. In this T2K model, we used T2K Runs 1-9, including the anti-neutrino beam, and set the $\sin^2\vartheta_{13}$ limit to 0.0220 ± 0.0007.

Figure 1 shows preliminary results from SK only atmospheric neutrino oscillation analysis with 484.2 kton·year data. The preliminary best-fit parameters are as follows: $sin^2\theta_{23} = 0.49$, $\delta_{CP} = 4.71$ (in 0-2π), and $\Delta m^2_{32} = 2.4 \times 10^{-3}\mathrm{eV}^2$ for both normal mass ordering (NO) and inverted mass orderings (IO). The SK atmospheric ν data favors maximal mixing on θ_{23}, $\delta_{CP} \approx -\frac{\pi}{2}$, and NO. The preliminary difference of the chi-squares between NO and IO from this analysis is 5.8. Figure 2 shows preliminary results from the atmospheric neutrino oscillation analysis with 484.2 kton·year data with the improved T2K model constraint. The preliminary best-fit parameters for NO are as follows: $sin^2\theta_{23} = 0.53$, $\delta_{CP} = 4.54$ (in 0-2π), and $\Delta m^2_{32} = 2.4 \times 10^{-3}\mathrm{eV}^2$. The

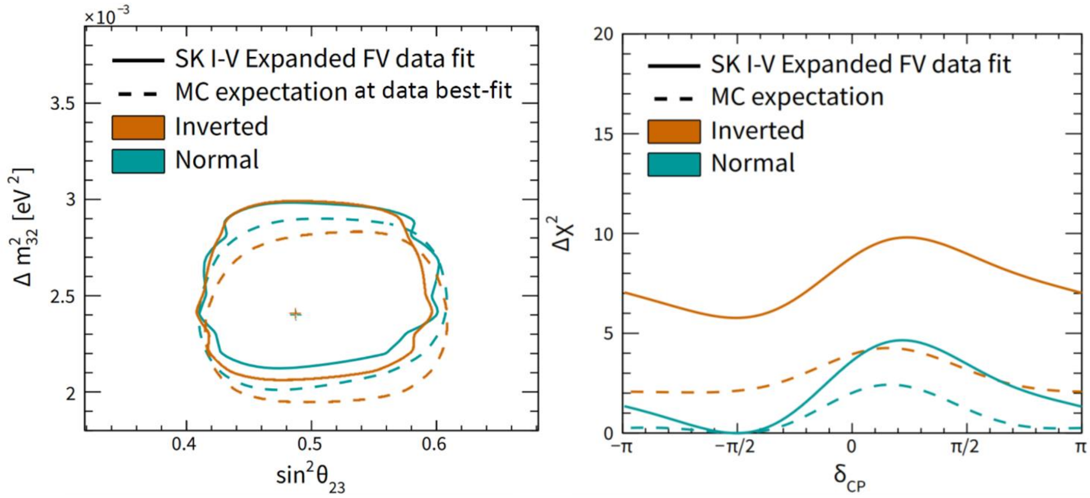

Figure 1: Preliminary results from SK only atmospheric neutrino oscillation analysis with 484.2 kton·year data. The plot on the left is the $\sin^2\vartheta_{23}$ vs. Δm^2_{32} distribution. The plot on the right is the δ_{CP} distribution.

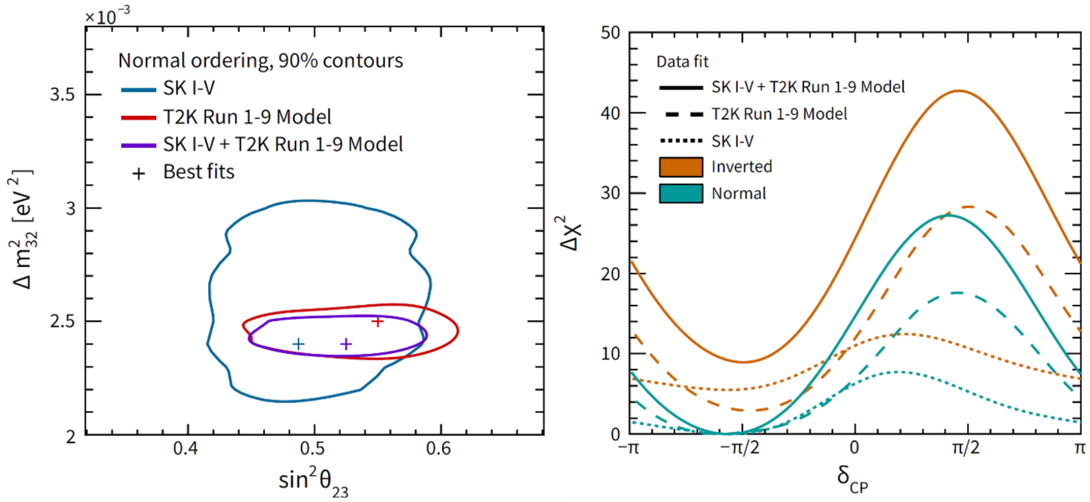

Figure 2: Preliminary results from the atmospheric neutrino oscillation analysis with 484.2 kton·year data with the improved T2K model constraint. The plot on the left is the $\sin^2\vartheta_{23}$ vs. Δm^2_{32} distribution. The plot on the right is the δ_{CP} distribution.

SK atmospheric ν data with T2K model analysis favors maximal mixing on θ_{23}, $\delta_{CP} \approx -\frac{\pi}{2}$, and NO. The preliminary difference of the chi-squares between NO and IO from this analysis is 8.9.

3. Solar neutrino oscillation results

Solar neutrinos are produced by nuclear fusion in the sun and are initially produced as electron neutrinos. ^{8}B solar neutrino flux, energy spectrum, and time distribution are measured with high statistical accuracy at SK. Energy spectral observations in SK are sensitive to the θ_{12} and Δm^2_{21} parameters. A global analysis that considers the results of other solar neutrino experiments and a long-baseline reactor neutrino experiment (KamLAND [13]) is more powerful. Due to matter effects in the sun, there is an energy dependence of the survival probability of

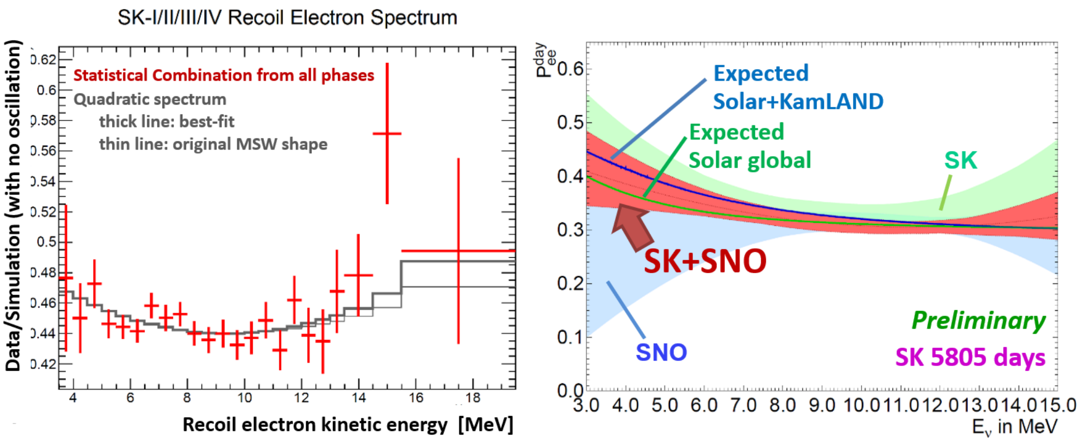

Figure 3: Preliminary energy distributions of observed solar neutrino spectrum (left) and allowed survival probability of electron neutrinos in daytime (right). The live time for this analysis is 5805 days. The plot on the left is the statistical combination of the observed energy spectrum of solar neutrinos during SK-I, II, III, and IV. The plot on the right is allowed reasions and expected lines from the spectral fitting based on the observed solar neutrino spectrum. The green, blue, and red bands correspond to SK only, SNO only, and SK+SNO allowed 1-sigma regions, respectively. In this analysis the same parametrization with SNO [15] is used.

electron neutrinos. If it is a standard matter effect, there should be an increase in the survival probability of electron neutrinos in the low-energy region of SK, which we call "upturn". We are trying to measure this upturn phenomenon with SK in order to verify the matter effect. It is known that there is a difference in solar neutrino flux between daytime and nighttime due to matter effects in the earth. This effect is particularly sensitive to the Δm^2_{21} parameter, and SK is trying to determine this parameter by precise measurements of the day-night variation of the ^{8}B flux.

Since the last publication [7], the following improvements were made: in May 2020, improvements were made to the analysis tool for SK-IV. In particular, PMT gain corrections were incorporated into the energy reconstruction to improve the long-term stability of the energy scale. In addition, more efficient reduction of background events due to spallation has been achieved by considering neutron events produced in the SK detector by cosmic-ray muons [14]. In May 2022, we re-evaluated the systematic uncertainties and compiled preliminary solar neutrino oscillation results in SK considering the results of the SNO experiment [15]. a global analysis considering other solar neutrino experiments such as Borexino [16] is currently in progress.

Figure 3 shows preliminary energy distributions of observed solar neutrino spectrum (left) and allowed survival probability of electron neutrinos in daytime (right). The detail of this spectrum fitting is explained in Ref. [7]. The uncertainty in the SK+SNO fitting region becomes smaller comparing to the analysis in Ref. [7]. Figure 4 shows preliminary results from the solar neutrino oscillation analysis with SK 5805 days dataset. The preliminary best-fit parameters from the SK+SNO+KamLAND analysis are as follows: $sin^2\theta_{12} = 0.305^{+0.013}_{-0.012}$, and $\Delta m^2_{21} = (7.49^{+0.19}_{-0.17}) \times 10^{-5}\mathrm{eV}^2$. Approximately 1.5 sigma level of tension still remains in the Δm^2_{21} values between SK+SNO and KamLAND.

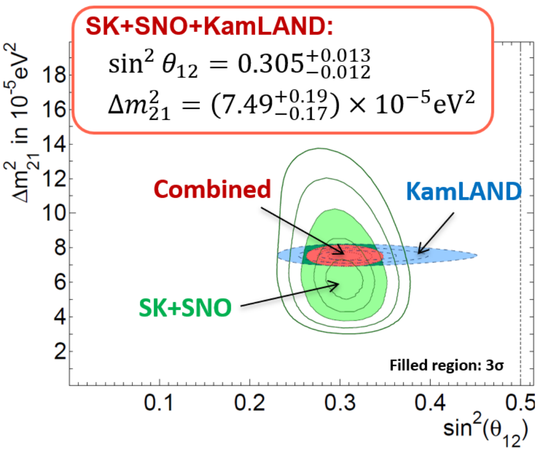

Figure 4: Preliminary results from the solar neutrino oscillation analysis with SK 5805 days dataset in the $\sin^2\vartheta_{12}$ vs. Δm^2_{21} parameter area. The filled regions are 3-sigma allowed areas and the inside lines correspond to 1- and 2-sigma levels, respectively. The 4- and 5-sigma allowed regions are also shown for SK+SNO.

4. Status and prospects of SK-Gd

Adding gadolinium (Gd) to SK, we have started a new experimental phase of SK-Gd. SK-Gd is expected to improve the detection efficiency of neutrons. The Gd concentrations (expected capture efficiency) are 0.011% (~50%) in SK-VI (18 Aug. 2020~) and 0.033% (~75%) in SK-VII (5 Jul. 2022~). In SK-Gd, our primary physics target is to detect the world's first Supernova Relic Neutrinos (SRN) (or Diffuse Supernova Neutrino Background, DSNB).

The neutron events at SK-Gd are monitored by several methods. Cosmic-ray muons produce neutrons by spallation and theses cosmogenic neutrons are measured in SK-VI [17]. In the left plot in Figure 5, such cosmogenic neutrons are used. It shows the smooth movement of the Gd-rich region from the bottom to the top during the operation. The right panel of Figure 5 shows the

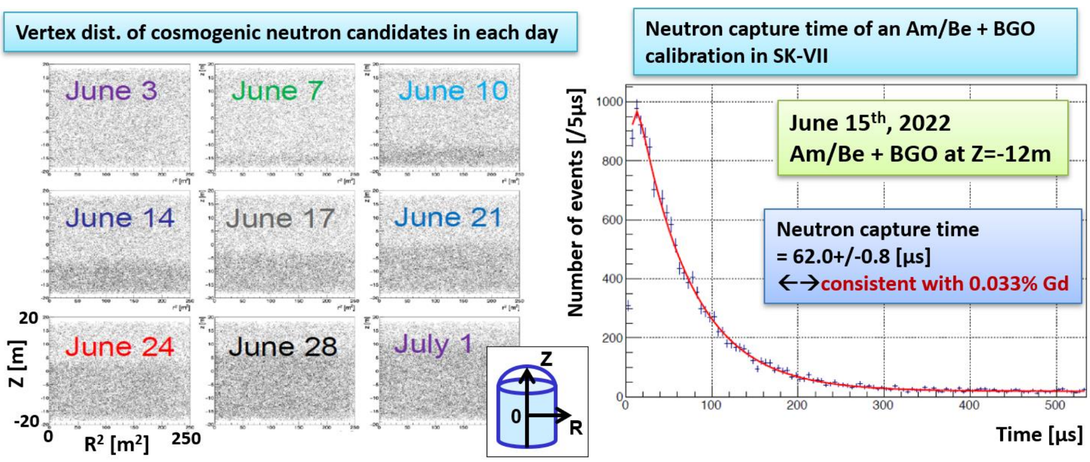

Figure 5: Exaples of neutron monitoring in SK-Gd. The plots on the left are daily measurements of cosmogenic neutron candidate locations during the Gd addition work from SK-VI to SK-VII. The plot on the right is the neutron capture time obtained from a calibration with an Am/Be neutron source and a BGO scintillator [2] in SK-VII.

observed neutron capture time in SK-VII is consistent with the expected capture time at a Gd concentration of 0.033%. Thus, SK-Gd has started the observation smoothly.

Due to the increased neutron tagging efficiency, improvements in neutrino oscillation analyses at SK are also expected. In the atmospheric neutrino analysis, since the discrimination between neutrino and anti-neutrino is enhanced, the purity of the electron-neutrino-like events will be improved also. Then, it will improve δ_{CP} and mass ordering sensitivities [18]. In the solar neutrino analysis, since the detection efficiency of cosmogenic neutrons is increased, the efficiency of the spallation cut will be improved. The remaining spallation events are the dominant background source in higher energy region of solar neutrino signals in SK. Therefore, it is expected to improve the statistical accuracy of solar neutrino measurements.

5. Summary

We are improving atmospheric and solar neutrino oscillation analyses at SK, continuously. The current preliminary results use 6511 live days (SK-I~V) for atmospheric and 5805 live days (SK-I~IV) for solar analyses. The new phase of SK-Gd is started in 2020. Clear neutron signals are observed in SK-Gd. Thanks to the enhanced neutron tagging efficiency, improvements in neutrino oscillation analyses are also expected.

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