Solar neutrino analysis of Super-Kamiokande

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Abstract: Super-Kamiokande-IV data taking began in September of 2008, and with upgraded electronics and improvements to water system dynamics, calibration and analysis techniques, a clear solar neutrino signal could be extracted at recoil electron kinetic energies as low as 3.5 MeV. The SK-IV extracted solar neutrino flux between 3.5 and 19.5 MeV is found to be (2.36±0.02(stat.±0.04(syst.))×10\(^9\) /cm\(^2\)sec). The SK combined recoil electron energy spectrum favors distortions predicted by standard neutrino flavour oscillation parameters over a flat suppression at 1σ level. A maximum likelihood fit to the amplitude of the expected solar zenith angle variation of the elastic neutrino-electron scattering rate in SK, results in a day/night asymmetry of –3.2±1.1(stat.)±0.5(syst.)%. The 2.7σ significance of non-zero asymmetry is the first indication of the regeneration of electron type solar neutrinos as they travel through Earth’s matter. A fit to all solar neutrino data and KamLAND yields sin\(^2\)\(\theta_{12}\) = 0.304±0.013, sin\(^2\)\(\theta_{13}\) = 0.031\(^{+0.017}_{-0.015}\) and Δ\(m^2_{21}\) = 7.45\(^{+0.20}_{-0.19}\)×10\(^{-5}\)eV\(^2\).

Keywords: Solar neutrino, neutrino oscillation, matter effects.

1 Introduction

Solar neutrino flux measurements from Super-Kamiokande (SK)\textsuperscript{1} and the Sudbury Neutrino Observatory (SNO)\textsuperscript{2} have provided direct evidence for solar neutrino flavor conversion. However, there is still no clear evidence that this solar neutrino flavor conversion is indeed due to neutrino oscillations and not caused by any other mechanism. Currently there are two testable signatures unique to neutrino oscillations. The first is the observation and precision test of the MSW resonance curve\textsuperscript{3}. Based on oscillation parameters extracted from solar neutrino and reactor anti-neutrino measurements, there is an expected characteristic energy dependence of the flavor conversion. The higher energy solar neutrinos (higher energy \(8^B\)B and hep neutrinos) undergo complete resonant conversion within the sun, while the flavor changes of the lower energy solar neutrinos (pp, \(7^Be\), pep, CNO and lower energy \(8^B\)B neutrinos) arise only from vacuum oscillations, which limits the average electron flavor survival probability to exceed 50%. The transition from the matter dominated oscillations within the sun, to the vacuum dominated oscillations, should occur near 3 MeV, making \(8^B\)B neutrinos the best choice when looking for a transition point within the energy spectrum. A second signature unique to oscillations arises from the effect of the terrestrial matter density on solar neutrino oscillations. This effect is tested directly by comparing solar neutrinos which pass through the Earth at nighttime to those which do not during the daytime. Those neutrinos which pass through the Earth will in general have an enhanced electron neutrino content compared to those which do not, leading to an increase in the nighttime electron elastic scattering rate (or any charged-current interaction rate), and hence a negative “day/night asymmetry”. SK detects \(8^B\)B solar neutrinos over a wide energy range in real time, making it a prime detector to search for both solar neutrino oscillation signatures.

In this Presentation, the energy spectrum results of SK-IV, the combined SK day/night asymmetry analysis, and an oscillation analysis of SK data and a global analysis which combines the SK results with other relevant experiments are presented.

2 Improvements of Super-Kamiokande IV

Super-Kamiokande is a large, cylindrical, water Cherenkov detector consisting of 50,000 tons of ultra pure water located underground, 1,000 m underneath Mount Ikenoyama, in Kamioka City, Japan. The SK detector is optically separated into 32.5 kton cylindrical inner detector (ID) surrounded by a 2.7 meter active veto outer detector (OD). The structure dividing the detector regions contains an array of photo-multiplier tubes (PMTs). In October of 2006, with 11,129 inner and 1,885 outer PMTs, data taking started as the SK-III phase\textsuperscript{5}. The fourth phase of SK (SK-IV) began in September of 2008, with new front-end electronics for both the inner and outer detectors, and continues to run.

Improving the front-end electronics, the water circulation system, calibration techniques and the analysis methods have allowed the SK-IV solar neutrino measurement to be made with a lower energy threshold and with a lower systematic uncertainty, compared to SK-I, II and III.

The new front-end electronics called QBEEs were installed, allowing for the development of a new online data acquisition system. The essential components on the QBEEs, used for the analog signal processing and digitization, are the QTC (high-speed Charge-to-Time Converter) ASICs\textsuperscript{6}, which achieve very high speed signal processing and allow the recording of every hit of every PMT. The resulting PMT hits information are sent to online computers where a software trigger searches for timing coincidences within 200 ns to pick out events. The energy threshold of this software trigger is only limited by the speed of the online computers.

Ultra-pure water is continuously supplied from the bottom of the detector and drained from the top, as it is circulated through the water purification system with a flow rate of 60 ton/hour. If a temperature gradient exists within the
detector and the supply water temperature is different from the
detector volume and radioactive radon gas, which is
usually produced by decays from the U/Th chain near the
edge of the detector, can make its way into the center of the
detector. Radioactivity coming from the decay
products of radon gas, most commonly $^{214}\text{Bi}$ beta decays, can
mimic the lowest energy solar neutrino events. In January
of 2010, a new automated temperature control system was
installed, allowing for control of the supply water temperature
at the ±0.01 K level. By controlling the water flow rate and
the supply water temperature (within 0.01 K), convection
within the tank can be kept to a minimum and the
background level in the central region of the fiducial vol-
ume has since become significantly lower.

In addition to hardware improvements, a new analysis
method had been developed. Even at the low energies of the
$^8\text{B}$ solar neutrinos, it is possible to use the PMT hit
pattern of the Cherenkov cones to reconstruct the multi-
ple Coulomb scattering of the resultant electrons. Very low
energy electrons will incur more multiple scattering than
higher energy electrons and thus have a more isotropic
PMT hit pattern. The radioactive background events such
as $^{214}\text{Bi}$ beta decays generally have less energy than $^8\text{B}$
solar neutrinos. To characterize this hit pattern anisotropy, a
“direction fit” goodness is used. This goodness is con-
structed by first projecting $42^\circ$ cones from the vertex po-
sition, centered around each PMT that was hit within a 20
ns time window (after time of flight subtraction). Pairs of
such cones are then used to define “event direction candi-
dates”, which are vectors taken from the vertex position to
the intersection points of the two projected cones on the
detector surface. Only cone pairs which intersect twice are
taken as “event direction candidates”. Clusters of these can-
didates are then found by forming vector sums which are
within 50° of a “central event direction”. Once an “event
direction candidate” has been used in the formation of a
cluster, it is then not used as a “central event direction” and
is skipped in further vector sums. Further iterations of this
process will use the vector sums as the “central event direc-
tions”, serving to maximize and center the clusters. After
a couple of iterations, the vector sum with the largest magni-
te is kept as the “best fit direction”. The multiple scatter-
ing goodness (MSG) is then defined by taking the magni-
tude of the largest vector sum (the “best fit direction”) and
normalizing it by the number of “event directions” which
would result using all hit PMTs within the 20 ns time win-
dow. For example, a MSG value of 0.4 would mean that
40% of all “event directions” based on hit PMTs within 20
ns are included in the vector sum.

3 Analysis Results

The start of physics data taking occurred on October 6th,
2008, with this paper including data taken until December
31st, 2012. The total livetime is 1306.3 days. The entire
data period was taken using the same low energy threshold,
with 84% triggering efficiency at 3.5–4.0 MeV, 99% at 4.0–
4.5 MeV and 100% above 4.5 MeV kinetic energy.

In the case of $\nu$–$e$ interactions of solar neutrinos in
SK, the incident neutrino and recoil electron directions are
highly correlated. Fig.1 shows the cos $\theta_{\text{sun}}$ distribution for
events between 3.5–19.5 MeV as well as the defini-
tion of cos $\theta_{\text{sun}}$. In order to obtain the number of solar neu-
trino interactions, an extended maximum likelihood fit is
used. This method is also used in the SK-I [1], II [4], and
III [5] analyses. The solid line of Fig.1 is the best fit to the
data. The dashed line shows the background compo-
nent of that best fit. SK-IV has $N_{\text{on}} = 22$ energy bins; 19
bins of 0.5 MeV width between 3.5-13.5 MeV, two energy
bins of 1 MeV between 13.5 and 15.5 MeV, and one bin
between 15.5 and 19.5 MeV. Below 7.5 MeV, each bin is
split into three sub-samples of MSG, with boundaries set
at MSG=0.35 and 0.45. These three sub-samples are then
fit simultaneously to a single signal and three independent
background components.

Fig.2 shows the measured angular distributions (as well as
the fits) of the lowest two (3.5–4.0 and 4.0–4.5 MeV) ki-
etic recoil electron energy bins for each MSG bin. As ex-
pected in the lowest energy bins, where the dominant part
of the background is due to very low energy gamma, beta
decays, the background component is largest in the lowest
MSG sub-sample. Also, the solar neutrino elastic scat-
tering peak sharpens as MSG is increased (and multiple
Coulomb scattering decreases). Using this method for re-
coil electron energy bins below 7.5 MeV gives 10% im-
provement on the statistical uncertainty of the number of
signal events.

The combined systematic uncertainty of the total flux in
SK-IV is found to be 1.7% as the quadratic sum of all com-
ponents. This is the best value seen throughout all phases of
SK, much improved over 2.2% in SK-III. The main con-
tributions to the reduction come from improvements in the
uncertainties arising from the energy-correlated uncertain-
ties (energy scale and resolution), the vertex shift, trigger
efficiency and the angular resolution. SK-III data below
6.0 MeV recoil electron kinetic energy has only about half
the livetime as the data above, while SK-IV’s livetime is
the same for all energy bins. As a consequence, the energy
scale and resolution uncertainties lead to a smaller system-
atic uncertainty of the flux in SK-IV than in SK-III. The addi-
tion of the 3.5 to 4.5 MeV data lessens the impact of en-
ergy scale and resolution uncertainty on the flux determina-
tion even further. The number of solar neutrino events (be-
tween 3.5 and 19.5 MeV) is $2222^{+225}_{-250}$(stat.) ± 429(syst.).
This number corresponds to an $^8\text{B}$ solar neutrino flux of
were fitted to all the SK-I to SK-IV spectra like SNO per-
679.9 days). The solar neutrino flux between 4.5 and 19.5
assuming a pure statistical plus energy-uncorrelated systematic uncertainties.

Φ

signal plus background, respectively.

and red histograms show the best fit to the background and

Figure 2: cos θ

for the two lowest (3.5-4.0 and 4.0-4.5
MeV) energy bins (upper and lower), for each MSG bin
(left to right). Black points show the data while the blue
and red histograms show the best fit to the background and
signal plus background, respectively.

Φ

(2.36 ± 0.02(stat.) ± 0.04(syst.)) × 10^6/(cm^2 sec),
assuming a pure νe flavor content. Fig 2 shows the result-
ing SK-IV energy spectrum, where below 7.5 MeV MSG
has been used and above 7.5 MeV the standard signal ex-
traction method without MSG is used.

To test the expected “upturn” distortion below ~6 MeV
from the MSW resonance effects, energy-dependent parame-
terized functions of the νe survival probability (P_{ee})
were fitted to all the SK-I to SK-IV spectra like SNO per-
formed

[7, 8]. The fitting result shows that SK spectra dis-

Figure 3: SK-IV energy spectrum using MSG below 7.5
MeV. The horizontal dashed line gives the SK-IV total flux
average (2.36 × 10^6/(cm^2 sec)). Error bars shown are sta-
tistical plus energy-uncorrelated systematic uncertainties.

The SK-IV livetime during the day (night) is 626.4 days
(679.9 days). The solar neutrino flux between 4.5 and 19.5
MeV and assuming no oscillations is measured as Φ_ν =
(2.29 ± 0.03(stat.) ± 0.05(sys.)) × 10^6/(cm^2 sec) during
the day and Φ_ν = (2.42 ± 0.03(stat.) ± 0.05(sys.)) × 10^6/(cm^2 sec) during the night.

A more sophisticated method to test the day/night ef-
fect is given in [1, 9]. For a given set of oscillation param-
eters, the interaction rate as a function of the solar zenith angle is predicted. Only the shape of the calculated solar zenith angle variation is used, the amplitude of it is scaled by an arbitrary parameter. The extended maximum likeli-
hood fit to extract the solar neutrino signal is expanded to allow time-varying signals. The likelihood is then eval-
uated as a function of the average signal rates, the back-
ground rates and the scaling parameter which is called the “day/night amplitude”. The equivalent day/night asym-

Figure 4: SK combined energy dependence of the fit-
ted day/night asymmetry (measured day/night amplitude
times the expected asymmetry (red)) for Δm^2_{21} = 4.89 \times 10^{-3} eV^2, \sin^2 θ_{23} = 0.314 and \sin^2 θ_{13} = 0.025. The error bars shown are statistical uncertainties only.

The day/night asymmetry coming from the SK-I to IV
combined amplitude fit can be seen as a function of recoil
electron kinetic energy in Fig 4 for Δm^2_{21} = 4.89 \times 10^{-3} eV^2,
\sin^2 θ_{23} = 0.314 and \sin^2 θ_{13} = 0.025. The day/night asymmetry in this figure is found by multiplying the fitted day/night amplitude from each energy bin, to the expected day/night asymmetry (red distribution) from the corresponding bin.

Fig 5 shows the Δm^2_{21} dependence of the SK all phases
combined day/night asymmetry for \sin^2 θ_{12} = 0.314 and \sin^2 θ_{13} = 0.025. Here the day/night asymmetry is found by multiplying the fitted day/night amplitude by the ex-
pected day/night asymmetry (red curve). The point where the best fit crosses the expected curve represents the value of Δm^2_{21} where the measured day/night asymmetry is equal to the expectation. Superimposed are the allowed ranges in Δm^2_{21} from the global solar neutrino data fit (green) and from KamLAND (blue). The amplitude fit shows no de-
pendence on the values of θ_{12} (within the LMA region of the
MSW plane) or θ_{13}.
We analyzed the SK-IV elastic scattering rate, the recoil electron spectral shape and the day/night variation to constrain the solar neutrino oscillation parameters. The combination of SK-I, II, III and IV solar neutrino data measure the solar mixing angle to \( \sin^2 \theta_{12} = 0.341^{+0.029}_{-0.023} \) and the solar neutrino mass splitting to \( \Delta m^2_{21} = 4.8^{+1.8}_{-0.9} \times 10^{-5} \text{eV}^2 \).

We then combined the SK-IV constraints with those of previous SK phases, as well as other experiments. The allowed contours of all solar neutrino data (as well as KamLAND’s constraints) are shown in Fig. 5 and 7. In Fig. 5 the contours from the fit to all solar neutrino data are almost identical to the ones of the SK+SNO combined fit. In figures some tension between the solar neutrino and reactor anti-neutrino measurements of the solar \( \Delta m^2_{21} \) is evident. This tension is mostly due to the SK day/night measurement. Even though the expected amplitude agrees well within 1\( \sigma \) with the fitted amplitude for any \( \Delta m^2_{21} \) in either the KamLAND or the SK range, the SK data somewhat favor the shape of the variation predicted by values of \( \Delta m^2_{21} \) that are smaller than KamLAND’s. In Fig. 7 the significance of non-zero \( \theta_{13} \) from the solar+KamLAND data combined fit is about 2\( \sigma \).

5 Conclusion

In the fourth phase of SK we measured the solar \(^8\text{B} \) neutrino-electron elastic scattering rate with the highest precision yet, \((2.36 \pm 0.02 \text{(stat.)} \pm 0.04 \text{(syst.)}) \times 10^6 \text{/(cm}^2\text{sec)}\). We find a 2.7 \( \sigma \) indication for the existence of a solar day/night effect in the SK solar neutrino data, measured as the solar neutrino elastic scattering day/night rate asymmetry of \(-3.2 \pm 1.1 \text{(stat.)} \pm 0.5 \text{(syst.)}\%\). SK’s solar zenith angle variation data results in the world’s most precise measurement of \( \Delta m^2_{21} = 4.8^{+1.8}_{-0.9} \times 10^{-5} \text{eV}^2 \), using neutrinos rather than antineutrinos. A fit to all solar neutrino data and KamLAND yields \( \sin^2 \theta_{12} = 0.304 \pm 0.015 \), \( \sin^2 \theta_{13} = 0.031^{+0.017}_{-0.015} \) and \( \Delta m^2_{21} = 7.45^{+0.20}_{-0.19} \times 10^{-5} \text{eV}^2 \). This value of \( \theta_{13} \) is in agreement with reactor neutrino measurements.

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