Solar neutrino results from Super-Kamiokande

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1, SK solar neutrino measurement

Super Kamiokande detector

- 50 kton water Cherenkov detector at 1000m underground (2700 w.e.)
- 32kton inner detector: 11129 PMTs (20inch)
- Fiducial volume: 22.5kton (2m from the wall)
- Outer detector: 1885 PMTs (8inch) for cosmic ray muon veto
Super Kamiokande experiment

1996 started on April
1998 Observed atmospheric neutrino oscillation
K2K experiment
2001 Solved solar neutrino problem together
with the SNO CC result.
2008 Upgrade of front-end electronics
and DAQ system
2009- T2K experiment

Physics
- **Solar neutrino measurement**
- Search for neutrino from supernova
- Atmospheric neutrino oscillation
- Neutrino from accelerator
- Proton decay search
- Indirect WIMP search
Solar Neutrino measurement at Super-K

\[ \nu + e^- \rightarrow \nu + e^- \text{ (elastic scattering)} \]

- Measure Cherenkov ring pattern from recoiled electron
- Timing information \(\rightarrow\) Vertex of interaction
- Hit pattern \(\rightarrow\) Direction
- Number of hit PMTs \(\rightarrow\) Energy

- High statistics for \(^8\)B neutrino
  \((\sim 15\text{evnts/day for } E_e > 5\text{MeV})\)
- Good angular resolution

Goal:
- Precise measurement of the solar neutrino parameters (flux, timing variation, oscillation parameters etc)
- Reduce the b.g. level and measure the upturn in the solar neutrino spectrum.

Expected rate with oscillation / without oscillation

- BG is 70% reduced compared to SK-I below 5.5 MeV
- Energy-cor. Syst. uncertainty is half compared to SK-I five years

Expected spectrum distortion with 5 years
- Low BG SK data

Black: stat. error
Blue: systematic error
2, Recent SK solar neutrino analysis (SK-III phase)

Data set

SK-III period: 2006/8/5-2008/8/18
(live time : 548 days, E≥6.5 MeV,
289 days, E< 6.5MeV)

2006/8/5-2007/1/24 : 100%eff @6.5MeV
livetime 121.7 days

2007/1/24-2008/4/17 : 100%eff @5.0MeV
livetime 331.5 days
(RR sample ◆ 210.7day)

2008/4/17-2008/8/18 : 100%eff @4.5MeV
livetime 94.8 days
(RR sample 87.5day)
◆RR sample : Radon Reduced sample for which high background rate periods are rejected from the normal run

Improvements in SK-III solar ν analysis

- Reduce Low energy BG ~70%
- Improved Systematics ~50%

http://arxiv.org/abs/1010.0118
2-1, Reduction of background

Improvement of water circulation and purification system

1. Improved water quality
   - Doubled circulation rate
   - Increased purification power

2. Optimized water flow in the tank

→ Lower Rn concentration in fiducial volume
Vertex distribution of final sample

Fiducial volume of each energy region is shown as red box: 12.3kt (4.5-5MeV), 13.3kt (5-5.5MeV), and 22.5kt (5.5-20MeV)

With upgrade of water system, water with higher radioactivity stays near bottom region. -> by applying tighter fiducial volume cut, low b.g. rate can be achieved for 4.5-5.5MeV region
Comparison of background rate between SK-I and III

Solar angular distribution for each energy range.

In lower energy region with tighter fiducial volume cut, SK-III has a lower b.g. rate due to lower radon concentration in water around the central region of the detector.
New cut for low energy events

Background events coming from radioactive sources in FRP cover of PMTs or wall have small clusters in space and timing distribution, when compared with neutrino events near the wall.

Cluster(space) Cluster(timing)

-> Use variables related with cluster size for b.g. reduction.
New cut for low energy events (cont’d)

Horizontal axis: Cluster size * concentration in timing distribution
2-2, Improved systematics

Timing Calibration improvement

Improve systematics (vertex shift)

New hit timing correction is installed.
Electronics linearity is corrected by this correction

Laser pulse width
4ns -> 0.2ns

Reduce low energy BG

R^2 < 150m^2
Z > -7.5m
(8.9kt)

After
R^2 < 180m^2
Z > -7.5m
(13.3kt)
Angular reconstruction

Calibration & MC tuning: black sheet reflectivity

Improving direction fitter

Made likelihood functions for different energy bins from MC

~10% improvement @ 5 MeV

SK-I angular res. (MC)

SK-III LINAC with New Fitter

SK-III LINAC with Old Fitter

Updated in 2009

Q_d (reflected light)/Q_d (direct light)

Degree

in tank Energy [MeV]
MC improvement

Top-bottom asym. (TBA) parameter is newly installed in SK-III MC’s water transparency parameters

Water parameters are carefully tuned

MC hit timing distribution of LINAC is perfectly matched to DATA
Energy scale

Difference between MC and DATA is within +/- 0.5%

Electron beam energy [MeV]
## Table of systematic uncertainties

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>SK-III (Preliminary)</th>
<th>SK-I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy scale</td>
<td>+/-1.4</td>
<td>+/-1.6</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>+/-0.2</td>
<td></td>
</tr>
<tr>
<td>8B spectrum shape</td>
<td>+/-0.2</td>
<td>+1.1/-1.0</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>+/-0.5</td>
<td>+0.4/-0.3</td>
</tr>
<tr>
<td>Vertex shift</td>
<td>+/-0.54</td>
<td>+/-1.3</td>
</tr>
<tr>
<td>Reduction</td>
<td>+/-0.65</td>
<td>+2.1/-1.6</td>
</tr>
<tr>
<td>Small cluster hits cut</td>
<td>+/-0.5</td>
<td></td>
</tr>
<tr>
<td>Spallation cut</td>
<td>+/-0.2</td>
<td>+/-0.2</td>
</tr>
<tr>
<td>External event cut</td>
<td>+/-0.25</td>
<td>+/-0.5</td>
</tr>
<tr>
<td>Background shape</td>
<td>+/-0.1</td>
<td>+/-0.1</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>+/-0.67</td>
<td>+/-1.2</td>
</tr>
<tr>
<td>Signal extraction method</td>
<td>+/-0.7</td>
<td></td>
</tr>
<tr>
<td>Cross section</td>
<td>+/-0.5</td>
<td>+/-0.5</td>
</tr>
<tr>
<td>Live time calculation</td>
<td>+/-0.1</td>
<td>+/-0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>+/-2.1</td>
<td>+3.5/-3.2%</td>
</tr>
</tbody>
</table>

Due to Improvement of detector MC, reconstruction tools and calibration, systematic errors were reduced from +3.5/-3.2%(SK-I) To +/-2.1%(SK-III). -> ~60%
3. Solar neutrino results in SK-III

**Reduction step**

For lower energy region, SK-III has lower b.g. level than SK-I.
Solar neutrino flux for $E=5$-$20$ MeV

SK-III 298 days (5-6.5 MeV) and 548 day (6.5-20 MeV)
Signal 8132+133-131 events

Flux $2.32 \pm 0.04$ (stat.) $\pm 0.05$ (sys.) $\times 10^6$ cm$^{-2}$ s$^{-1}$
(with Winter06 B8 spectrum)

- SK-III result is consistent with SK-I and II.
- Systematic error is reduced.

$\text{SK-I}: 2.38 \pm 0.02$ (stat.) $\pm 0.08$ (sys.) $\times 10^6$ cm$^{-2}$ s$^{-1}$
$\text{SK-II}: 2.41 \pm 0.05$ (stat.) $\pm 0.16$ (sys.) $\times 10^6$ cm$^{-2}$ s$^{-1}$
(re-fitted by Winter06 spectrum)
Angular distribution for E=4.5-5.0MeV

For 4.5-5.0MeV region,

232. ±59. event
2.14 ± 0.54-0.54(stat.)
×10^6 cm^{-2}sec^{-1}

Solar neutrino in this energy region was measured with 4σ significance.
\( ^{8}\text{B} \) Energy spectrum of SK-III data

Consistent with

- SK-I result
- No distortion

4.5 MeV (total energy)
4.0 MeV (kinetic energy)
Day/Night flux

SK-III 298 days (5–6.5 MeV) and 548 days (6.5–20 MeV) (with Winter06 B8 spectrum)

day Signal = 3830 +92 -90 (stat.) events

day $^8$B Flux = 2.25 +/- 0.05 (stat.) (x 10$^6$/cm$^2$/s)

night Signal = 4299 +96 -94 (stat.) events

night $^8$B Flux = 2.38 +0.05 -0.05 (stat.) (x 10$^6$/cm$^2$/s)

Data
- Best-fit
- Background

$\Delta m^2 = 6.0 \times 10^{-5} \text{eV}^2$
$tan^2 \theta = 0.44$
(Solar best fit parameter)

SK-I: $A_{DN} = -1.8 \pm 1.6 \, ^{+1.3}_{-1.2} \%$
SK-II: $A_{DN} = -3.6 \pm 3.5 \pm 3.7\%$
SK-III: $A_{DN} = -4.1 \, ^{+2.5}_{-2.6} \, \pm 1.3\%$
combined: $ADN = -2.3 \pm 1.3\%$(stat) sys : under study
Seasonal variation

Consistent with the eccentricity of the orbit

\[ \chi^2 = 3.6 \]
(only stat)
With dof = 7
Probability 89%

SK-I, II, III
SK-I 1496day average
SK-II 791day
SK-III 5.0-20MeV

\[ \text{SK- I, II, III} \]
\[ \text{consistent with eccentricity of orbit} \]
\[ \text{SK- I, II, III} \]
\[ \text{only stat} \]
\[ \text{dof } = 7 \]
\[ \text{Probability 89\%} \]

Flux (x10^6/cm^2/s)

SK 22.5kt All the eccentricity correction is not applied.
SK-I 1496day average
SK-I 1496day 5.0-20MeV
SK-II 791day 8.0-20MeV
SK-III 5.0-20MeV

YEAR

Consistent with the eccentricity of the orbit
4. Oscillation results

2-flavor SK-I/II/III with flux constraint

- SK-I 1496 days, spectrum 5.0-20MeV + D/N : E ≥ 5.0MeV
- SK-II 791 days, spectrum 7.0-20MeV + D/N : E ≥ 7.5MeV
- SK-III 548 days, spectrum 5.0-20.0MeV + D/N : E ≥ 5.0MeV

$B_8$ rate is constrained by SNO(NCD+LETA) NC flux = $(5.14\pm0.21) \times 10^6 \text{cm}^{-2}\text{s}^{-1}$

Hep is constrained by SSM flux with uncertainty(16%)

Best fit value (preliminary)

- $\Delta m^2 = 6.1 \times 10^{-5} \text{eV}^2$
- $\tan^2 \theta = 0.48$
- $\Phi_{B_8} = 5.2 \times 10^6 \text{cm}^{-2}\text{s}^{-1}$

Only LMA (i.e. LOW excluded)
Global oscillation analysis

Data set
- SK-I/II/III
- **SNO**: CC flux (Phase-I & II & III)
  - NC flux (Phase-III & LETA combined)
    - ($= (5.14 +/- 0.21) \times 10^6 \text{cm}^{-2}\text{s}^{-1}$)
    - Day/Night asymmetry (Phase-I & II)
- **Radiochemical**: Cl, Ga
  - New Ga rate: 66.1 +/- 3.1 SNU (All Ga global)
  - Cl rate: 2.56 +/- 0.23 (Astrophys. J. 496 (1998) 505)
- **Borexino**
  - $^7\text{Be}$ rate: 48 +/- 4 cpd/100tons
    - (PRL 101: 091302, 2008)
- **KamLAND**: 2008
2-flavor global analysis

Best fit value (preliminary)

**Solar global**
- $\Delta m^2 = 6.2 \times 10^{-5}$ eV$^2$
- $\tan^2 \theta = 0.48$
- $\Phi_{B8} = 5.3 \pm 0.2 \times 10^6$ cm$^{-2}$s$^{-1}$

**Solar global + KamLAND**
- $\Delta m^2 = 7.6 \times 10^{-5}$ eV$^2$
- $\tan^2 \theta = 0.3$
- $\Phi_{B8} = 5.1 \pm 0.1 \times 10^6$ cm$^{-2}$s$^{-1}$
3-flavor global analysis: $\theta_{12} - \Delta m_{12}^2$

Free parameters:
$\theta_{12}, \theta_{13}, \Delta m_{12}$

Best fit value (preliminary)

**Solar global**
- $\Delta m^2 = 6.2 \times 10^{-5} \text{ eV}^2$
- $\sin^2 \theta_{12} = 0.31$
- $\sin^2 \theta_{13} = 0.010$
- $\Phi_{B8} = 5.3 \pm 0.2 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$

**Solar global+KamLAND**
- $\Delta m^2 = 7.7 \times 10^{-5} \text{ eV}^2$
- $\sin^2 \theta_{12} = 0.31$
- $\sin^2 \theta_{13} = 0.025 \pm 0.018$ \text{ to } -0.016
- $\Phi_{B8} = 5.3 +0.1 -0.2 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$
3-flavor global analysis: $\theta_{12} - \theta_{13}$
## 5. SK-IV status

### 1. SK-IV Electronics and DAQ system were updated at the beginning of SK-IV phase)

<table>
<thead>
<tr>
<th>Improvements of front-end electronics</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 5 times wider dynamic range for charge measurement (&gt;2000pC)</td>
</tr>
<tr>
<td>• Larger amount of data can be sent to Online system via 100Base/T Ethernet</td>
</tr>
<tr>
<td>• Low power consumption ( &lt; 1W/ch )</td>
</tr>
</tbody>
</table>

### Improvements of online-DAQ system

- SK-I/II/III DAQ system
  - Hardware trigger was used. Only Triggered hit data was sent to online system.
- SK-IV system
  - All the hit data is sent to the online system and event building is done by software
  - -> capable of lower energy threshold

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### 2. Fine water temperature control for inlet water -> Lower radon concentration in fiducial volume
Background level in SK-IV

4.5-5.0 MeV

5.0-5.5 MeV

Same level of b.g. level as SK-III have been achieved in SK-IV phase.
6. Summary

- Results of solar measurement in SK-III phase have been reported.

- There are improvements for b.g. level and systematic uncertainty in SK-III data analysis due to
  -- Water system modification
  -- Improvement of reconstruction tools
  -- Precise calibration and upgrade of detector simulation

- Solar flux, energy spectrum and oscillation results are upgraded including SK-III data

- Measurement in SK-IV phase is on-going, after upgrading front-end electronics and DAQ system.
Definition of SK $\chi^2$

$\chi^2 = \sum_{p}^{N_{phase}} \left( \sum_{i} \frac{(d_{i,p} - \rho_{i,p})^2}{\sigma^2_{i,p}} + \delta^2_{S,p} + \delta^2_{R,p} \right) + \delta^2_{B} + \frac{(\beta - \beta_{NC})^2}{\sigma_{NC}^2} + \frac{(\eta - 1)^2}{\sigma_{hep}^2}$

oscillated/unoscillated of $^8$B ($hep$) flux


B$^8$ rate is constrained by SSM flux and uncertainty.

$\delta_{B}, \delta_{S}, \delta_{R}$ are chosen to minimize the spectrum fit $\chi^2$.
Select period with stable event rate
Figure 12.3: SK-III data with Winter and Ortiz $^8$B spectrum. Green shows SSM with Winter $^8$B spectrum, and red shows SSM with Ortiz $^8$B spectrum.
Figure 12.6: Comparison of the $^8$B flux between SNO results and the results obtained by this thesis. The error size corresponds to 1 $\sigma$ uncertainty of (stat.+sys.). Square mark shows theoretical predictions and cross marks shows experimental results.
Contribution of SK-III result

\[ \Delta m^2 = 6.0 \times 10^{-5} \text{eV}^2 \]

\[ \tan^2 \theta = 0.44 \]

95% C.L. solar global w/ SK-III
Definition of $\chi^2$s for global analysis

$$
\chi^2_{SK+SNO} = \sum_{p}^{N_{\text{phase}}} \left( \sum_{i}^{N_{\text{bin},p}} \frac{(d_{i,p} - \rho_{i,p})^2}{\sigma_{i,p}^2} + \delta_{S,p}^2 + \delta_{R,p}^2 \right) + \delta_B^2 + \frac{(\eta - 1)^2}{\sigma_{\text{hep}}^2} + \chi^2_{SNO,\text{flux}}(\beta, \eta)
$$

$\chi^2_{SK,\text{time variation}} = \sum_{p}^{2} \frac{(\Delta \chi^2_{t.v.,p}(\beta, \eta, \delta_B, \delta_S, \delta_R, \rho))}{(\Delta \chi^2_{t.v.,p}(\beta, \eta))}
$

$\chi^2_{SNO,\text{flux}}(\beta, \eta) = \sum_{p=1}^{3} \left( \frac{D_{\text{CC}}^p - (\beta B_{\text{CC}}^p + \eta H_{\text{CC}}^p))^2}{(\sigma_{\text{CC}}^p)^2} \right) + \left( \frac{D_{\text{NC}} - (\beta B_{\text{SSM}} + \eta H_{\text{SSM}})^2}{(\sigma_{\text{NC}})^2} \right)
$

$\beta, \eta$ and $\delta$s are chosen to minimize $(SK\ spectrum+SNO\ flux\ fit)\ \chi^2$.

$$
\chi^2_{GaCl} = \sum_{n,m=1}^{N(=2)} \left( R_{n,\text{exp}}^t - R_{n,\text{theor}} \right) [\sigma_{nm}^2]^{-1} \left( R_{m,\text{exp}}^t - R_{m,\text{theor}} \right)
$$

Ga/Cl

$$
\chi^2_{GaCl\ Bore} = \sum_{n,m=1}^{N(=3)} \left( R_{n,\text{exp}}^t - R_{n,\text{theor}} \right) [\sigma_{nm}^2]^{-1} \left( R_{m,\text{exp}}^t - R_{m,\text{theor}} \right)
$$

Ga/Cl/Borexino
1D plot – this time analysis

95% C.L.
solar global: $\sin^2 \theta_{13} < 0.060$
KamLAND: $\sin^2 \theta_{13} < 0.075$
solar global + KamLAND: $\sin^2 \theta_{13} < 0.059$

$\sin^2 \theta_{13} = 0.025 \pm 0.018 \pm 0.016$
Sensitivity calculation

\[ \beta = 1 : \text{expected curve} \]
\[ \beta = 0 : \text{flat} \]

SK-IV, 5 years, cor-E is same as SK-I
13.3kton (< 5.5MeV) and 22.5kton (> 5.5MeV),
\( (\sin^2 \theta, \Delta m^2) = (0.30, 7.9 \times 10^{-5}) \)

\[ \chi^2 = \sum_{i=1}^{21} \frac{(d_i - \beta(\alpha(f_i(\delta) - C) + C))^2}{\sigma_i^2} + \frac{\delta^2}{\sigma_{cor}^2} \]
Sensitivity of the upturn measurement

In the case of \((\sin^2\theta, \Delta m^2) = (0.30, 7.9 \times 10^{-5})\)

- First target: 2 sigma level up-turn discovery for 3 years observation. (or exclude the up-turn)
- Need to enlarge fiducial volume with low BG as large as possible
- Also the reduction of the energy correlated systematic error is important.

(1) Enlarge fiducial volume to 22.5kton with low B.G.
(2) Half energy correlated systematic error as SK-1.

The black line shows the 13.3kton (<5.5MeV), 22.5kton (>5.5MeV) fiducial volume with the same energy correlated error as SK-1
Oscillation parameter dependence

The correlated error is half as SK-1 13.3kton (< 5.5MeV) and 22.5kton (> 5.5MeV)
If theta12 is determined, the precise $^8$B flux measurement in SK may be possible to contribute the improvement of the Solar Model.