Solar Neutrino Results from Super-Kamiokande

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Solar neutrinos

Nuclear fusion reaction deep inside the Sun

$4p \rightarrow ^2\text{He} + 2e^+ + 2\nu_e$

($\sim 6.6 \times 10^{10}$ neutrinos/sec/cm$^2$)

This reaction is actually realized through pp-chain / CNO cycle.

Feature/Purpose of measurement

- Measurement of the current status in the center of the Sun.
- Study of
  - the mechanism of energy generation in the Sun
  - the property of neutrinos
Observation in Super-K

Neutrino-electron elastic scattering

\[ \nu + e^- \rightarrow \nu + e^- \]

- Find solar direction
- Realtime measurements
  - day/night flux differences
  - Seasonal variation
- Energy spectrum
Solar neutrino spectrum

Neutrino Flux (cm$^{-2}$/sec/MeV)

Neutrino energy (MeV)

$\pm X\%$ is theoretical uncertainties

$^7$Be, pep : integrated flux

(Bahcall-Pena-Garay-Serenelli 2008)

$^7$Be $\pm 5.8\%$

$^8$B $\pm 11.3\%$

hep $\pm 15.5\%$

Super-Kamiokande

$^7$Be, $^8$B, pep : integrated flux

$^{13}$N $+15%$ $-14%$

$^{15}$O $+16%$ $-15%$

$^{17}$F $+19%$ $-17%$

$^7$Be $\pm 5.8\%$

Neutrino energy (MeV)
Motivation

See the MSW effect directly

* Spectrum distortion
* Day/Night flux asymmetry

Neutrino survival probability measured by several experiments

![Graph showing neutrino survival probability and mass difference](chart)

\[ A_{DN} = \frac{(\Phi_{Day} - \Phi_{Night})}{(\Phi_{Day} + \Phi_{Night})/2} \]

\[ \Delta m^2 = 6 \times 10^{-4} \text{ eV}^2 \]

\[ \sin^2(\theta) \]

- $0.6\%$
- $1.0\%$
- $1.8\%$
- $3.2\%$
- $5.6\%$
- $10\%$

See this up-turn!
RESULTS
What’s new

- mistake in SK-III calculation of expected solar neutrino event rate: best fit flux changes $2.32 \rightarrow 2.40 \times 10^6/(\text{cm}^2 \cdot \text{sec})$

- First results from SK-IV (1069.3 days of data)
  - Large statistics with lower backgrounds.
  - Reduce systematic error (1.7% for flux)
    - new electronics: 2.1% (SK-III) 3.4% (SK-I)
    - better timing determination
    - better MC model of trigger eff.
  - Lower threshold (~3.5 MeV (kin.))

- Introduce multiple scattering goodness

Multiple scattering effect

- hit pattern
  - lower energy
  - more isotropic
  - higher energy
  - more forward
Lower background

(event/day/kton @ 4.0-4.5MeV(kin.))

Solar angular distribution
(3.5~4.0MeV(kin.))

SK-III

SK-IV

Achieve stable low background level

B8 neutrino signal

= 763 + 113 - 111 (stat.)

Signal @~7σ level
Total solar neutrino event

SK-I, II, III, IV 3904 days
SIGNAL = 57721.3 events

best fit: $0.451 \pm 0.007$

$\phi_{B} = 5.25 \times 10^{6}/(\text{cm}^{2} \cdot \text{sec})$
$\phi_{\text{hep}} = 7.88 \times 10^{3}/(\text{cm}^{2} \cdot \text{sec})$

- about 19,000 events more than from pure $\nu_{e}$
- small systematic uncertainty
- rate is consistent between all the SK phases
Recoil electron spectrum

Winter 06 Spectrum
Blue: Total uncertainty
• : Energy-cor. Sys.

SK-I Energy Spectrum
Green: Average Flux(4.5-19.5MeV(kin))
MC $^8$B Flux = $5.25 \times 10^6$/cm$^2$/s

SK-II Energy Spectrum
Green: Average Flux(6.5-19.5MeV(kin))
MC $^8$B Flux = $5.25 \times 10^6$/cm$^2$/s

SK-III Energy Spectrum
Green: Average Flux(4.5-19.5MeV(kin))
MC $^8$B Flux = $5.25 \times 10^6$/cm$^2$/s

SK-IV Energy Spectrum
Green: Average Flux(4.0-19.5MeV(kin))
MC $^8$B Flux = $5.25 \times 10^6$/cm$^2$/s
Recoil electron spectrum

SK I/II/III/IV LMA Spectrum

<table>
<thead>
<tr>
<th>Oscillation par's</th>
<th>$\chi^2$</th>
<th>$\phi_B$ / (cm$^2$·sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2\theta_{13}=0.025$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sin^2\theta_{12}=0.304 \ast$, $\Delta m^2=7.41\times 10^{-5}$ eV$^2$</td>
<td>SK spec: 78.51 (global: 82.55)</td>
<td>$5.37\times 10^6$ (5.24$\times 10^6$)</td>
</tr>
<tr>
<td>$\sin^2\theta_{12}=0.314 \ast$, $\Delta m^2=4.8\times 10^{-5}$ eV$^2$</td>
<td>SK spec: 75.76 (global: 79.33)</td>
<td>$5.48\times 10^6$ (5.32$\times 10^6$)</td>
</tr>
<tr>
<td>Flat probability</td>
<td>SK spec 74.68</td>
<td>$5.55\times 10^6$</td>
</tr>
<tr>
<td>Flat prob., d$\sigma$ ratio</td>
<td>SK spec 73.10</td>
<td>$5.53\times 10^6$</td>
</tr>
</tbody>
</table>

$\phi_B=5.25\times 10^6/(\text{cm}^2\cdot\text{sec})$

$\phi_{\text{hep}}=7.88\times 10^3/(\text{cm}^2\cdot\text{sec})$

Unoscillated shape favored $\sim 1.1$ to $1.9 \sigma$
Comparison with other experiments

\[ \phi_{8B} = 5.25 \times 10^6 / \text{(cm}^2 \cdot \text{sec)} \]

\[ \phi_{\text{hep}} = 7.88 \times 10^3 / \text{(cm}^2 \cdot \text{sec)} \]
DAY/NIGHT FLUX DIFFERENCES
Day/Night variation

From Phys. Rev. D69 011104 (2004): $\Delta m_{21}^2 = 6.3 \cdot 10^{-5} \text{eV}^2$

$\sin^2 \theta_{12} = 0.314$; $\Delta m_{21}^2 = 4.8 \cdot 10^{-5} \text{eV}^2$

Day/Night Asym.: $A_{\text{DN}} = 2(\phi_D - \phi_N)/(\phi_D + \phi_N)$

<table>
<thead>
<tr>
<th>experiment</th>
<th>D/N amplitude</th>
<th>$A_{\text{DN}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>-2.0±1.7±1.0%</td>
<td>-2.1±2.0±1.3</td>
</tr>
<tr>
<td>SK-II</td>
<td>-4.3±3.8±1.0%</td>
<td>-6.3±4.2±3.7</td>
</tr>
<tr>
<td>SK-III</td>
<td>-4.3±2.7±0.7%</td>
<td>-5.9±3.4±1.3</td>
</tr>
<tr>
<td>SK-IV</td>
<td>-2.8±1.9±0.7%</td>
<td>-5.2±2.3±1.4</td>
</tr>
<tr>
<td>SK comb.</td>
<td><strong>-2.8±1.1±0.5</strong></td>
<td>-4.0±1.3±0.8</td>
</tr>
</tbody>
</table>

Day-Night amplitude consistent with zero @ 2.3 $\sigma$
Day/Night amplitude fits as a function of $\Delta m^2$

$\sin^2 \theta_{12} = 0.314$

SK-I/II/III/IV Combine Day/Night Asymmetry

Best Fit
1 Sigma Stat.
1 Sigma Stat. + Sys.

Expected
1 Sigma Kamland
1 Sigma Solar
Allowed oscillation parameter region from Day/Night

KamLAND 1σ

SK Day/Night Amplitude 1σ
NEUTRINO OSCILLATION ANALYSIS
Neutrino oscillation analysis

\[ \sin^2 \theta_{13} = 0.030 \pm 0.017 \]

Solar+KamLand

Consistent with SBL reactor experiments (0.025)

Constraint to the following neutrino oscillation analysis

\[ \sin^2 \theta_{12} = 0.304^{+0.059}_{-0.040} \]
\[ \sin^2 \theta_{13} = 0.031^{+0.038}_{-0.036} \]
\[ \sin^2 \theta_{12} = 0.305^{+0.021}_{-0.016} \]
\[ \sin^2 \theta_{13} = 0.014^{+0.027}_{-0.021} \]
\[ \sin^2 \theta_{12} = 0.306^{+0.015}_{-0.014} \]
\[ \sin^2 \theta_{13} = 0.030^{+0.017}_{-0.015} \]
Only Super-K solar

\[
\sin^2(\theta_{12}) = 0.309^{+0.040}_{-0.029}
\]
\[
\Delta m^2_{21} = (7.49^{+0.21}_{-0.19}) \times 10^{-5} \text{eV}^2
\]

\[
\sin^2(\theta_{12}) = 0.339^{+0.028}_{-0.024}
\]
\[
\Delta m^2_{21} = (4.69^{+1.80}_{-0.83}) \times 10^{-5} \text{eV}^2
\]

\[
\sin^2(\theta_{12}) = 0.322^{+0.024}_{-0.020}
\]
\[
\Delta m^2_{21} = (7.46^{+0.20}_{-0.20}) \times 10^{-5} \text{eV}^2
\]
All solar neutrino data

\[ \sin^2(\theta_{12}) = 0.309 \pm 0.013 \]
\[ m_{21} = (7.49 \pm 0.21) \times 10^{-5} \text{eV}^2 \]

\[ \sin^2(\theta_{12}) = 0.310 \pm 0.014 \]
\[ m_{21} = (4.86 \pm 1.44) \times 10^{-5} \text{eV}^2 \]

\[ \sin^2(\theta_{12}) = 0.304 \pm 0.015 \]
\[ m_{21} = (7.49 \pm 0.21) \times 10^{-5} \text{eV}^2 \]
Summary

* Solar neutrino data taking in Super-K successfully keep going and improvement, e.g. lower threshold, lower background, small systematic uncertainties, large statistics, etc...

* No significant spectrum distortion can be seen.

* Some hint of non-zero day/night flux asymmetry. (2.3σ)

* Neutrino oscillation parameters are updated from Solar +KamLand global analysis; \( \Delta m^2_{21} = 7.44^{+0.20}_{-0.19} \times 10^{-5} \text{eV}^2 \), \( \sin^2 \theta_{12} = 0.304 \pm 0.013 \), \( \sin^2 \theta_{13} = 0.030^{+0.017}_{-0.015} \)
BACK UP
Problem in Solar $\nu$ MC vector generation in SK-III

**Expected solar neutrino rate**

\[ F(T_e) dT_e = \int_0^{E_{\nu,\text{max}}} \phi(E_{\nu}) \left( \frac{d\sigma}{dT_e} dE_{\nu} \right) dT_e \]

Not include this energy dependence...
How does it affect?

- No energy dependence in differential cross section.
  - The shape was shifted directed to higher region.
  - The Total flux was not changed.
- If you apply the energy cut, e.g. above 5MeV, though the spectrum was not changed, the expected flux became large.
How are the results changed?

**SK-III energy spectrum**

- **$^8$B Flux ($10^6$/cm$^2$/s)**
- **Total energy of recoil electrons (MeV)**

Flux results:
- **2.40 (fixed)**
- **2.32 (before)**

3% difference
Multiple Scattering Goodness (MSG)

• Lower energy electrons will incur more multiple scattering and will have more unit vectors pointing along different directions, giving a lower goodness.

• Higher energy electrons will scatter less and will have unit vectors in better agreement, resulting in higher goodness.

• Although the Bi\textsuperscript{214} decay electrons (majority of low energy background) fluctuate up above 5.0 MeV in energy, they truly have energy <3.3 MeV and should have more multiple scattering than true 5.0 MeV electrons, and therefore a lower MSG.
Recoil electron spectrum

\( \phi_{\text{B}} = 5.25 \times 10^6/(\text{cm}^2 \cdot \text{sec}) \)

\( \phi_{\text{hep}} = 7.88 \times 10^3/(\text{cm}^2 \cdot \text{sec}) \)
Recoil electron spectrum

$\phi_{8B} = 5.25 \times 10^6 / (\text{cm}^2 \cdot \text{sec})$

$\phi_{\text{hep}} = 7.88 \times 10^3 / (\text{cm}^2 \cdot \text{sec})$
Day/Night amplitude fits as a function of $\sin^2\theta_{12}$

$\Delta m_{21}^2 = 4.84 \times 10^{-5}$

![Graph showing the Day/Night asymmetry as a function of $\sin^2\theta_{12}$](image)
Only SNO

\[ \sin^2(\theta_{12}) = 0.309 \pm 0.016 \]
\[ \Delta m^2_{21} = (7.49 \pm 0.21) \times 10^{-5} \text{eV}^2 \]

\[ \sin^2(\theta_{12}) = 0.321 \pm 0.017 \]
\[ \Delta m^2_{21} = (4.93 \pm 2.72) \times 10^{-5} \text{eV}^2 \]

\[ \sin^2(\theta_{12}) = 0.309 \pm 0.016 \]
\[ \Delta m^2_{21} = (7.48 \pm 0.21) \times 10^{-5} \text{eV}^2 \]
\[
\sin^2(\theta_{12}) = 0.309^{+0.040}_{-0.029} \quad \Delta m^2_{21} = (7.49^{+0.23}_{-0.18}) \times 10^{-5} \text{eV}^2
\]

\[
\sin^2(\theta_{12}) = 0.317^{+0.014}_{-0.016} \quad \Delta m^2_{21} = (4.85^{+1.14}_{-0.54}) \times 10^{-5} \text{eV}^2
\]

\[
\sin^2(\theta_{12}) = 0.309\pm0.014 \quad \Delta m^2_{21} = (7.44^{+0.21}_{-0.18}) \times 10^{-5} \text{eV}^2
\]

SK Day/Night picks best-fit solar \( \Delta m_{21} \); allowed regions much smaller

KamLAND