Latest Solar Neutrino Results from Super-Kamiokande
Neutrino Flavour Physics

- similar physics program as quark mixing, but...
- large mixing and small cross sections
- best probed by oscillation experiments

Michael Smy, UC Irvine
Neutrino Flavour Mixing: MNS Matrix

\[ U = \begin{pmatrix}
    c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\
    -s_{12}c_{23} - e^{-i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\
    -e^{i\delta}c_{12}s_{13}c_{23} + s_{12}s_{23} & -e^{i\delta}s_{12}s_{13}c_{23} - c_{12}s_{23} & c_{13}c_{23}
\end{pmatrix} \]

- **Known Parameters**
  - Two Mass\(^2\) Diff. scales
    - atmospheric: \(\Delta m^2_{23}\)
    - solar /KamLAND: \(\Delta m^2_{12}\)
  - Two Mixing Angles
    - atmospheric: \(\theta_{23}\)
    - solar/KamLAND: \(\theta_{12}\)
  - Mass\(^2\) ordering
    - solar: \(\Delta m^2_{12}\)

- **Unknown Parameters**
  - Third Mixing Angle \(\theta_{13}\) (only limit)
  - CP-Violating Phases
    - accessible via \(\nu\) oscillation: \(\delta\)
    - accessible only via \(0\nu\beta\beta\): \(\alpha_1, \alpha_2\)
  - Mass\(^2\) ordering
    - atmospheric: \(\Delta m^2_{23}\)
  - Other
    - Mass?
    - Majorana or Dirac?

Courtesy T. Maruyama, KEK
Solar Neutrinos

- conclusive proof that the sun shines because of nuclear reactions
- directly monitor the solar core
- MSW-resonant flavor conversion happens in the sun for high energy solar neutrinos (>~3 MeV)
- flavor conversion modified if neutrinos pass through the earth
Solar pp Chain and ν Detection
Solar ν Spectrum

Neutrino Flux rate seen from ν-e⁻ elastic scattering

Michael Smy, UC Irvine
SK-III result for $^8$B Flux:

$$2.32\pm 0.04\text{(stat.)} \pm 0.05\text{(syst.)} \times 10^6\text{/cm}^2\text{/s}$$

(somewhat larger since oscillated solar neutrinos contribute)
Water-Cherenkov Technique

• electron-neutrino elastic scattering:
  – no threshold
  – strongly forward-peaked: recoil electrons point to the source
  – kinematic reconstruction required to measure neutrino energy

• preserve directional signature, but multiple Coulomb scattering prevents kinematic reconstruction

• low light yield implies high threshold (∼3 MeV) and large energy resolution (∼14% at 10 MeV)

Michael Smy, UC Irvine
Water Cherenkov Technique

Super-Kamiokande
Run 1742 Event 102496
96-05-31 07:13:23
Inner: 103 hits, 123 pE
Outer: -1 hit, 0 pE (in-time)
Trigger ID: C433
E = 9.086 GeV, \( \cos \theta_{\text{sun}} = 0.945 \)
Solar Neutrino

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

- Timing information \( \rightarrow \) vertex position
- Ring pattern \( \rightarrow \) direction
- Number of hit PMTs \( \rightarrow \) energy

\(~6\text{hit} / \text{MeV} \) (SK-I, III, IV)

Resolution (for 10MeV electrons)

<table>
<thead>
<tr>
<th>Energy</th>
<th>Vertex</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>14%</td>
<td>87cm</td>
<td>26° SK-I</td>
</tr>
<tr>
<td>14%</td>
<td>55cm</td>
<td>23° SK-III</td>
</tr>
</tbody>
</table>

E_e = 9.1MeV \( \cos \theta_{\text{sun}} = 0.95 \)

(box: time)

Outer Detector

Inner Detector

Courtesy Y. Takeuchi, ICRR
Super-Kamiokande History

inner detector mass: 32kton  
fiducial mass: 22.5kton

---|---|---|---|---|---|---|---|---|---|---|---|---|---
SK-I | SK-II | SK-III | SK-IV

### SK-I
- 11146 ID PMTs (40% coverage)
- Acrylic (front) + FRP (back)
- Energy Threshold: 5.0 MeV

### SK-II
- 5182 ID PMTs (19% coverage)
- Aug-2002
- Energy Threshold: 7.0 MeV

### SK-III
- 11129 ID PMTs (40% coverage)
- Apr-2006
- Energy Threshold: 4.5 MeV
- Work in progress

### SK-IV
- Electronics Upgrade
- Energy Threshold: < 4.0 MeV
- Target
Impact of SK-I Solar Data on $\nu$ Oscillation

Before Super-Kamiokande-I:

- Really Oscillations?
- Active or Sterile Oscillations?
- SMA, VAC, LMA, LOW?

After Super-Kamiokande-I:

- Active Oscillation! (June 2000)
- Large Angle! (June 2000)
- Not VAC, SMA! (June 2000)
- Not LOW! (December 2001)
- LMA-I (September 2003)
- Really Osc.! (with SNO: 2001)

September 2003, Seattle
hep-ex/0309011

Michael Smy, UC Irvine
... but now what?

- after completion of Super-Kamiokande-I and SNO, solar neutrino flavor conversion is well established, parameters are measured and in agreement with reactor neutrino measurements.
- however, transition from solar resonance to averaged vacuum oscillation has not been probed; resulting distortion to the observed spectrum so far not confirmed.
- modification of conversion by Earth matter effect is unobserved.
- better measurement of solar mass splitting $\Delta m^2_{12}$ desirable to compare to reactor neutrino measurements.

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Super-Kamiokande III

• added PMT enclosures (acrylic front, fiberglass back) lead to higher radioactivity level
• reduce this by software (better event reconstruction)
• reduce background due to dissolved Radon gas by better control of water flow in detector (via injection water temperature; very fickle: need about 0.01 degrees measurements)
• still have a convection cell at the bottom of the detector transporting Radon deep inside
• Tight fiducial volume cut is applied in $E_{\text{total}} < 5.5\text{MeV}$ to remove the background events. (probably Rn, $\gamma$-rays from detector wall).
<table>
<thead>
<tr>
<th>Source</th>
<th>SK-III</th>
<th>SK-I (PRD73, 112001)</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>Total</td>
<td>+/-2.1</td>
<td>+3.5/-3.2%</td>
</tr>
</tbody>
</table>

Energy region: \( E_{\text{total}} = 5.0-20.0 \text{MeV} \)

The systematic error on total flux of SK-III is reduced by precise calibrations and software improvements.

Courtesy Y. Takeuchi, ICRR
SK-III solar neutrino results

- Total live time: 548 days, $E_{\text{total}} \geq 6.5$ MeV
  
  289 days, $E_{\text{total}} < 6.5$ MeV

- Energy region: $E_{\text{total}} = 5.0$-20.0 MeV

- $^8$B Flux: $2.32 \pm 0.04 \text{(stat.)} \pm 0.05 \text{(syst.)} \times 10^6$/cm$^2$/s
  - SK-I: $2.38 \pm 0.02 \text{(stat.)} \pm 0.08 \text{(syst.)}$
  - SK-II: $2.41 \pm 0.05 \text{(stat.)} \pm 0.08 \text{(syst.)}$

  (SK-I,II are recalculated with the Winter06 $^8$B spectrum)

- Day / Night ratio:
  \[
  A_{DN} = \frac{(\Phi_{\text{Day}} - \Phi_{\text{Night}})}{(\Phi_{\text{Day}} + \Phi_{\text{Night}})/2} = -0.056 \pm 0.031 \text{(stat.)} \pm 0.013 \text{(syst.)}
  \]
  - SK-I: $-0.021 \pm 0.020 \text{(stat.)} \pm 0.013 \text{(syst.)}$
  - SK-II: $-0.063 \pm 0.042 \text{(stat.)} \pm 0.037 \text{(syst.)}$

Courtesy Y. Takeuchi, ICRR
Angular distributions in SK-III

- Angular resolution in SK-III is better.
- In $E_{\text{total}} = 5.0-5.5\text{MeV}$, SK-III has better Signal to Noise ratio.
- BG level in 4.5-5.0MeV region is similar as that in 5.0-5.5MeV of SK-I.

Courtesy Y. Takeuchi, ICRR
Consistent with no distortion

$E_{\text{total}}=4.5-5.0\text{MeV}$ data isn’t used in the oscillation analysis.
Data set for oscillation analysis

• SK
  – 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

• SNO
  – CC flux (Phase-I & II & III)
  – NC flux (Phase-III & LETA combined) (= (5.14+/-0.21) 10^6 cm^-2 s^-1)
  – Day/Night asymmetry (Phase-I & II)

• Radiochemical : Cl, Ga
  – Cl rate:  2.56+/-0.23 (Astrophys. J. 496 (1998) 505)

• Borexino
  – 7Be rate: 48 +/- 4 cpd/100tons (PRL101, 091302(2008))

• KamLAND : 2008

updates since our previous oscillation analysis (PRD78,032002(2008))

Courtesy Y. Takeuchi, ICRR
2-flavor SK-I/II/III with flux constraint

Min $\chi^2 = 48.8$
$\Delta m^2 = 6.1 \times 10^{-5} \text{ eV}^2$
$\tan^2 \theta = 0.48$
$\Phi_{B8} = 0.89 \times \Phi_{B8,SSM}$

B8 rate is constrained by SNO(NCD+LETA) NC flux
$= (5.14 \pm 0.21) \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$

*hep* rate is constrained by SSM flux and uncertainty(16%).

Only LMA solution

Courtesy Y. Takeuchi, ICRR
**Two-Flavor Global Analysis**

\[
\begin{align*}
\text{Min } \chi^2 & = 53.7 \\
\Delta m^2 & = 6.0 \times 10^{-5} \text{ eV}^2 \\
\sin^2 \theta_{12} & = 0.31 \\
\Phi_{B8} & = 0.92 \times \Phi_{B8, SSM}
\end{align*}
\]

\[
\begin{align*}
\text{Min } \chi^2 & = 57.7 \\
\Delta m^2 & = 7.7 \times 10^{-5} \text{ eV}^2 \\
\sin^2 \theta_{12} & = 0.31 \\
\Phi_{B8} & = 0.89 \times \Phi_{B8, SSM}
\end{align*}
\]

---

**Solar global**

- 95% C.L.

**Solar global + KamLAND**

- 95% C.L.
Three-Flavor analysis: $\theta_{12} - \Delta m_{12}^2$

Solar global:
- $\text{Min } \chi^2 = 52.8$
- $\Delta m^2 = 6.0 \times 10^{-5} \text{ eV}^2$
- $\sin^2 \theta_{12} = 0.31$
- $\sin^2 \theta_{13} = 0.010$
- $\Phi_{B8} = 0.92 \times \Phi_{B8, SSM}$

Solar global + KamLAND:
- $\text{Min } \chi^2 = 71.2$
- $\Delta m^2 = 7.7 \times 10^{-5} \text{ eV}^2$
- $\sin^2 \theta_{12} = 0.31$
- $\sin^2 \theta_{13} = 0.025$
- $\Phi_{B8} = 0.91 \times \Phi_{B8, SSM}$
Three-Flavor Analysis: $\theta_{12} - \theta_{13}$

Solar global:

$\sin^2 \theta_{13} < 0.060$

@95% C.L.

Solar global + KamLAND:

$\sin^2 \theta_{13} = 0.025^{+0.018}_{-0.016}$

(<0.059 @95% C.L.)

Cf. PRC81, 055504 (2010)

$\sin^2 \theta_{13} = 0.020^{+0.021}_{-0.016}$

(<0.057 @95% C.L.)
SK-IV’s new DAQ: QBEE replaces ATM

QTC-Based Electronics with Ethernet (QBEE)

- 24 channel input
- QTC (custom ASIC)
  - three gain stages
  - wider (5x!) dynamic range
- Pipe line processing
  - multi-hit TDC (AMT3)
  - FPGA
- Ethernet Readout
- 60MHz common clock
- Internal calibration pulser
- Low (<1W/ch!) power
**Former readout system**

- **Former Electronics (ATM)**
- **Trigger (1.3μsec x 3kHz)**
- **Readout (backplane, SCH, SMF)**
- **HITSUM**
- **Hardware Trigger using number of hit (HITSUM)**
- **1.3μsec event window**

**New readout system**

- **New Electronics (QBEE)**
- **Periodic trigger (17μsec x 60kHz)**
- **Clock**
- **Readout (Ethernet)**
- **Variable event window by software trigger**

**No hardware trigger. All hits are read out. Apply software trigger.**
Wideband Intelligent Trigger

I. online conversion of ADC/ TDC to times/charges
II. sort hits by time
III. pre-filter based on $N_{230}$ (# of hits within 230ns)
IV. Software Triggered Online Reconstruction of Events:
   coincidence after time-of-flight subtraction using vertices from selected four-hit combinations
V. fast vertex fit
VI. if fiducial, precision vertex fit
VII. if fiducial, save event
Test with Ni-Cf $\gamma$ Source

center (top view) | bottom (top view)

center (side view) | bottom (side view)

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SK IV Low Energy Trigger

• so far, WIT is not running yet
• just emulate previous hardware trigger with larger trigger rate
• use same CPUs as the high energy trigger
• ~100% efficient at 4.5 MeV total energy
New Ideas for Analysis

• from now on, I’m showing work I did with my student Andrew Renshaw
• not official results approved by SK collaboration unless specifically indicated
How to Reduce Radon Background?

- Radon decays to $^{214}\text{Bi}$ which $\beta$ decays
- real electrons $<3.1\text{MeV}$ fluctuating in light yield up to $6.5\text{ MeV}$ equivalent
- however, multiple Coulomb scattering is still that of $\sim2$ to $3\text{ MeV}$ electrons, so events should be somewhat more isotropic than $5\text{ MeV}$ solar neutrinos
Reconstructing Amount of
Multiple Coulomb Scattering

Hough transformation for PMT pairs:

1. assign a unit direction vector to each PMT hit
2. Draw cone around each vector with the Cherenkov angle as the opening angle
3. the cone intersections are candidates for particle direction: each pair typically contributes two
4. define “goodness” as the length of the vector sum of all candidates within a maximum deviation angle
5. normalize goodness by the longest possible vector sum

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Goodness Distribution $4\text{MeV} < E < 6.5\text{MeV}$

SK3+SK4 solar neutrinos
$\cos \theta_{\text{sun}}>0$ - $\cos \theta_{\text{sun}}<0$

SK3+SK4 background
$\cos \theta_{\text{sun}}<0$

SK3 $^8\text{B}$ Monte Carlo

Radon Injection Sample
The “ES peak” sharpens in regions of higher goodness (true for all LINAC momenta at all positions)

```
goodness<0.33
0.33<goodness<0.45
goodness>0.45
```

defined as the angle between –z (beam direction) and reconstructed direction

4.8 MeV Linac Data taken at (-3.9,-0.1,0)m
SK IV $\cos \theta_{\text{sun}}$ Distributions

- **4.0-4.5 MeV**
- **4.5-5.0 MeV**
- **5.0-5.5 MeV**

- **goodn < 0.33**
- **0.33 < goodn < 0.45**
- **goodn > 0.45**
SK-IV Stat. Error :
Official vs. MS Constraint

(Percentage error of official result)
(Percentage error of multi-scat constraint)
first SK IV solar signal between 4 and 4.5 MeV (trigger efficiency < 100%)
SK I/III/IV Spectrum with MS Constr

LMA: favored by ~1.5 to 2σ

flat suppression of $^8$B

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Day/Night Effect at KamLAND $\Delta m_{12}^2$
Fit Day/Night Amplitude to SK Data

- used for SK-I: $A_{DN}(I) = -0.018 \pm 0.016\text{(stat)} \pm 0.013\text{(syst)}$
- $A_{DN}(II) = -0.036 \pm 0.035\text{(stat)}$, $A_{DN}(III) = -0.040 \pm 0.025\text{(stat)}$
- depends on $\Delta m^2$
- Combine SK-I/II/III: $-0.026 \pm 0.013\text{(stat)}$
  at KamLAND $\Delta m^2$
- consistent with expected amplitude
- consistent with zero within $2\sigma$
- systematic uncertainty under study

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Favored and Disfavoured Oscillation Parameters

- in this case, amplitude is not fit; just compared D/N effect to no D/N effect!!!
- blue area has D/N effect favored by at least one $\sigma$
- red area has D/N disfavored by at least one $\sigma$

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Conclusions

• SK-III data has already impacted solar neutrino global fits:
  – lower background
  – solar neutrino flux estimate below 5 MeV
  – three flavor analysis

• SK-IV can go lower in threshold: the goal is 4 MeV total recoil electron energy and it seems within reach

• SK solar analysis begins to see oscillation signatures