Status of solar neutrino physics at SK

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European Workshop on Water Cherenkov Precision Detectors for Neutrino and Nucleon Decay Physics

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Contents

■ Solar neutrino measurement with water Cherenkov
  - Solar neutrino
  - Water Cherenkov detectors
  - Solar neutrino interactions in water
  - Brief summary of solar neutrino measurement

■ Latest results from Super-Kamiokande
  - Solar neutrino flux measurements
  - Energy spectrum
  - Oscillation analysis

■ Summary
Solar neutrino

**Production of solar neutrino**

- Solar neutrinos are produced via nuclear fusions in the core.

\[ 4p \rightarrow \alpha + 2e^+ + 2\nu_e + 26.7\text{MeV} - E_\nu \]

- Several processes produce electron-neutrino \((\nu_e)\).
  
  \(pp, \ pep, \ ^7\text{Be}, \ ^8\text{B}, \ hep\) and \(CNO\)

- Standard solar model (SSM) predicts their fluxes.
Water Cherenkov detectors

- Kamiokande
- Super-Kamiokande
- SNO

As solar neutrino detector

**H$_2$O**

**D$_2$O**

*Phys. Rev. D 38, 448 (1998).*

*Phys. Rev. C 75, 045502 (2007).*
## Reaction channels
- 3 reactions (CC/NC/ES) are used in the water Cherenkov detector.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Reaction</th>
<th>Energy Threshold</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged current (CC) (SNO)</td>
<td>$\nu_e + d \rightarrow e^- + p + p$</td>
<td>1.4 MeV</td>
<td>Sensitive only to $\nu_e$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>pure $\nu_e$ energy spectrum</td>
</tr>
<tr>
<td>Neutral current (NC) (SNO)</td>
<td>$\nu_X + d \rightarrow \nu_X + p + n$</td>
<td>2.2 MeV</td>
<td>Equally sensitive to all flavor but only to $^8$B $\nu$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\rightarrow$ Total $^8$B neutrino flux</td>
</tr>
<tr>
<td>Elastic scattering (ES) (SK &amp; SNO)</td>
<td>$\nu_X + e^- \rightarrow \nu_X + e^-$</td>
<td>------</td>
<td>Sensitive to all flavor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Small contribution of $\nu_{\mu/\tau}$</td>
</tr>
</tbody>
</table>

## Physics from reactions above
- The total $\nu_X$ flux and the $\nu_e$ flux would be **separately determined**.
- The CC/NC ratio gives the survival probability of solar neutrino.
- This provides **independent test** of the $\nu$-oscillation hypothesis and the standard solar model (SSM).
Solar neutrino oscillation

Allowed oscillation parameters

- 4 possible oscillation solutions in 1990s.
  1. **LOW & LMA**: No energy distortion, day/night flux difference.
  2. **SMA**: Large energy distortion.
  3. **VAC**: Energy distortion, seasonal variation.

→ Energy spectrum, seasonal variation and day-night are key.

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**Allowed region of the oscillation parameters.**

**Survival probability as a function of energy**

- **LOW** & **LMA**: No energy distortion, day/night flux difference.
- **SMA**: Large energy distortion.
- **VAC**: Energy distortion, seasonal variation.

→ Energy spectrum, seasonal variation and day-night are key.
Kamiokande & SK-I

**Kamiokande**
- First real-time measurement of solar neutrino.
  → Signals really come from the Sun.
- Observed rate over the SSM: $0.46 \pm 0.13 \text{(stat.)} \pm 0.08 \text{(syst.)}$.
  → Confirmation of the solar neutrino problem.  

**Super-Kamiokande**
- Precise flux/energy spectrum measurement.
  → No distortion in the energy spectrum.

More precise

Clear solar ν signal
SK-I results

- **Era of precise measurement**

- SK data: **No energy distortion, no significant zenith dependence and small day/night flux asymmetry.**
- SK data excluded SMA, VAC and demonstrated no Just so$^2$.  
- SK data preferred LMA (higher $\Delta m_{21}^2$ region of large mixing).

![Diagram showing the flavor oscillation parameters with regions excluded and remained.](image-url)
SNO’s flux measurements with SK

- The first evidence of the solar $\nu$ oscillation was obtained by comparing SK ES with SNO CC (non-electron $\nu$ component in ES).

<table>
<thead>
<tr>
<th>SNO CC</th>
<th>$\nu_e$</th>
<th>$1.75 \pm 0.07^{+0.12}_{-0.11}\text{(stat.)} \pm 0.05\text{(thor.)} \times 10^6 \text{cm}^{-2}\text{sec}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK ES</td>
<td>$\nu_e + 0.15(\nu_\mu + \nu_\tau)$</td>
<td>$2.39 \pm 0.34^{+0.15}_{-0.14}\text{(stat.)} \times 10^6 \text{cm}^{-2}\text{sec}^{-1}$</td>
</tr>
<tr>
<td>Difference</td>
<td></td>
<td>$(0.57 \pm 0.17) \times 10^6 \text{cm}^{-2}\text{sec}^{-1}$</td>
</tr>
</tbody>
</table>

→ Clear evidence for non-zero $\nu_\mu/\nu_\tau$ flux (flavor change, 3.3$\sigma$).
→ Either of the results alone could not provided the evidence.

Neutrino oscillation

- Survival probability

- NC flux measurement is in good agreement with the prediction of the total $^8$B solar neutrino in SSM.

<table>
<thead>
<tr>
<th>Measured total $^8$B flux [$\times 10^6$ cm$^{-2}$sec$^{-1}$]</th>
<th>Prediction (BP04) [$\times 10^6$ cm$^{-2}$sec$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5.25 \pm 0.16^{+0.11}_{-0.13}$ Phys. Rev. C 88, 025501 (2013)</td>
<td>$5.79(1 \pm 0.23)$ Phys. Rev. Lett. 92, 121301 (2004)</td>
</tr>
</tbody>
</table>

- The CC/NC ratio extracts survival probability: $0.317 \pm 0.016 \pm 0.009$.

→ Octant ambiguity of $\theta_{12}$ is solved (CC/NC $< 0.5 \rightarrow \theta_{12} < 45^\circ$).

The latest results from SK
Super-Kamiokande (SK)

**Detector**
- Located at Kamioka Japan.
- **50 kton** of ultra pure water tank.
  - 20-inch PMTs, **11,129** for ID (since SK-III).
  - **22.5 kton** for analysis fiducial volume.
- Water **Cherenkov light** technique.

**History of SK**
- Long term operation since 1996 (~22 years).
- Total live time is more than 5,500 days.
- Refurbishment works toward SK-Gd have started since May 31st, 2018.

<table>
<thead>
<tr>
<th>PMT</th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV</th>
<th>SK-Gd</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996-2000</td>
<td>PMT 11,146 (40%*)</td>
<td>PMT 5,182 (19%*)</td>
<td>PMT 11,129 (40%*)</td>
<td>PMT 11,129 (40%*)</td>
<td>Nobel prize</td>
</tr>
<tr>
<td>4.5 MeV**</td>
<td>6.5 MeV**</td>
<td>4.0 MeV**</td>
<td>3.5 MeV**</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Photo coverage [%], ** Recoil electron kinetic energy [MeV].
Motivations of solar neutrino

Goal of solar neutrino measurement in SK

1. Test the transition of solar ν oscillation btw vacuum and matter.
   → Lowering threshold & reducing BG to test MSW up-turn.

2. Day-night flux asymmetry
   → Regeneration of νₑ due to the Earth’s matter effect is expected.
      (~2.5σ indication, update of this analysis is in progress).
**8B solar neutrino signals**

- Elastic scattering \((\nu_x + e^- \rightarrow \nu_x + e^-)\).
  
  1. **Timing** \(\rightarrow\) **Vertex position & real-time measurement**
  2. **Ring pattern** \(\rightarrow\) **Direction of the incoming neutrino**
  3. **# of hit PMTs** \(\rightarrow\) **Energy** (~6 p.e./MeV)

- ~20 events/day in SK-IV (SK-I~IV 5695 days: ~93k events).

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**Preliminary**

SK-IV 2860days
55,810\(\pm\)360 (stat. only)

**Background**

**Solar v signals**

**Super-Kamiokande**

- **Time (ns)**
  - < 810
  - 810 - 820
  - 820 - 830
  - 830 - 840
  - 840 - 850
  - 850 - 860
  - 860 - 870
  - 870 - 880
  - 880 - 890
  - 890 - 900
  - 900 - 910
  - 910 - 920
  - 920 - 930
  - 930 - 940
  - 940 - 950
  - 950 - 960
  - 960 - 970
  - 970 - 980
  - 980 - 990
  - 990 - 1000
  - 1000 - 1005
  - 1005 - 1010
  - 1010 - 1015
  - 1015 - 1020
  - 1020 - 1025
  - 1025 - 1030
  - 1030 - 1035
  - 1035 - 1040

**E_{total} = 9.1MeV\**

\[\cos\theta_{\text{sun}} = 0.95\]
**8B solar neutrino flux**

- **Flux measurements**
  - SK has measured the 8B solar neutrino flux for 22 years.
  - Fluxes are consistent within uncertainties among all SK phases.

<table>
<thead>
<tr>
<th>SK ES flux/SNO NC flux</th>
<th>8B solar ν flux assuming no oscillation [×10^6 cm^2 sec^-1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4432 ± 0.0084 (stat.+syst.)</td>
<td>2.33 ± 0.04 (stat.+syst.)</td>
</tr>
</tbody>
</table>

- **Correlation of the flux with the solar activity**
  - Solar activity is strongly correlated with sunspot numbers.
  - **No correlation** with the 11-years solar activity is observed.

\[ \chi^2 = 21.57/21 \]
\[ \text{Prob.} = 41.4\% \]

Sun spot number: http://www.sidc.be/silso/datafiles
Source: WDC-SILSO, Royal Observatory of Belgium, Brussels.
Day-night flux asymmetry

**Flux measurement**
- Regeneration of $\nu_e$ in night.
  → Higher flux in night.

\[
A_{DN} = \frac{\Psi_{\text{day}} - \Psi_{\text{night}}}{(\Psi_{\text{day}} + \Psi_{\text{night}})/2}
\]

- Regeneration depends on oscillation parameters.
- Update analysis is in progress.

<table>
<thead>
<tr>
<th>SK-phase</th>
<th>Amplitude fit [%]</th>
<th>Straight calc. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>-2.0 ± 1.8 ± 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>-5.5 ± 4.2 ± 3.7</td>
</tr>
<tr>
<td>SK-III</td>
<td>-4.2 ± 2.7 ± 0.7</td>
<td>-5.9 ± 3.2 ± 1.3</td>
</tr>
<tr>
<td>SK-IV</td>
<td>-3.6 ± 1.6 ± 0.6</td>
<td>-4.9 ± 1.8 ± 1.4</td>
</tr>
<tr>
<td>Combined</td>
<td>-3.3 ± 1.0 ± 0.5</td>
<td>-4.1 ± 1.2 ± 0.8</td>
</tr>
</tbody>
</table>

(3.0 $\sigma$ from zero)  (2.8 $\sigma$ from zero)

$\Delta m_{21}^2$ vs Day/Night Asymmetry

$\sin^2 \theta_{12} = 0.311$,  $\sin^2 \theta_{13} = 0.025$
Recoil electron energy spectrum

SK I Spectrum

- SK-I: 4.5 MeV
- 1496 days

SK II Spectrum

- SK-II: 6.5 MeV
- 791 days

SK III Spectrum

- SK-III: 4.0 MeV
- 548 days

SK IV Spectrum

- SK-IV: 3.5 MeV
- 2860 days

Preliminary
Combined spectrum

Energy spectrum vs. MSW predictions

- Introduce quadratic function to test the MSW prediction.
- Quadratic fit is consistent with solar $\Delta m^2_{21}$ within 1.2$\sigma$, while it disfavors KamLAND $\Delta m^2_{21}$ by 2.0$\sigma$.

\[
P_{ee}(E_\nu) = c_0 + c_1 \left( \frac{E_\nu}{\text{MeV}} - 10 \right) + c_2 \left( \frac{E_\nu}{\text{MeV}} - 10 \right)^2
\]

All SK phase are combined without regard to energy resolution or systematic uncertainty in this figure.
Comparison among solar neutrino experiments

- Neutrino energy spectrum is de-convoluted from the recoil electron energy spectrum → Extract survival probability ($P_{ee}$).
- This analysis gives the strongest constraint on $P_{ee}$ shape.

Solar neutrino experiments:
- Borexino (pp)
- Borexino ($^7$Be)
- Borexino (pep)
- Borexino ($^8$B)
- Homestake+SK
- SNO (CNO)
- SK+SNO ($^8$B)

Allowed survival probability

$\Delta m_{21}^2$

$\sin^2 \theta_{12}$

Survival probability ($P_{ee}$)

$\nu$ Energy in MeV
Global oscillation analysis input

Super-Kamiokande

<table>
<thead>
<tr>
<th>Phase</th>
<th>Livetime [days]</th>
<th>Recoil electron spectrum</th>
<th>Day/Night</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>1496</td>
<td>4.5-19.5 MeV</td>
<td>Above 4.5 MeV</td>
</tr>
<tr>
<td>SK-II</td>
<td>791</td>
<td>6.5-19.5 MeV</td>
<td>Above 7.0 MeV</td>
</tr>
<tr>
<td>SK-III</td>
<td>548</td>
<td>4.0-19.5 MeV</td>
<td>Above 4.5 MeV</td>
</tr>
</tbody>
</table>

SNO

Radiochemical (Ga, Cl)

Borexino
- $^7$Be flux: arXiv:1707.09279. (Phase-II result)

KamLAND

$^8$B spectrum
Oscillation parameters are determined using the latest solar $\nu$ data. 2σ tension in $\Delta m_{21}^2$ between the solar global and KamLAND. Further precise measurement is required in future.
Summary

- Last 20 years, water Cherenkov detectors (Kamiokande/SK/SNO) contribute to the solar neutrino measurement.
  → Determined the total \( ^8 \)B solar neutrino flux.
  → Found flavor conversion of solar neutrino.

- Solar neutrino results from SK
  ■ Solar neutrino flux measurements:
    → Elastic scattering rate: \( 2.33 \pm 0.04 \text{ (stat.+syst.)} \times 10^6 \text{ cm}^{-2}\text{sec}^{-1}. \)
    → \(^8\)B ν flux has no significant correlation with the solar activity.

  ■ Recoil electron energy spectrum:
    → Achieved at the lowest energy threshold: \( 3.5 \text{ MeV}. \)
    → SK+SNO spectrum shape gives strong constraint on \( P_{ee} \) shape.

  ■ Oscillation parameters:
    → \( \sin^2 \theta_{12} = 0.310 \pm 0.012, \Delta m_{21}^2 = 7.49^{+0.19}_{-0.17} \times 10^{-5} \text{ eV}^2. \)
    → 2σ tension in \( \Delta m_{21}^2 \) between the solar global and KamLAND.