Highlights from Super-Kamiokande

S. Moriyama
ICRR, University of Tokyo
2014/8/2
ICNFP 2014 @ Crete, Greece
Super-Kamiokande detector

50,000ton water Cherenkov detector (22.5 kton fiducial mass)

11,129 20” PMTs for inner detector

1885 8” PMTs for outer detector

1000m underground 
(2700 m water equivalent)

<table>
<thead>
<tr>
<th>Year</th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>96</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>97</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>98</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>99</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>06</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>07</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Original configuration

half # of ID PMTs

Full recovery of ID PMTs

Electronics/DAQ upgraded
Physics at Super-K

- Neutrino Physics
  - Massive neutrinos beyond the SM
  - $\Delta m^{2}_{ij}$ & $\theta_{ij}$ measured/acc. improved
  - $\text{MH, } \theta_{23} \text{ oct. (}\gtrsim \pi/2\text{), and } \mathcal{CP} \text{ (atm. } \nu\text{)}$
  - Matter effects (solar $\nu$)
  - $\tau$ appearance
  - sterile, exotics...

- Search for proton decay
  - General prediction of GUT

- Astrophysical objects
  - Supernova physics
  - Dark matter annihilation

\[ P(\nu_a \rightarrow \nu_b) \neq P(\bar{\nu}_a \rightarrow \bar{\nu}_b) \]
\[ \mathcal{CP} \text{ phase } \delta \neq 0, \pi \]
Atmospheric neutrinos: 
π, K decay \rightarrow\text{nuclear interactions}

Wide range of L and E enables us to study neutrino oscillations.
Mass hierarchy, $\theta_{23} \geq \pi/2$, and CP

- MH: utilize resonance effect in $\nu_\mu \leftrightarrow \nu_e$ (driven by $\theta_{13}$)
  - presence of $e^-$ (no $e^+$) in the Earth: $V = \pm \sqrt{2}G_F n_e \pm(\cdot)$ for $\nu_e(\bar{\nu}_e)$

$$i \partial_x \Psi(x) = \frac{\Delta m^2}{4E} \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ -\sin 2\theta & \cos 2\theta \end{pmatrix} \Psi(x) + \begin{pmatrix} \frac{V}{2} & 0 \\ 0 & -\frac{V}{2} \end{pmatrix} \Psi(x) = \frac{\Delta M^2}{4E} \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ -\sin 2\theta & \cos 2\theta \end{pmatrix} \Psi(x)$$

- $\nu_e$ ($\bar{\nu}_e$) undergoes resonance only for normal (inverted) hierarchy @2-10GeV

- $\theta_{23}$ octant: Strength of the resonance

$$P(\nu_\mu \leftrightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left( \frac{1.27 \Delta m^2_{12} L}{E} \right).$$

- CP violation: interference term btw $\Delta m^2_{12}$ & $\Delta m^2_{23}$

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2 \cdot (r \cdot \cos^2 \theta_{23} - 1) - r \cdot \sin \tilde{\theta}_{13} \cdot \cos^2 \tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos \delta \cdot R_2 - \sin \delta \cdot I_2) + 2 \sin^2 \tilde{\theta}_{13} \cdot (r \cdot \sin^2 \theta_{23} - 1)$$
The size of the resonance effect is sensitive to $\sin^2\theta_{23}$ and MH. Broad range of data useful for MH. 1d figures are the ratio to 2 flavor oscillation.
Signatures in the three flavor oscillation

downward ~1000km

\[ P(\nu_\mu \rightarrow \nu_\mu) \]

upward ~10000km

\[ P(\nu_\mu \rightarrow \nu_e) \]

assuming normal MH

effect of CPV

The low energy electron events (between \( \Delta m^2_{12} \) & \( \Delta m^2_{23} \)) are affected by CP violation phase.

1d figures are the ratio to 2 flavor oscillation.
Data set and recent improvements

- 1775 days of SK-IV, in total, 4581.4 days, ~40,000 ev
- $\nu_e/\bar{\nu}_e$ enriched samples to enhance MH sensitivity.
  - $\nu_e$ CC produces more $\pi^+ \rightarrow$ more $\mu$ decays, etc.

<table>
<thead>
<tr>
<th></th>
<th>$\nu_e$ CC</th>
<th>anti-$\nu_e$ CC</th>
<th>others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-GeV 1 ring $\nu_e$ like</td>
<td>60%</td>
<td>10%</td>
<td>30%</td>
<td>100%</td>
</tr>
<tr>
<td>Multi-GeV 1 ring anti-$\nu_e$ like</td>
<td>57%</td>
<td>34%</td>
<td>9%</td>
<td>100%</td>
</tr>
</tbody>
</table>

- “Multi-ring others” which fails both $\mu/e$ selection added.
- Treatment of systematic errors improved.
**Fixed $\theta_{13}$, results with SK only**

- Normal hierarchy slightly favored at $\chi^2_{\text{IH}} - \chi^2_{\text{NH}} = 0.9$
- $\theta_{23} > \pi/2$ slightly ($\sim 1\sigma$ level) preferred.
- Driven by excess of up-going e-like events consistent with the effects of $\theta_{13}$.
- $\delta_{CP} \sim 3\pi/2$ is slightly preferred by excess in Multi-Ring e-like $\overline{\nu}_e$ and deficit in Multi-GeV 1R $\mu$-like. Consistent with sensitivity.
Including the external T2K result

• T2K’s published constraints on $\Delta m^2_{23}/\theta_{23}$ could enhance mass hierarchy determination power.
  – Matter effect for T2K is small since baseline $\sim$295km.

• Preference of NH is strengthened: $\chi^2_{IH} - \chi^2_{NH} = 1.2$

• T2K favors $\theta_{23} = \pi/2 + \epsilon$ because of max. red. of $\nu_\mu$ obs.

• Preference of $\delta_{CP} \sim 3\pi/2$ strengthened, but CP conservation ($\delta_{CP} = 0$ and $\pi$) is still allowed at 90% C.L.
Solar $\nu$ observation by $\nu$+e scattering:
Motivation of the measurement

See the clear evidence that the neutrino flavor conversion is indeed due to neutrino oscillations.

**Spectrum distortion**

Vacuum oscillation dominant
Matter oscillation dominant
Solar best fit
Super-K

Super-K can search for the spectrum “upturn” expected by neutrino oscillation MSW effect

**Day-Night flux asymmetry**

Expected

Regenerate $\nu_e$ by earth matter effect

Solar $\nu$ observation by $\nu$+e scattering:
Solar best fit

MoWvaWon	
  of	
  the	
  measurement

See the clear evidence that the neutrino flavor conversion is indeed due to neutrino oscillations.
D/N effect as a direct confirmation of matter effect on neutrino oscillations

PRL 112, 091805 (2014) uses 1306d data: this results uses 1669d data.
D/N effect as a direct confirmation of matter effect on neutrino oscillations

PRL 112, 091805 (2014) uses 1306d data; this results uses 1669d data.
Day/night differences

Expected time variation as a func. of $\cos \theta_z$

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Amplitude fit</th>
<th>Straight calc. $(D-N)/((D+N)/2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta m^2_{21}$</td>
<td>$\Delta m^2_{21}$ = 7.50x10^{-5} eV²</td>
</tr>
<tr>
<td>SK-I</td>
<td>-2.0±1.8±1.0%</td>
<td>-1.9±1.7±1.0%</td>
</tr>
<tr>
<td>SK-II</td>
<td>-4.4±3.8±1.0%</td>
<td>-4.4±3.6±1.0%</td>
</tr>
<tr>
<td>SK-III</td>
<td>-4.2±2.7±0.7%</td>
<td>-3.8±2.6±0.7%</td>
</tr>
<tr>
<td>SK-IV</td>
<td>-3.6±1.6±0.6%</td>
<td>-3.3±1.5±0.6%</td>
</tr>
<tr>
<td>combined</td>
<td>-3.3±1.0±0.5%</td>
<td>-3.1±1.0±0.5%</td>
</tr>
<tr>
<td>non-zero significance</td>
<td>3.0σ</td>
<td>2.8σ</td>
</tr>
</tbody>
</table>

Expected $\Delta m^2_{21}$ = 4.84x10^{-5} eV²
$\sin^2 \theta_{12}$ = 0.311
$\Delta m^2_{21}$ dependence

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

$\sin^2 \theta_{12} = 0.311$, $\sin^2 \theta_{13} = 0.025$

The first indication at $2.8-3.0\sigma$ of terrestrial matter effect.
Evidence for $\tau$ neutrino appearance

Published in PRL 110, 181802 (2013)

$\nu_\mu \rightarrow \nu_\tau$ channel has been confirmed by $\tau$ identification

$N_{\tau}^{\text{DATA}} / N_{\tau}^{\text{exp}} = 1.42 \pm 0.35 \text{(stat)} + 0.14 - 0.12 \text{(syst)}$

3.8$\sigma$ significance for null $\tau$

$\nu_\mu \rightarrow \nu_\tau$ channel has been confirmed by $\tau$ identification

Neural network to enhance events consistent with hadronic decays of $\tau$

Zenith Distribution of $\tau$-like events
Summary

• Using atmospheric neutrino data and solar neutrino data we are searching for the matter effect in order to find the mass hierarchy, octant of $\theta_{23}$, CP violation, and a direct evidence of $\nu$ oscillation of solar $\nu$.

• For the mass hierarchy, using 4538 days data there is a $\sim 1\sigma$ preference for the NH and the second octant.

• The first indication at $2.8-3.0\sigma$ of terrestrial matter effect in 4504 days data of $^8$B solar $\nu$.

• $\nu_\mu \to \nu_\tau$ channel as a solution of “atmospheric neutrino anomaly” has been confirmed by the evidence of $\tau$ appearance at $3.8\sigma$. 