Super-Kamiokande

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Super-K detector

- Ring-imaging water Cherenkov detector
  - Fiducial volume 22 kton (Total volume 50 kton)
  - Photon yield ~10p.e./MeV
  - Atmospheric $\nu$ ~10 events/day
  - Solar $\nu$ ~15 events/day
  - Accelerator $\nu$ a few events/day (depends on the accelerator power)
  - always ready for Supernova $\nu$ and nucleon decays
- Observables
  - Direction of recoiled charged particles (leptons, pions, $\gamma$) by neutrinos
  - Particle spices (neutrino flavor)
  - Energy
  - Time

11,129 x 20inch PMTs (inner detector, ID)
3-flavor oscillation scheme

\[ t(\nu_e, \nu_\mu, \nu_\tau) = U_{\text{MNS}}^{\text{MNS}} t(\nu_1, \nu_2, \nu_3) \]

\[ U_{\text{MNS}}: \text{Maki-Nakagawa-Sakata Matrix} \]

Parameterized by 4 (mixing matrix) and 2 (difference of squared masses)

- \( \theta_{23} \sim 45 \pm 5^\circ \)
- \( |\Delta m_{32}^2| = 2.4 \times 10^{-3} \text{eV}^2 \)
- \( \theta_{12} \sim 34 \pm 3^\circ \)
- \( \Delta m_{21}^2 = +7.6 \times 10^{-5} \text{eV}^2 \)
- \( \theta_{13} \sim 9^\circ \)
- \( \delta = \text{unknown} \)

**Atmospheric \( \nu \), Accelerator \( \nu \)**

**Solar \( \nu \), Reactor \( \nu \)**

**Accelerator \( \nu \), Reactor \( \nu \), Atm & Solar \( \nu \)**

Mass hierarchy (\( \Delta m_{32}^2 = m_3^2 - m_2^2 > 0 \) or \( \Delta m_{32}^2 < 0 \)) is also unknown:

- Accelerator \( \nu \), **Atmospheric \( \nu \)**, Reactor \( \nu \)

Solar&Atmospheric \( \nu \)'s played pioneering roles in the past and would also play important roles in future.
Stable operation and det. response

- Very stable operation
  - <1% Downtime
- Energy scale uniformity and stability w/ RMS <0.4% by correcting
  - time-dependent light attenuation length in water
  - time-dependent, production-period-dependent PMT gain

![Graph showing stable operation and detector response](image)

- PMT gain w.r.t. April 2009
- SK-IV ~8 years
- ±1% PMT gain w.r.t. April 2009
- ±1% Decay-electron [MeV/c]
Reviewed past scientific achievements but...
Many problems remains
  - unknown parameters ($\delta$, mass hierarchy, $\theta_{23}$ octant), Solar Day/Night, spectrum, Supernova $\nu$, proton decays, WIMP...
Discussed future prospects:
  - Gadolinium loading and Hyper-Kamiokande
Contents

• Atmospheric neutrinos
• Solar neutrinos
• SK-Gd
• Proton decays
Studies of atmospheric ν

- Dominant effect is νμ disappearance (discovered in 1998)
- Oscillatory signature (evidence in 2004)
- ντ appearance (established in 2013)
- Full three flavor analysis
  - Studies on νe and νμ flux change to extract information on mass hierarchy, δCP, θ23 octant
- Test of various non-standard scenarios
Evidence for $\tau$ neutrino appearance

- Event-by-event ID is difficult
- Define neural network to enhance hadronic decays of $\tau$

**Update from PRL 110, 181802 (2013)**

- 2D unbinned fit
- $N_{\tau}^{\text{DATA}}/N_{\tau}^{\text{exp}} = 1.47 \pm 0.32 (\text{stat+syst.})$
- 4.6 $\sigma$ significance for zero $\tau$

**Atm. $\nu$ anomaly has been concluded by $\nu_\mu \rightarrow \nu_\tau$ observation**

**Ongoing study to extract $\nu_\tau$ CC crosssection.**
Through the matter effect in the Earth, we study on

- **Mass hierarchy**: resonance in multi-GeV $\nu_e$ or $\bar{\nu}_e$
- **CP δ**: interference btw two $\Delta m^2$ driven oscill.
- **$\theta_{23}$ octant**: magnitude of the resonance

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**“Fractional change of upward $\nu_e$ flux ($\cos(\Theta_{\text{zenith}}) = -0.8$)”**

- (a) $\cos \theta_\nu = 0.8$, NH, $\sin^2 \theta_{23} = 0.4$, $\sin^2 \theta_{13} = 0.025$, $\delta = 40^\circ$
  - solar term
  - interference term
  - $\theta_{13}$ resonance term
  - total

- (b) $\cos \theta_\nu = 0.8$, NH, $\sin^2 \theta_{23} = 0.6$, $\sin^2 \theta_{13} = 0.025$, $\delta = 40^\circ$
  - $\sin^2 \theta_{23} = 0.4$ or 0.6

- (c) $\cos \theta_\nu = 0.8$, NH, $\sin^2 \theta_{23} = 0.6$, $\sin^2 \theta_{13} = 0.025$, $\delta = 220^\circ$
  - CP = 40° or 220°

- (d) $\cos \theta_\nu = 0.8$, IH, $\sin^2 \theta_{23} = 0.6$, $\sin^2 \theta_{13} = 0.025$, $\delta = 40^\circ$

**Hierarchy is NH or IH**

**Resonance in $\bar{\nu}_e$ (not shown) in the case of IH.**

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**EARTH**

- Crust
- Mantle
- Core
**ν_e-like and anti-ν_e-like sample**

\[ \nu_e + N \rightarrow e^- + X \]
\[ \bar{\nu}_e + N \rightarrow e^+ + X \]

- **ν_e CC** produce more positive \( \pi^+ \) than \( \nu_e \)-bar
- because of negative lepton (e^-)
- more muon decays
- More energy transfer to hadronic system
- more pions and muon decays
- lower charged lepton energy

Define likelihood to make enhanced samples

- Multi-GeV (1-ring) \( \nu_e \)
- Multi-GeV (1-ring) \( \bar{\nu}_e \)
- Multi-GeV Multi-ring \( \nu_e \)-like
- Multi-GeV Multi-ring \( \bar{\nu}_e \)-like

<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><strong>IR</strong> ( \nu_e )-like</td>
<td>62%</td>
<td>9%</td>
<td>29%</td>
<td>100%</td>
</tr>
<tr>
<td><strong>IR</strong> ( \bar{\nu}_e )-like</td>
<td>55%</td>
<td>37%</td>
<td>8%</td>
<td>100%</td>
</tr>
<tr>
<td><strong>MR</strong> ( \nu_e )-like</td>
<td>56%</td>
<td>10%</td>
<td>34%</td>
<td>100%</td>
</tr>
<tr>
<td><strong>MR</strong> ( \bar{\nu}_e )-like</td>
<td>53%</td>
<td>27%</td>
<td>20%</td>
<td>100%</td>
</tr>
</tbody>
</table>
Oscillation fit to SK Atmν data

1. $\sin^2\theta_{13} = 0.0219$ (PDG14), additional scale factor $\alpha$ for Earth’s matter effect
2. $\sin^2\theta_{13} = 0.0219$ (PDG14)
3. MH sensitivity enhanced w/ T2K constraint

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2_{21}$</td>
<td>$7.53\pm0.18 \times 10^{-5}\text{eV}^2$ (fix)</td>
</tr>
<tr>
<td>$\sin^2\theta_{12}$</td>
<td>$0.304\pm0.014$ (fix)</td>
</tr>
<tr>
<td>$\Delta m^2_{32}$</td>
<td>free</td>
</tr>
<tr>
<td>$\sin^2\theta_{23}$</td>
<td>free</td>
</tr>
<tr>
<td>$\sin^2\theta_{13}$</td>
<td>$0.0219\pm0.0012$ (fix)</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td>free</td>
</tr>
<tr>
<td>Mass Hierarchy</td>
<td>free</td>
</tr>
</tbody>
</table>
Matter effect fit

\[ H_{\text{matter}} = \begin{pmatrix} \frac{m_1^2}{2E} & 0 & 0 \\ 0 & \frac{m_2^2}{2E} & 0 \\ 0 & 0 & \frac{m_3^2}{2E} \end{pmatrix} + U^\dagger \begin{pmatrix} \alpha & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} U \]

\( \alpha: \) scale factor
\( a = \sqrt{2} \ G_f N_e \)

- Best fit \( \alpha = 1 \) for NH, consistent w/ standard matter effect
- \( \Delta \chi^2 = 5.2 \) for \( \alpha = 0 \), Data disfavors zero matter-effect by >2\( \sigma \)
electron’s Up/Down ratio

Up(cos\(\Theta\)<-0.4) to Down(cos\(\Theta\)>0.4) event ratio for multi-GeV electrons

Some data points favors matter-effect

Indication of excess at \(\sim 5\)GeV where resonance is expected to occur.
Mass hierarchy: $\Delta \chi^2 = \chi^2_{\text{NH}} - \chi^2_{\text{IH}} = -4.3$ (-3.1 expected)

Under IH hypothesis, the probability to obtain -4.3 or less is 3.1\% ($\sin^2 \theta_{23} = 0.6$) and 0.7\% ($\sin^2 \theta_{23} = 0.4$).

Under NH hypothesis, it is as large as 45\% ($\sin^2 \theta_{23} = 0.6$)
Atmν data fit w/ T2K

Publicly available T2K data is used as an external constraints
T2K’s constraints on $\theta_{23}$ and $\Delta m^2_{32}$ help sensitivity to mass hierarchy

### Normal Hierarchy

**Fit (585 dof)**

|          | $\chi^2$ | $\sin^2 \theta_{13}$ | $\delta_{\text{CP}}$ | $\sin^2 \theta_{23}$ | $|\Delta m^2_{32}| \text{ eV}^2$ |
|----------|----------|----------------------|----------------------|----------------------|-------------------------------|
| SK+T2K (IH) | 644.82   | 0.0219 (fix)         | 4.538                | 0.55                 | 2.5x10^{-3}                  |
| SK+T2K (NH) | 639.61   | 0.0219 (fix)         | 4.887                | 0.55                 | 2.4x10^{-3}                  |

• SK+T2K: $\Delta \chi^2 = \chi^2_{\text{NH}} - \chi^2_{\text{IH}} = -5.2$ (-3.8 exp’d for SK best point, -3.1 for combined best)

• Under IH hypothesis, the probability to obtain -5.2 or less is 2.4% ($\sin^2 \theta_{23}=0.6$) and 0.1%($\sin^2 \theta_{23}=0.4$).

• Under NH hypothesis, it is 43% ($\sin^2 \theta_{23}=0.6$)

Paper in preparation
Solar Neutrinos

- Remaining issues: precision measurements of day/night and spectrum upturn
  - They will be compelling evidence of solar $\nu$ oscillations
  - Precision measurement of $\nu_e$’s $\theta_{12}$ and $\Delta m^2_{21}$ necessary to address the 2$\sigma$ tension between Solar and KamLAND

- Recent Activities
  - Reduce Radon BG in water
  - Effort to lowering trigger threshold
    - $\text{eff. @}E_{\text{kin}} = 3.5\text{-}4.0\text{MeV}$ 84%→99%

100% trigger efficiency above 2.5MeV(kin.)
Flux measurement updates

All SK I-IV, 5200 days

- 84k signal for 5200 days
- Data/MC = 0.4486 ± 0.0062 (stat+syst)
- $\varphi = 2.355 ± 0.033$ (stat+syst) [$10^6$ cm$^{-2}$s$^{-1}$]
- $\chi^2$ for flat = 15.52/19 d.o.f.
- p-value = 68.9%

Data is consistent with a constant flux emission by Sun
Spectrum

All SK phase are combined without regard to energy resolution or systematics in this figure

<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(total # of bins of SK-IV is 83, 80 dof)</td>
<td></td>
</tr>
<tr>
<td>Solar+KamLAND</td>
<td>76.60</td>
</tr>
<tr>
<td>Solar</td>
<td>73.86</td>
</tr>
<tr>
<td>quadratic fit</td>
<td>72.33</td>
</tr>
</tbody>
</table>

Disfavor $\sim 2\sigma$
Day/Night asymmetry

Assuming the expected time variation as a function of $\cos \theta_z$ like below, amplitude of $A_{DN}$ was fitted.

For solar global parameter:

\[
\Delta m^2_{21} = 4.84 \times 10^{-5} \text{ eV}^2 \\
\sin^2 \theta_{12} = 0.311
\]

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

<table>
<thead>
<tr>
<th>$A_{DN}$</th>
<th>$A_{fit}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>$-2.0 \pm 1.8 \pm 1.0%$</td>
</tr>
<tr>
<td>SK-II</td>
<td>$-4.4 \pm 3.8 \pm 1.0%$</td>
</tr>
<tr>
<td>SK-III</td>
<td>$-4.2 \pm 2.7 \pm 0.7%$</td>
</tr>
<tr>
<td>SK-IV</td>
<td>$-3.6 \pm 1.6 \pm 0.6%$</td>
</tr>
<tr>
<td>combined</td>
<td>$-3.3 \pm 1.0 \pm 0.5%$</td>
</tr>
<tr>
<td>non-zero significance</td>
<td>3.0 $\sigma$</td>
</tr>
</tbody>
</table>

(Preliminary)
SK spectrum and D/N favor lower $\Delta m^2_{21}$ that causes $\sim 2\sigma$ tension w/ KamLAND. More data is needed to conclude.
SK-Gd

- Discovery of relic SN neutrinos is expected by $O(1)$ sensitivity improvement
- 0.1% Gd loading to tag $\bar{\nu}_e+p\rightarrow e+n$, Gd+n$\rightarrow$Gd+γs
- R&D in test tank and water system construction going on
- Start SK-Gd in a few yrs

Model
<table>
<thead>
<tr>
<th>电视 Model</th>
<th>10-16MeV</th>
<th>16-28MeV</th>
<th>Total (10-28MeV)</th>
<th>Significance 2 energy bin</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 MeV</td>
<td>11.3</td>
<td>19.9</td>
<td>31.2</td>
<td>5.3σ</td>
</tr>
<tr>
<td>6 MeV</td>
<td>11.3</td>
<td>13.5</td>
<td>24.8</td>
<td>4.3σ</td>
</tr>
<tr>
<td>4 MeV</td>
<td>7.7</td>
<td>4.8</td>
<td>12.5</td>
<td>2.5σ</td>
</tr>
<tr>
<td>1987a</td>
<td>5.1</td>
<td>6.8</td>
<td>11.9</td>
<td>2.1σ</td>
</tr>
<tr>
<td>BG</td>
<td>10</td>
<td>24</td>
<td>34</td>
<td>--</td>
</tr>
</tbody>
</table>

PDecay-BG reduction by neutrons

- We expect that neutrino events are often accompanied with neutrons (e.g. $\bar{\nu}_e + p \rightarrow e^+ + \pi^0 + n$), recoiled protons kick neutrons in water etc.
- Neutron emission probability in proton decay is expected to be small.

Since SK-IV we have started recording faint signature of neutrons; $n+p \rightarrow d+\gamma (2.2\text{MeV}, \tau \sim 200 \mu\text{sec})$ by new high speed pipelined electronics. BG reduction by $\sim 2$

**SK-IV 1297 days atmν Data**

- Tagged $\gamma$'s Timing ($\mu$sec)
- Black: Tagged $\gamma$ average $\sim 0.9$
- Red: True neutrons average $\sim 4$

**BG Monte Carlo**

- $p \rightarrow e^+ \pi^0$
Potential BG reduction by tighter cut

- $P_{tot} < 250$ MeV/c (SK cut)
  - $BG = 2.2$ ev/Mtonyrs, eff.$ = 44\%$
  - **BG reduction by $\sim 15$**
- $P_{tot} < 100$ MeV/c (tighter cut)
  - $BG = 0.15$ ev/Mtonyrs, eff.$ = 17.4\%$

main target is **free proton decays**

$16O \rightarrow 15N e^+\pi^0$

$P_{tot} < 250$ MeV/c (SK cut)
- $BG = 2.2$ ev/Mtonyrs, eff.$ = 44\%$
- $P_{tot} < 100$ MeV/c (tighter cut)
- $BG = 0.15$ ev/Mtonyrs, eff.$ = 17.4\%$

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Shiozawa, talk@NNN00-Fermilab
Proton decays into lepton+meson

- $p \rightarrow e^+\pi^0$:
  - 0 candidates (40% eff. & 0.61BG)
  - $\tau_p/\text{Br} > 1.6 \times 10^{34}$ yrs

- $p \rightarrow \mu^+\pi^0$:
  - 2 candidates (40% eff. & 0.87BG),
    one is rejected after energy re-calibration
  - $\tau_p/\text{Br} > 7.7 \times 10^{33}$ yrs
Summary

- **Atmospheric neutrino**
  - τ appearance (4.6σ) concluded the atmν anomaly
  - Data consistent w/ Earth’s matter effect (>2σ)
  - Mass hierarchy: preference to Normal hierarchy
    - SK+T2K: Δχ² = χ²_{NH} - χ²_{IH} = -5.2
      Under IH hypothesis, the probability to obtain -5.2 or less is 2.4% (sin²θ_{23}=0.6) and 0.1%(sin²θ_{23}=0.4).

- **Solar neutrinos**
  - SK spectrum and D/N favor lower Δm²_{21} that causes ~2σ tension w/ KamLAND.

- **SK-Gd**
  - Discovery is within the reach. Start in a few years.

- **Proton decays**
  - Continuous efforts to reduce BG and keep BG-free regions.