Super Kamiokande
atmospheric & solar neutrinos

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for Super-Kamiokande collaboration
Recent results of neutrino oscillation analysis

• Atmospheric Neutrinos

\[ \nu_\mu \leftrightarrow \nu_\tau \] 2 flavor oscillations from

I. Zenith angle analysis

II. L/E analysis

• Solar Neutrinos

Results from SK un-binned maximum likelihood method

Combined result with all solar + KamLAND experiments
Super-Kamiokande-I detector

Water Cherenkov detector

- 1000 m underground
  (2700 m of water equivalent)
- 50,000 ton of pure water
- 2 concentric cylindrical region
- 11,146 20 inch PMTs
  (40% photocathode coverage)
- 1,885 anti-counter PMTs
Atmospheric neutrinos

$\pi^\pm, K^\pm, \nu_\mu, \nu_e, \mu^\pm, p, \text{He}$...

Downward
$L=10\sim 100 \text{ km}$

Upward
$L=\text{up to 13000 km}$

Zenith angle

Up/Down Symmetry

$\theta$
Atmospheric neutrinos in SK

Event classification

- Fully Contained $(E_\nu \sim 1\text{GeV})$
- Partially Contained $(E_\nu \sim 10\text{GeV})$
- Stopping $\mu$ $(E_\nu \sim 10\text{GeV})$
- Through-going $\mu$ $(E_\nu \sim 100\text{GeV})$

- e-like
- $\mu$-like
\[ \nu_\mu \leftrightarrow \nu_\tau \]

2-flavor oscillations

Null oscillation

Best fit: \( \sin^2 2\theta = 1.0, \Delta m^2 = 2.0 \times 10^{-3} \text{ eV}^2 \)

Zenith angle distributions

- Sub-GeV e-like
- Sub-GeV \( \mu \)-like
- Multi-GeV e-like
- Multi-GeV \( \mu \)-like

Upward stopping \( \mu \)

Upward through \( \mu \)

multi-ring \( \mu \)-like

+ PC
FC+PC+up-$\mu$ zenith angle analysis

$\chi^2_{\text{min}} = 170.8/170$ d.o.f
at $\Delta m^2 = 2.0 \times 10^{-3}, \sin^2 2\theta = 1.00$

$1.3 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3}$ eV$^2$
$0.90 < \sin^2 2\theta$ at 90% C.L.

Fof SK-I final result ...

Improvements of systematic errors
L/E analysis

Neutrino oscillation:
\[ P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2 \left( 1.27 \frac{\Delta m^2 L}{E} \right) \]

Neutrino decay:
\[ P_{\mu\mu} = (\cos^2 \theta + \sin^2 \theta \exp(-\frac{m}{2\tau} \frac{L}{E}))^2 \]

Neutrino decoherence:
\[ P_{\mu\mu} = 1 - \frac{1}{2} \sin^2 2\theta \times (1 - \exp(-\gamma_0 \frac{L}{E})) \]

Use events with high resolution in L/E

The first dip can be observed

\[ \rightarrow \text{Direct evidence for oscillations} \]
\[ \rightarrow \text{Strong constraint to oscillation parameters, especially } \Delta m^2 \text{ value} \]
L/E resolution cut

Select events with high resolution in L/E

Bad L/E resolution for

- horizontally going events → due to large dL/dcosθ
- low energy events → due to large scattering angle

Selected events for FC single-ring

$\Delta(L/E) = 70\%$
Event samples in L/E analysis

**FC single-ring, multi-ring $\mu$-like**

Expand fiducial volume

More statistics for high energy muons

**PC**

Classify PC events using OD charge

- I. OD stopping
- II. OD through going

Different L/E resolution

- OD stopping
- OD through-going

Preliminary

- OD stopping MC
- OD through-going MC

1.5m from top & bottom

22.5kt → 26.4kt

1m from barrel
## Event summary of L/E analysis

<table>
<thead>
<tr>
<th>Category</th>
<th>Data</th>
<th>MC</th>
<th>CC $\nu_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>single-ring $\mu$-like</td>
<td>1619</td>
<td>2105.6</td>
<td>(98.3%)</td>
</tr>
<tr>
<td>multi-ring $\mu$-like</td>
<td>502</td>
<td>813.0</td>
<td>(94.2%)</td>
</tr>
<tr>
<td>PC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>stopping</td>
<td>114</td>
<td>137.0</td>
<td>(95.4%)</td>
</tr>
<tr>
<td>through-going</td>
<td>491</td>
<td>670.1</td>
<td>(99.2%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2726</td>
<td>3725.7</td>
<td></td>
</tr>
</tbody>
</table>
L/E in atmospheric neutrino data

Null oscillation
MC

Preliminary

Mostly downward

Best-fit expectation

$\Delta m^2 = 2.4 \times 10^{-3}$, $\sin^2 \theta = 1.00$

$\chi^2_{\text{min}} = 37.8 / 40$ d.o.f

First dip is observed as expected from neutrino oscillation

1489.2 days FC+PC

Best fit expectation w/ systematic errors

Mostly upward
Constraint to neutrino oscillation parameters

\[ \Delta m^2 = 2.4 \times 10^{-3}, \sin^2 2\theta = 1.00 \]
\[ \chi^2_{\text{min}} = 37.8/40 \text{ d.o.f} \]
\[ (\sin^2 2\theta = 1.02, \chi^2_{\text{min}} = 37.7/40 \text{ d.o.f}) \]

1.9x10^{-3} < \Delta m^2 < 3.0x10^{-3} \text{ eV}^2
0.90 < \sin^2 2\theta \quad \text{at 90\% C.L.}

Consistent with standard zenith angle analysis

L/E analysis
Zenith angle analysis

90\% allowed regions
Tests for neutrino decay & decoherence

First evidence that neutrino transition probability obeys sinusoidal function as predicted in neutrino oscillation.
Solar neutrinos in SK

SK-I 1496 day 5.0-20 MeV 22.5 kt

$^8$B flux:
2.35 $\pm$ 0.02 $\pm$ 0.08 $[x \ 10^6 /\text{cm}^2/\text{sec}]$

0.465 $\pm$ 0.005 $^{+0.016}_{-0.015} \times$ SSM

solar $\nu$ events
Constraints from SK solar $\nu$

Un-binned maximum likelihood method (with time variation)

$\Delta m^2$ in $eV^2$

Zenith Seasonal Spectrum $\nu_e \rightarrow \nu_{\mu/\tau}$ (95% C.L.)

Spectrum (Data/SSM)

Day

Night

Mantle

Core
LMA is the only solution with 99% C.L. With all solar neutrino experiments

Combined oscillation fits with other experiments

Preliminary
Conclusions (1)

• Atmospheric neutrino oscillation studies:

  Zenith angle analysis
  – $1.3 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3} \text{ eV}^2$, $0.90 < \sin^2 2\theta$ at 90% C.L.
  – SK-I final result will be published with improved systematic errors

  L/E analysis
  – First dip was observed as expected from neutrino oscillation
    → cannot be explained by alternative hypotheses
      (3.4 $\sigma$ to $\nu$ decay, 3.8 $\sigma$ to $\nu$ decoherence)
  – $1.9 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3} \text{ eV}^2$, $0.90 < \sin^2 2\theta$ at 90% C.L.
    → consistent with zenith angle analysis

  First evidence that neutrino transition probability obeys sinusoidal function as predicted in neutrino oscillation
Conclusions (2)

• Solar neutrino oscillation studies:
  – New analysis method (un-binned maximum likelihood method) has been installed.
  – No day/night asymmetry nor spectrum distortion is observed in SK.
  – Only LMA-I solutions remain at 99% C.L. combined with all the solar neutrino data.