Direct oscillatory evidence from L/E analysis in Super-Kamiokande

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for Super-Kamiokande collaboration
Zenith angle distributions

Other models can explain zenith angle dependent muon deficit.

How can we distinguish oscillation from other hypotheses?
Neutrino oscillation:
\[ P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E}) \]

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

The first dip can be observed:
→ Direct evidence for oscillations
→ Strong constraint to oscillation parameters, especially \( \Delta m^2 \) value
Neutrino energy is reconstructed from observed energy using relations based on MC simulation.

Neutrino flight length is estimated from zenith angle of particle direction.

Zenith angle \( \cos(\Theta) \) → Flight length

Neutrino energy

Neutrino flight length
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

Δ(L/E)=70%
FC single-ring, multi-ring $\mu$-like

Expand fiducial volume

PC

Classify PC events using OD charge

I. OD stopping
II. OD through going

observed charge / expectation from through-going

1.5m from top & bottom
1m from barrel

22.5kt
26.4kt

OD stopping MC

OD through-going MC

Preliminary
<table>
<thead>
<tr>
<th>Type</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</td>
<td>1619</td>
<td>2105.6</td>
<td>(98.3%)</td>
</tr>
<tr>
<td>multi-ring</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>Total</td>
<td>2726</td>
<td>3725.7</td>
<td></td>
</tr>
</tbody>
</table>
First dip is observed as expected from neutrino oscillation.

Mostly upward

Preliminary

Null oscillation

MC

Data/Prediction (null oscillation)

Best fit expectation w/ systematic errors

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

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

Mostly downward

Best-fit expectation

1489.2 days FC+PC
Definition of $\chi^2$

$$L (N_{\text{exp}}, N_{\text{obs}}) = \prod_{n=1}^{43} \frac{\exp(-N_{\text{exp}}^n)(N_{\text{exp}}^n)^{N_{\text{obs}}^n}}{N_{\text{obs}}^n!} \times \prod_{i=1}^{25} \exp\left( -\frac{\varepsilon_i^2}{2\sigma_i^2} \right)$$

Poisson with systematic errors

$$\chi^2 \equiv -2 \ln \left( \frac{L (N_{\text{exp}}, N_{\text{obs}})}{L (N_{\text{obs}}, N_{\text{obs}})} \right) = \sum_{n=1}^{43} \left[ 2(N_{\text{exp}}^n - N_{\text{obs}}^n) + 2N_{\text{obs}}^n \ln\left( \frac{N_{\text{obs}}^n}{N_{\text{exp}}^n} \right) \right] + \sum_{i=1}^{25} \left( \frac{\varepsilon_i}{\sigma_i} \right)^2$$

$N_{\text{obs}}$: observed number of events
$N_{\text{exp}}$: expectation from MC
$\varepsilon_i$: systematic error term
$\sigma_i$: sigma of systematic error

Various systematic effects in detector, flux calculation and neutrino interaction are taken into account
Preliminary

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

\( (\sin^2 2\theta = 1.02, \chi^2_{\text{min}} = 37.7 / 40 \text{ d.o.f}) \)

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

- 99\% C.L.
- 90\% C.L.
- 68\% C.L.

90\% allowed regions
5FTUTGPSOFVUSJOPEFDBZEFDPIFSFODF

Oscillation: $\chi^2_{\text{min}}=37.8/40$ d.o.f
Decay: $\chi^2_{\text{min}}=49.2/40$ d.o.f $\rightarrow \Delta\chi^2=11.4$
Decoherence: $\chi^2_{\text{min}}=52.4/40$ d.o.f $\rightarrow \Delta\chi^2=14.6$

First dip observed in data cannot be explained by alternative hypotheses.

$3.4 \sigma$ to $\nu$ decay

$3.8 \sigma$ to $\nu$ decoherence

Preliminary
Sensitivities to alternative models

\[ \Delta \chi^2 \]

\( \nu \) decoherence

\( \nu \) decay

Consistent with the expectation

\( \nu_\mu \leftrightarrow \nu_\tau \) obtained \( \Delta \chi^2 \)

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

L/E resolution cut at 70%
Conclusions

Measurement of L/E dependence of flavor transition probability

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)

→ gives strong constraint to neutrino oscillation parameters
  \[ 1.9 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3} \text{eV}^2 \]
  \[ 0.90 < \sin^2 2\theta \quad \text{at 90}\%\text{C.L.} \]

consistent with zenith angle analysis

First evidence that neutrino transition probability obeys sinusoidal function as predicted in neutrino oscillation