Solar and Atmospheric Neutrinos at Super Kamiokande

Jennifer Raaf
Boston University
on behalf of the Super-K collaboration

NNN09
Oct. 8-10, 2009
Estes Park, CO
Super-Kamiokande

Kamioka-Mozumi zinc mine
1 km (2700 meters-water-equiv.) rock overburden

Water Čerenkov detector
50 ktons (22.5 ktons fiducial)

Instrumented with
50-cm PMTs in Inner Detector (ID)
20-cm PMTs in Outer Detector (OD)

**Goals of Super-K**
- Solar neutrinos
- Supernova neutrinos (+ relic SN)
- Atmospheric neutrinos
- Proton decay

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**Energy Spectrum**
- Solar \( \nu \): \( \approx 5 \text{-} 20 \) MeV
- Relic SN \( \nu \): \( \approx 20 \text{-} 50 \) MeV
- Atmospheric \( \nu \): \( \approx 1 \) TeV
- Proton decay: \( \approx 100 \) GeV

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J.L. Raaf, Boston University

NNN '09
Timeline


SK-I (1996-2001)
11,146 ID PMTs (40% coverage)
1,885 OD PMTs

SK-II (2003-2005)
5182 ID PMTs (19% coverage)
Acrylic shields added

SK-III (2006-2008)
11,129 ID PMTs (40% coverage)
OD segmentation (top/barrel/bottom)

SK-IV (2008-...)
new front-end electronics (ID and OD)
new DAQ
record-all-hit data-taking + software trigger

During SK-III construction

Fiberglass backing
Solar Neutrinos
Low Energy Events in Super-K

Timing information ➔ vertex position
Ring pattern ➔ direction
Number of hit PMTs ➔ energy

Recoil electron energy threshold (total energy)

<table>
<thead>
<tr>
<th></th>
<th>SK-I</th>
<th>Energy response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.0 MeV</td>
<td>~6 hits/MeV</td>
</tr>
<tr>
<td></td>
<td>7.0 MeV</td>
<td>~3 hits/MeV</td>
</tr>
<tr>
<td></td>
<td>4.5 MeV (in progress)</td>
<td>~6 hits/MeV</td>
</tr>
<tr>
<td></td>
<td>4.0 MeV (goal)</td>
<td>~6 hits/MeV</td>
</tr>
</tbody>
</table>
Current Status of Solar Neutrino Analysis

SK-III

- Working to reduce and estimate systematic errors
- Most reconstruction tools and reduction criteria recently retuned
- Global oscillation analysis including SK-III is underway
- SK-III results will be summarized this year
- Improved tools may also be applied to SK-I data

SK-IV

- Currently at 100% trigger efficiency at $E_{\text{total}} = 4.5$ MeV
- Trigger threshold will be lowered in the future
  Target: $E_{\text{total}} \leq 4.0$ MeV  ($E_{\text{kinetic}} \leq 3.5$ MeV)
Angular Distributions

Angular distribution for 3 energy bins (using 13.3 kton fiducial volume in center of tank)

- Reduced background levels in central region of detector for low energy events
- Improved reconstruction of event vertex and direction $\Rightarrow$ 10% better angular resolution in SK-III
Observed $^8$B Flux in SK-III

Extract number of signal events by fit to signal + background shapes

SK-III SLE 298days 5.0-20MeV (Preliminary)

Signal = 4968 $\pm$ 108-106 (stat.) events
$^8$B Flux = 2.31 $\pm$ 0.05 (stat.) ($\times 10^6$/cm$^2$/s)

Data
Best-fit
Background

$^8$B flux = 2.35$\pm$0.02(stat)$\pm$0.08(sys) $\times 10^6$/cm$^2$/s

Flux consistent with SK-I
Future Prospects for Solar Neutrinos at SK

Try to observe expected upturn in $^8$B spectrum in region of transition from vacuum to matter oscillations

Low energy upturn $\sim 10\%$ effect in Super-K

In order to see it, we must:
- reduce statistical errors
- reduce energy-correlated sys errors ($0.5 \times$ SK-I)
- lower energy threshold
  - $\rightarrow$ easier task with new electronics in place
Atmospheric Neutrinos
**Event Categories**

<table>
<thead>
<tr>
<th>Event Category</th>
<th>Event Rate (events/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>SK-I</strong> (1489 days)</td>
</tr>
<tr>
<td>Fully Contained (FC)</td>
<td>8.18 ± 0.07</td>
</tr>
<tr>
<td>Partially Contained (PC)</td>
<td>0.61 ± 0.02</td>
</tr>
<tr>
<td>Upward-stopping ( \mu ) (Upstop)</td>
<td>0.25 ± 0.01</td>
</tr>
<tr>
<td>Upward-thrugoing ( \mu ) (Upthru)</td>
<td>1.12 ± 0.03</td>
</tr>
</tbody>
</table>

Event rates consistent across all phases of SK
Atmospheric $\nu$'s at Super-K (simulated events)
What can we learn from atmospheric neutrinos?

\[ U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta_{CP}} & 0 & c_{13}
\end{pmatrix} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \]

**Atmospheric Mixing Parameters**

- Two-flavor zenith angle analysis
- L/E analysis
- Solar terms analysis \( \rightarrow \theta_{23} \) octant

**Mass Hierarchy and Value of \( \theta_{13} \)**

- Three-flavor zenith angle analysis

Several methods for probing different neutrino sectors using Super-K data.
Zenith Angle Analyses

Data binned according to:

\[
\chi^2 = \sum_{i=1}^{N_{\text{bins}}} 2 \left( N_i^{\text{exp}} - N_i^{\text{obs}} + N_i^{\text{obs}} \ln \frac{N_i^{\text{obs}}}{N_i^{\text{exp}}} \right) + \sum_{j=1}^{N_{\text{sys}}} \left( \frac{\varepsilon_j}{\sigma_{j}^{\text{sys}}} \right)^2
\]

where

\[
N_i^{\text{exp}} = N_i^0 \cdot P(\nu_\alpha \rightarrow \nu_\beta) \left( 1 + \sum_{j=1}^{N_{\text{sys}}} f_j^i \varepsilon_j \right)
\]

\( N_{\text{bins}} \) systematic error terms to account for uncertainties in:
- Neutrino flux
- Cross sections
- Event reconstruction
- Data reduction

Datasets:
- SK-I FC/PC: 1489 days
- SK-I Upmu: 1646 days
- SK-II FC/PC: 798 days
- SK-II Upmu: 828 days
- SK-III FC/PC: 518 days
- SK-III Upmu: 635 days

Look for distortion of zenith angle distributions
SK-1+2+3 Data (Preliminary)

Sub-GeV samples subdivided to improve sensitivity to low energy oscillation effects

- Data
  - MC (no oscillations)
  - MC (best fit oscillations)
L/E Analysis: SK-1+2+3

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E_\nu} \right) \]

Datasets
- SK-I FC/PC \( \mu \)-like: 1489 days
- SK-II FC/PC \( \mu \)-like: 798 days
- SK-III FC/PC \( \mu \)-like: 518 days

Use only event categories with good L/E resolution:
- Partially-contained muons
- Fully-contained muons

\( \chi^2 \) fit to 43 bins of \( \log_{10}(L/E) \) with 29 systematic error terms

Compare against:
- Neutrino decay (disfavored @ 4.4\( \sigma \))
- Neutrino decoherence (5.4\( \sigma \))

Grossman and Worah: hep-ph/9807511
Lisi et al.: PRL85 (2000) 1166
Results of two-flavor oscillation analyses

**Zenith angle analysis best fit**

\[ \sin^2 2\theta_{23} = 1.0 \]
\[ \Delta m^2_{23} = 2.1 \times 10^{-3} \text{eV}^2 \]
\[ \chi^2 / d.o.f. = 468 / 420 \]

**L/E analysis best fit**

\[ \sin^2 2\theta_{23} = 1.0 \]
\[ \Delta m^2_{23} = 2.2 \times 10^{-3} \text{eV}^2 \]
\[ \chi^2 / d.o.f. = 119 / 126 \]

Complementary analyses:
- Equally strong \( \sin^2 2\theta_{23} \) constraint
- L/E has stronger \( \Delta m^2 \) constraint
Results of two-flavor oscillation analyses

\[
\sin^2 2\theta_{23} = 1.0 \\
\Delta m_{23}^2 = 2.1 \times 10^{-3} \text{eV}^2 \\
\chi^2 / d.o.f. = 468 / 420
\]

\[
\sin^2 2\theta_{23} = 1.0 \\
\Delta m_{23}^2 = 2.2 \times 10^{-3} \text{eV}^2 \\
\chi^2 / d.o.f. = 119 / 126
\]

Results agree well with other experiments
LBL better constrains \( \Delta m^2 \)
Atmospheric still has stronger \( \sin^2 2\theta \) constraint
Solar Terms Analysis

May be possible to determine octant of $\theta_{23}$ by observing changes in the flux of low-energy $\nu_e$ samples.

Driven by $\Delta m^2_{12}$ and $\theta_{12}$.

In constant density matter:

$$P(\nu_e \leftrightarrow \nu_\mu) = \cos^2 \theta_{23} P(\nu_e \rightarrow \nu_x)$$

- $\cos^2 \theta_{23} < 0.5$  $\nu_e$ flux reduction
- $\cos^2 \theta_{23} = 0.5$
- $\cos^2 \theta_{23} > 0.5$  $\nu_e$ flux enhancement

Look for changes in low energy $\nu_e$ flux induced by solar-sector oscillations, assuming $\theta_{13} = 0$. 
Solar Terms Analysis

Fit using 3-flavor oscillation probabilities with and without solar terms, assume $\theta_{13} = 0$.

**Solar terms off (best fit)**

- $\Delta m_{12}^2 = 0$ (fixed)
- $\Delta m_{23}^2 = 2.1 \times 10^{-3} \text{eV}^2$
- $\sin^2 \theta_{12} = 0$ (fixed)
- $\sin^2 \theta_{23} = 0.50$
- $\chi^2/dof = 470.2/418$

**Solar terms on (best fit)**

- $\Delta m_{12}^2 = 7.59 \times 10^{-5} \text{eV}^2$
- $\Delta m_{23}^2 = 2.1 \times 10^{-3} \text{eV}^2$
- $\sin^2 \theta_{12} = 0.30$
- $\sin^2 \theta_{23} = 0.51$
- $\chi^2/dof = 471.2/416$

*Solar parameters are constrained with $\Delta \chi^2$ map information from combined fit to solar neutrino experiment data + KamLAND data.

Fogli et al. (hep-ph/0808.2016)

Addition of solar terms shows no significant deviation of $\theta_{23}$ from $\pi/4$. 

*Preliminary*
Addressing Non-zero $\theta_{13}$ with Atmospheric Neutrinos

$P(\nu_\mu \rightarrow \nu_e)$

$\sin^2 \theta_{13} = 0.005$  \hspace{1cm} $\sin^2 \theta_{13} = 0.015$  \hspace{1cm} $\sin^2 \theta_{13} = 0.04$

MSW effect gives rise to additional scattering amplitudes in matter (for $\nu_e$ only).

Clearest indication of non-zero $\theta_{13}$ at Super-K:
resonance @ $\sim$2-10 GeV for up-going e-like events

Normal hierarchy $\Rightarrow$ neutrino enhancement
Inverted hierarchy $\Rightarrow$ anti-neutrino enhancement

Analysis uses 3 parameters ($\sin^2 \theta_{13}$, $\sin^2 \theta_{23}$, $\Delta m^2_{23}$)
assuming a single “dominant mass scale” ($\Delta m^2_{23} \gg \Delta m^2_{12}$).
Clear distortion of muon-like zenith distribution, well-described by 2-flavor $\nu_\mu \to \nu_\tau$ disappearance...

Allow also $\nu_\mu \to \nu_e$ appearance in 3-flavor analysis, look for enhancement of high-energy upward-going e-like events.

No distortion in electron-like samples... no evidence for matter-enhanced $\nu_e$ appearance.
Three-flavor results

Data consistent with both hierarchies; no electron-like excess observed.

<table>
<thead>
<tr>
<th></th>
<th>$\chi^2$/dof</th>
<th>$\Delta m^2_{23}$</th>
<th>$\sin^2\theta_{23}$</th>
<th>$\sin^2\theta_{13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>469/417</td>
<td>2.1x10^{-3}</td>
<td>0.50</td>
<td>0</td>
</tr>
<tr>
<td>Inverted</td>
<td>468/417</td>
<td>2.1x10^{-3}</td>
<td>0.55</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Future Prospects for Atmospheric Neutrinos at SK

$P(\nu_\mu \rightarrow \nu_e)$

The global picture...

combine solar terms analysis with three-flavor analysis

No results yet, analysis underway
Summary

SK-I+II+III
12 years dataset for solar and atmospheric neutrinos

Solar:
- results with SK-III will be summarized this year
- currently working to reduce systematic errors

Atmospheric:
- standard 2- and 3-flavor analyses updated to include SK-I+II+III
- 3-flavor analysis with solar terms underway

SK-IV
Detector improvements by upgraded electronics
- capability for lowering analysis energy threshold in SK-IV

Super-K will continue to study “Standard Model” oscillation physics
- help constrain solar parameters
- precisely measure atmospheric parameters
- try to observe every predicted effect

Thank you!
Extras
Oscillation Analyses

Zenith angle analysis (fine-binned)

- Use many subsamples of data
- Look for zenith angle distortion

L/E analysis

- Use much more selective subsample of data
- Require good L/E resolution
- Look for first oscillation dip
**ID/OD Optical Segmentation**

Goal: improve selection criteria for **PC event** (0.8/day) versus **corner clipping muons** (100,000s per day)

**New Tyvek optical barriers in RED**
MINOS can distinguish neutrinos from anti-neutrinos on an event-by-event basis by +/-charged particle discrimination.

Super-K must rely on statistical sensitivity from different fluxes, cross sections, etc.
Non-standard Interactions (NSI): SK-I + SK-II

Non-standard interactions (beyond Standard Model) may coexist with $\nu$ oscillations, but would be subdominant:

- matter-dependent
- could enhance or suppress oscillations (variety of signatures)

$$A_{NSI} = \sqrt{2} G_f N_f \begin{pmatrix} \varepsilon_{ee} & 0 & \varepsilon_{e\tau} \\ 0 & 0 & 0 \\ \varepsilon_{e\tau}^* & 0 & \varepsilon_{\tau\tau} \end{pmatrix}$$

Flavor-changing neutral currents

Lepton non-universality

Assume 2-flavor oscillation parameters ($\nu_\mu \rightarrow \nu_\tau$): $$(\sin^2 \theta, \Delta m^2) = (0.5, 2.1 \times 10^{-3})$$

Determine best fit parameters for NSI under an oscillation + NSI hypothesis

Best fit NSI parameters:

$$\begin{pmatrix} \varepsilon_{ee}, \varepsilon_{e\tau}, \varepsilon_{\tau\tau} \end{pmatrix} = (-0.250, 0.016, 0.024)$$

$$\chi^2_{min}/d.o.f = 830/747$$
Limits on Non-Standard Interactions

facility

Lepton Non-Universality

SK-1+2 limit (90% CL)

Flavor Changing Neutral Currents
**GADZOOKS!**

- $\bar{\nu}_e$ signal could be separated from BG by neutron tagging.
- Vertex correlation: $\sim 50$ cm
- Load 0.2% Gd into SK water to detect gamma by neutron capture.

(M. Vagins and J. Beacom)

**With 10 years SK data:**
- Signal = 33 events, B.G. = 27 events
  - $E_{vis} = 10-30$ MeV

Assuming 67% detection efficiency.

Assuming invisible muon B.G. can be reduced by a factor of 5 by neutron tagging. (will be checked in SK-IV by using 2.2 MeV $\gamma$)

EGADS

Evaluating Gadolinium’s Action on Detector Systems
Make 100 ton class test tank and demonstrate the GADZOOKS! idea.

Budget was approved in 2009