Results from Super Kamiokande

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on behalf of Super Kamiokande collaborators

Duke University

April 15, 2007

APS meeting at Jacksonville in FL
Super-Kamiokande Collaboration

140 collaborators from 35 institutes of 5 countries


(Super-Kamiokande Collaboration)

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(Received 25 July 2006; published 23 October 2006)
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A 50 kton Water Cherenkov detector

- 1000m rock overburden (2600m w.e.)
- 22.5 kton fiducial mass
- Inner Detector (ID) : 11146 20-inch PMT tubes
- Outer Detector (OD) : 1885 8-inch PMT tubes
- Optical separation between inner and outer detector
More than a Decade of SK

- **SK1 (1996-2001)**
  - 11146 inner(ID)/ 1885 outer(OD) PMT's; 40% of ID coverage
  - Solar ν, atmospheric ν, proton decay results; K2K I target

- **SK2 (2003-2005)**
  - Recovered 2001 accident with 19% ID coverage (shielded by acrylic covers), full OD
  - Nearly same sensitivity as SK1; K2K II target

- **SK3 (2006-present)**
  - Data taking since July 2006 with full coverage
  - Ready for T2K off-axis beam from J-PARC in 2009

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SK Event Categories

- Neutrino observed via charged-current interactions with nuclei in water
  1. If lepton has enough energy it will make Cherenkov light
  2. Outgoing Cherenkov light is observed by the PMTs
  3. Energy and Position (vertex) of the event can be reconstructed
  4. Particle ID: e/μ like

- FC (~1 GeV)
- FC multi ring (~3 GeV)
- PC stop (~5 GeV)
- PC through (~10 GeV)
- Up μ stop (~10 GeV)
- Up μ through (~100 GeV)
- Up μ shower (~1 TeV)
Atmospheric neutrino results

Recent atmospheric neutrino research at SK

- Search for neutral Q-balls in SK II (Phys. Lett. B 647, 18 (2007))
- Observation of the anisotropy of 10 TeV primary cosmic ray nuclei flux with the Super-Kamiokande-I detector (Phys. Rev. D75, 062003 (2007))
- $\nu_\mu \rightarrow \nu_\tau$ oscillation is compared with alternative exotic models (sterile neutrino, neutrino decay and neutrino decoherence)
1. Primary cosmic ray interaction in the atmosphere

2. Cascade of secondary $\pi$, K

3. Decay of secondaries

Flux up/down symmetric - differences in upward and downward going flux is a signal of neutrino physics

$E_\nu : 100\text{MeV} \sim 10\text{TeV}$

Zenith angle $\theta$

Downward (L=10~100 km)

Upward (L=up to 13000 km)
Zenith angle distributions (SK1+SK2)

$\nu_\mu-\nu_\tau$ oscillation (at best fit point)

null oscillation

$P_{\mu\to\tau} = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 L}{E}\right)$

SK1: 1489 days
SK2: 804 days
23,000 $\nu$'s
100 MeV-10 TeV

Upward through-going showering $\mu$

New

Excellent agreement with $\nu_\mu \to \nu_\tau$ oscillation hypothesis
Allowed Oscillation Parameters (SK1+SK2)

$\nu_\mu \rightarrow \nu_\tau$

Best Fit:

$(\Delta m^2, \sin^2 2\theta) = (2.5 \times 10^{-3} \text{ eV}^2, 1.00)$

$\chi^2 = 839.7 / 755 \text{ dof (18%)}$

90\% C.L.:

$1.9 \times 10^{-3} < \Delta m^2 < 3.1 \times 10^{-3} \text{ eV}^2$

$\sin^2 2\theta > 0.93$

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**Tau neutrino appearance (SK1)**

SK atmospheric $\nu$ data favor $\nu_\mu \rightarrow \nu_\tau$ oscillations as a dominant source of the deficit of $\nu_\mu$.

$$\nu_\mu \rightarrow \nu_\tau$$

Energy Threshold: 3.5 GeV

Typical MC $\tau$ event

According to MC, expect about 80 $\tau$'s in current sample... but they are hard to distinguish from other multi-ring $\nu$ interaction events.
Select Tau Neutrino like events (SK1)

- Two analyses (Likelihood and Neural Network) yield consistent answers
- A best fit $\nu_\tau$ appearance signal (shaded area)
  - $138\pm48$ (stat.) +14.8/-31.6 (syst.)
  - significance : 2.4$\sigma$
- Consistent with the expected number of $\nu_\tau$ from MC ($\Delta m^2=2.4\times10^{-3}$ eV$^2$)
  - $78.4\pm26$ (sys)
Does it have to be tau neutrino?

- LEP experiments: Z decay cross section indicates there are only three active neutrino flavors, $N_{\nu}=2.992\pm0.020$
- If only three flavors of neutrinos, it has to be tau neutrino
  - $\nu_{\mu}\rightarrow\nu_{e}$ oscillation does not explain the SK data
- Sterile neutrino ($\nu_{s}$: no electric, strong or weak charge) is a potential candidate of Atmospheric neutrino disappearance
  - Some theoretical models predict the existence of $\nu_{s}$
  - So, Compare $\nu_{\mu}\rightarrow\nu_{\tau}$ oscillation and $\nu_{\mu}\rightarrow\nu_{s}$ oscillation
    - Inside detector: Less NC events
    - During the propagation: Has Matter Effect ($\nu_{\mu}\rightarrow\nu_{\tau}$ doesn't have)
Tau neutrino vs Sterile neutrino

Exclusion level : 7.2σ

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What about admixtures?

- Admixtures are model dependent
- SK analysis is based on Fogli et al PRD 63 (053008) 2001
  - A 2+2 mass hierarchy model
  - Construct a superposition of $\nu_s$ and $\nu_\tau$ states $\to$ 2 flavor mixing

**Diagram:**

- **ATM:** $m_4$, $m_3$
- **LSND:** $m_2$, $m_1$
- **Solar:** $m_4$, $m_3$

Sterile mixing portion

\[
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix} =
\begin{pmatrix}
\cos(\xi) & \sin(\xi) \\
-\sin(\xi) & \cos(\xi)
\end{pmatrix}
\begin{pmatrix}
\nu_\tau \\
\nu_s
\end{pmatrix}
\]

- Allowed sterile neutrino admixture limit at 90% C.L. : $\sin^2 \xi < 0.23$

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Neutrino disappearance: L/E (SK1+SK2)

Survival probability of $\nu_\mu$ is a function of L/E for 2 flavor oscillation:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)$$

Best fit: $\Delta m^2=2.3 \times 10^{-3}$, $\sin^2 2\theta=1.00$

$$\chi^2_{\text{min}}=83.9/83 \text{ d.o.f.}$$
Alternative models of Neutrino Disappearance

What about other possibilities?

- Neutrino Decay
  - Assuming the dominant component of $\nu_\mu$, i.e., $\nu_2$, to be the only unstable state with a lifetime $\tau_0$
  - $\nu_\mu \approx \cos \theta \nu_2 + \sin \theta \nu_3$, $\nu_e \approx \nu_1$
  - $P_{\mu\mu} = \sin^4 \theta + \cos^4 \theta \times \exp(-\frac{m_2^2 L}{2\tau E})$

- Neutrino Decoherence effect induced by new physics
  - $P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \times (1 - \exp(-\tau_0 L)) \times \cos(\frac{\Delta m^2 L}{2E})$

- Can test the first dip in L/E

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Test of other modes with L/E of SK1+SK2

The data/prediction for 3 models as a function of L/E

- Decoherence: $\chi^2(\text{decoherence}) = 112.5/82$ d.o.f., $\Delta \chi^2 = 27.6$ (5.3$\sigma$)
- Decay: $\chi^2(\text{decay}) = 107.1/82$ d.o.f., $\Delta \chi^2 = 23.2$ (4.8$\sigma$)
- Oscillation: $\chi^2(\text{osc}) = 83.9/82$ d.o.f.

Neutrino decoherence and decay models are excluded at $\sim 5\sigma$
ν oscillation and decoherence (decay) coexistence

In addition, we compared two models:

1) Neutrino Oscillation + Neutrino Decay

\[ \frac{m}{\tau_0} < 3.2 \times 10^{-5} \text{ GeV} \]

99% C.L.
90% C.L.
68% C.L.

\[ \frac{m}{\tau_0} \text{(GeV/s)} \]

2) Neutrino Oscillation + Neutrino Decoherence

\[ \gamma_0 < 1.4 \times 10^{-22} \text{ GeV} \]

99% C.L.
90% C.L.
68% C.L.

\[ \gamma_0 \times 10^{-21} \text{ GeV} \]

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Three flavor oscillation analysis (SK1)

3 flavor mixing looks like this:

\[
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix} = U \begin{pmatrix}
m_1 \\
m_2 \\
m_3
\end{pmatrix}, \quad U = \begin{pmatrix}
1 & 0 & 0 \\
0 & C_{23} & S_{23} \\
0 & -S_{23} & C_{23}
\end{pmatrix} \begin{pmatrix}
C_{13} & 0 & S_{13} e^{i\delta} \\
0 & 1 & 0 \\
-S_{13} e^{i\delta} & 0 & C_{13}
\end{pmatrix} \begin{pmatrix}
C_{12} & S_{12} & 0 \\
-S_{12} & C_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\(c_{ij} = \cos(\theta_{ij})\), \(s_{ij} = \sin(\theta_{ij})\)

- In the full expression of \(U\), we have 6 parameters
  - \(\theta_{12}, \theta_{13}, \theta_{23}, \Delta m_{12}^2, \Delta m_{23}^2\), where \(\Delta m_{ij}^2 = m_j^2 - m_i^2\), and \(\delta_{CP}\)

Open question in neutrino physics:

- \(\theta_{13}, \delta_{CP}\) are nonzero?
- What is the mass hierarchy?

\[\begin{array}{ccc}
\text{Mass} & \text{Normal} & \text{Inverted} \\
\hline
\text{m}_1 & \text{m}_2 & \text{m}_3 \\
\end{array}\]
The effect on $P(\nu_\mu \rightarrow \nu_e)$ for nonzero $\theta_{13}$ can be large.

- We can look for extra e-like events at high energy as an indication of $\theta_{13}$.
- SK can not discriminate between $\nu$ and $\bar{\nu}$ on an event-by-event basis.
- However, the amount of e-like excess depends on the magnitude of $\theta_{13}$, and on the sign of the hierarchy.
- For inverted hierarchy anti-$\nu$'s experience this resonance.
Three flavor oscillation Results (SK1)

- The up-down asymmetry as a function of momentum is consistent with expectation of $\theta_{13} = 0$.
- No significant e-like excess has been seen.
- Both normal and inverted mass hierarchy hypothesis are tested and both are consistent.
- Obtained upper limits on $\theta_{13}$ is consistent with CHOOZ limit.

![Graphs showing momentum vs. asymmetry and mass square vs. sine squared of theta 13]
Past experiments and SK have set severe constraints on viable GUTs. Minimal SU(5), Minimal SUSY SU(5) are ruled out.

New modes are being tested.
n-¯n oscillation (SK1)

- Other models of GUTs predict $\Delta (B-L) = 2$ processes, such as $n-\bar{n}$ oscillation.
- $\bar{n}N$ annihilation arising from $n\bar{n}$ oscillation which occur in the H2O nuclei produce multiple particles. $\rightarrow$ multi-rings
  - Detection efficiency = 10.4%
- Main source of BG is from atm.$\nu$
- Observed: 20, Expected BG: 21.31
- $1.77 \times 10^{32}$ yr at 90% C.L. with SK1 data
Solar neutrino

- SK observes $^8$B neutrino scattering on electrons
- Event Reconstruction energy threshold $\sim 6$MeV

![Graph showing neutrino flux and energy spectrum]

- Gallium
- Chlorine
- Super-K

Neutrino Flux

- $5.94(1+/^{-0.01})\times 10^{10} \text{ /cm}^2/\text{s}$ (BP04 SSM)
- $5.79(1+/^{-0.23})\times 10^{6} \text{ /cm}^2/\text{s}$

Neutrino energy (MeV)

PRL92(2004)121301
http://www.sns.ias.edu/~jnb

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\(^{8}\)B flux

Signal = 7213 +153/-151 (stat.) events

\(^{8}\)B Flux for SK1 and SK2 : [cm\(^{-2}\)s\(^{-1}\)]

- 2.35 \pm 0.02 \text{ (stat.)} \pm 0.08 \text{ (syst.)} \text{ (SK1)}
- 2.38 \pm 0.05 \text{ (stat.)} +0.16/-0.15 \text{ (syst.)} \text{ (SK2)}
Energy distribution of Solar Neutrino at SK

\[ ^{8}\text{B flux} = 0.90 \times SSM = 5.21 \times 10^6 \text{ cm}^{-2}\text{s}^{-1} \]

\[ \text{hep flux} = 8.62 \times SSM = 6.79 \times 10^4 \text{ cm}^{-2}\text{s}^{-1} \]
Combined results from SK + other experiments

Solar neutrino oscillation analysis combining SK, SNO and radio chemical experiments (Gallex/SNO/SAGE)

\[ \chi^2_{\text{global}}(\beta, \eta) = \chi^2_{\text{SK}}(\beta, \eta) + \chi^2_{\text{SNO}}(\beta, \eta) + \chi^2_{\text{radiochem}}(\beta, \eta) \]

Favors the large mixing angle solution

\[ \tan^2 \theta = 0.40 \]

\[ \Delta m^2 = 6.03 \times 10^{-5} \text{ eV}^2 \]
The Future of SK: T2K (Tokai to Kamioka)

- 295 km, 0.75 MW beam, 2.5 degrees of off-axis, start in 2009

- Upgrade of new electronics, DAQ, GPS systems at SK

Near (280m) + Intermediate (2km) + Far (SK)
Summary

- SK3 started taking data on June 2006 with full PMT coverage
- $\nu_\mu \rightarrow \nu_\tau$ oscillation is compared with alternative models
  - Mass induced $\nu_\mu \rightarrow \nu_s$ oscillation: excluded at 7.2$\sigma$ level
  - Admixture of $\nu_s$ is allowed $\sin^2 \xi < 0.23$ at 90% C.L.
- $\nu_\tau$ excess events have been observed in upward-going FC $\nu$.
- SK1 Three Flavor analysis is consistent with both mass hierarchies and the CHOOZ limit
- n-n oscillation with SK1: $1.77 \times 10^{32}$ yr at 90% C.L.
- Solar neutrino oscillation analysis combining SK, SNO and radio chemical experiments (Gallex/SNO/SAGE) favor the LMA solution ($\tan^2 \theta = 0.40$, $\Delta m^2 = 6.03 \times 10^{-5}$ eV$^2$)
- Upgrades for T2K experiment are underway
Supernova Burst Search

Kamiokande, IMB, Baksan experiments observed the neutrino burst from SN1987A on Feb 23, 1987. Since then, neutrino astronomy was started.

SK typical core collapse SN explosion emits all types of neutrinos and has a total energy output of \( \sim 3 \times 10^{53} \) ergs, i.e. generate 10,000 events (9,000 without n oscillation) at SK in the case of SK at 10 kpc.

SK is sensitive to ??? (distance?)

2589.2 live-days of data (SK1+SK2)
To investigate SN clusters in lower energy (<17 MeV) events, 
**Set the criteria of Higher multiplicity and Shorter timewindow**

- \( \geq 3 \text{events} / 0.5 \text{ sec} \)
- \( \geq 4 \text{events} / 2.0 \text{ sec} \)
- \( \geq 8 \text{events} / 10 \text{ sec} \)

I confirmed that one of them is flasher events, 
The other one is spallation events.
Oscillation induced by LIV and CPTV

- Neutrino oscillation without mass
- Pure Lorentz Invariant Violation effect
- CPT violation
CPT violation

$\Delta \phi = 0$

$\Delta \phi = \pi$

$\Delta \phi = 0$

$68\% \text{ C.L.}$
$90\% \text{ C.L.}$
$99\% \text{ C.L.}$

$\Delta \phi = \pi$

$68\% \text{ C.L.}$
$90\% \text{ C.L.}$
$99\% \text{ C.L.}$

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