Measurement of solar neutrinos at Super-Kamiokande

NDM03 on
June 10th, 2003

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for Super-Kamiokande collaboration
Miyagi University of Education

- Introduction
- Results from SK-I solar neutrino data
- Oscillation analysis
- Search for $\bar{\nu}_e$ from the Sun
- Reconstruction and SK-II measurement
- Summary
The Super-Kamiokande Collaboration

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Kamioka Observatory
Research Center for Cosmic Neutrinos (RCCN)
Boston University
Brookhaven National Laboratory
University of California, Irvine
California State University, Dominguez Hills
George Mason University
Gifu University
University of Hawaii
High Energy Accelerator Research Organization (KEK)
Kobe University
Kyoto University
Los Alamos National Laboratory
Louisiana State University
University of Maryland at College Park
Massachusetts Institute of Technology
University of Minnesota
State University of New York at Stony Brook
Niigata University
Osaka University
Seoul National University
Shizuoka University
Tohoku University
The university of Tokyo
Tokai University
Tokyo Institute of Technology
Warsaw University
University of Washington

27 institution, 122 collaborator
(as of Sep 2002)
Introduction

- Pure electron neutrino
- pp-\(^7\)Be neutrino : 99.8% of total flux, but low energy
- \(^8\)B neutrino : 8 \(\times\) 10\(^{-5}\) of total flux, however high energy
Solar neutrino problem
Without SK data (Chlorine, Gallium, SNO CC)
Results from SK-I solar neutrino data

- Photo coverage 40%  Fid. Vol. for solar $\nu$  22.5kton
- $^8$B $\nu$ measurement  $\nu_e + e^- \rightarrow \nu_e + e^-$
- Sensitive to other $\nu$  $\sigma(\nu_{\mu(\tau)} + e^-) = \sim 0.15 \sigma(\nu_e + e^-)$
- High statistics  $\sim 15$ev/day
- Real-time and energy measurement  D/N and spectrum observable
- Resolution  (10MeV $e^-$)  Pos : 87cm  E : 14%  Dir : 26 degree
Angular distribution to the solar direction

May 31st, 1996 ~ 15th July 2001

SK-I 1496day 5.0-20MeV 22.5kt
(Preliminary)

Best fit
Non-flat BG
Data

22,385 ± 230 events

flux is

2.35 ± 0.02(stat.)±0.08(sys.)×10⁶/cm²·s

or 0.465 ± 0.005(stat.)±0.016(sys.) × SSM

(BP2001)
Combined flux analysis of SK, SNO CC and NC

<table>
<thead>
<tr>
<th></th>
<th>SK</th>
<th>SNO</th>
<th>SNO</th>
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<tbody>
<tr>
<td>$\phi_{ES}$</td>
<td>$2.35\pm0.09$ [x10$^6$/cm$^2$/s]</td>
<td>$\phi_{ES} = \phi_e + 0.15 \phi_{\mu,\tau}$</td>
<td>$\phi_{SSM} = 5.05\pm1.01/-0.81$</td>
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<tr>
<td>$\phi_{CC}$</td>
<td>$1.76\pm0.11$</td>
<td>$\phi_{CC} = \phi_e$</td>
<td>$\phi_{NC} = \phi_e + \phi_{\mu} + \phi_{\tau}$</td>
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<tr>
<td>$\phi_{NC}$</td>
<td>$5.09\pm0.64$</td>
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Obtained total flux: $\phi_{exp} = 5.3 \pm 0.7$ (cf. $\phi_{SSM} = 5.05\pm1.01/-0.81$)
Seasonal variation of $^8$B solar neutrino flux

<table>
<thead>
<tr>
<th>Yearly variation</th>
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<tr>
<td>Data/SSM</td>
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- SK-I 1496day 5.0-20MeV 22.5kt (Preliminary)

$\chi^2$ for eccentricity = 4.7  C.L. = 69%
$\chi^2$ for flat = 10.3  C.L. = 17%
(8-1 d.o.f.) (with sys. err.)
Time variation of solar neutrino flux
Periodic modulation analysis

Like Milsztajn (hep-ph/0301252) we get large Lomb Power (~10) at (13.76d)$^{-1}$

Lomb Power decreases, if Correct bin-time is used!!
Energy spectrum of recoiled electrons

$\chi^2_{(\text{flat})} = 20.2/20 \ (44.3\% \ C.L.)$

(preliminary)
Expected energy spectrum by $\nu$ oscillation

SK-I 1496day 5.0-20MeV 22.5kt

Data/SSM

Energy (MeV)

Data/SSM vs Energy (MeV)

SK-I 1496day 5.0-20MeV 22.5kt

SMA

Just-so

LMA
Day/Night asymmetry

\[ A_{DN} = -0.021 \pm 0.020^{+0.013}_{-0.012} \]
Zenith spectrum

\[ \tan^2 \theta = 0.34 \]
\[ \Delta m^2 = 2.2 \times 10^{-5} \text{ eV}^2 \]

\[ \tan^2 \theta = 0.65 \]
\[ \Delta m^2 = 10^{-7} \text{ eV}^2 \]
Oscillation analysis (combined fit)

\[ \nu_e \rightarrow \nu_\mu/\nu_\tau \text{ (95\% C.L.)} \]

- \[ \Delta m^2 \text{ in eV}^2 \]
  - \[ 10^{-12} \]
  - \[ 10^{-11} \]
  - \[ 10^{-10} \]
  - \[ 10^{-9} \]
  - \[ 10^{-8} \]
  - \[ 10^{-7} \]
  - \[ 10^{-6} \]
  - \[ 10^{-5} \]
  - \[ 10^{-4} \]
  - \[ 10^{-3} \]

\[ \tan^2(\theta) \]

- SK 1496 Days
- allowed (Ga+Cl+SNO CC Rates)
- excluded (rate not constrained)
Zenith spectrum with flux constraint

\[ \nu_{e} \rightarrow \nu_{\mu/\tau} \text{ (95\% C.L.)} \]

\[ \Delta m^2 \text{ in eV}^2 \]

\[ \tan^2(\Theta) \]

SK 1496 Days

allowed (rate constrained to solar model)
$\Delta \chi^2$ distribution along to the $\tan^2\theta$ and $\Delta m^2$
Combined fit with SNO
Global fit using results from all experiments
Global fit without Cl rate

(preliminary)
Global fit without Ga rate

(preliminary)
Comparison with KamLAND data

D/N asymmetry contour in SK

KamLAND allowed region

Precise measurement of D/N asymmetry is important for defining oscillation parameter
Search for $\bar{\nu}_e$ from the Sun

If neutrinos have magnetic moment,

$$\nu_e \rightarrow \bar{\nu}_e \text{ (Dirac } \nu) \quad \nu_e \rightarrow \bar{\nu}_\mu, \bar{\nu}_\tau \rightarrow \text{(osc.)} \rightarrow \bar{\nu}_e \text{ (Majorana } \nu)$$

Search for $\bar{\nu}_e + p \rightarrow n + e^+$

Solar $\nu_e$

B.G + $\bar{\nu}_e$ (?)

Evaluate spallation background

Angular distribution of $e^+$

June 10th, 2003

Y.Fukuda at NDM03
Flux limit for solar $\bar{\nu}_e$

Combine 8-20 MeV,
$\bar{\nu}_e$ flux < 0.8% of SSM
(90% C.L.)

Reconstruction and SK-II measurement

SK-II (half PMT density with acrylic case) is back now…

Reconstruction on May~Oct, 2002
Super-Kamiokande has been restarted


Tank was full on December 10, 2002.
(13 months after the accident.)

**Total number of PMTs in SK-II: ~5200 PMTs ~47% of SK-I**
(cf. 11146 PMTs in SK-I)

Typical cosmic ray muon in SK-II
Detector calibration for SK-II

- PMT relative gain calibration by using Ni(n,\(\gamma\))Ni source and an uniform light source (Xe-scintillation ball).
- Timing calibration by \(\text{N}_2\)-DYE laser ball.

LINAC calibration data were taken from Apr.26 to May.8 at 6 positions.
Energy: 13.4, 8.7, 6.8, and 5.8 MeV
Linac calibration in SK-II

Energy resolution is about 30-40% worse than SK-I as expected from the total number of PMTs.

Current trigger threshold is Nhit=~17 (@50% eff.) corresponds to ~ 6MeV. It will be lowered soon.
Future plan

Now ~ 2005 summer (SK-II)
- $^8$B ν measurement above ~6 MeV
- Increase statistics for analyzing the Day/Night asymmetry at higher energy data
- Supernova search

2006 summer ~ (SK-III)
- Full detector will start
- Improve lower energy data (~4.5 MeV) due to reduce radon backgrounds
- Precisely measurement of Day/Night asymmetry to constraint LMA solution
Backgrounds in low energy region

4.5-5.0 MeV
-50% reduction

5.0-5.5 MeV

5.5-6.0 MeV

SK 1258 day 5.0-5.5 MeV R<10m
(preliminary)
Improvement of reduction for Rn background (1)

**SK-I**
- Radon was transported to deep into the fiducial volume by supplied water.
- Single supply line both to OD and ID.

**SK-II**
- Reduce water convection by horizontal supply flow.
- Adjust water flow to inner and outer detectors.
- PMT is now in low radon material (acrylic+FRP case).

New water pipe
Improvement of reduction for Rn background (2)

Acrylic (10 mm; front) and Fiberglass (5mm; back)

No diffusion of Rn from surface is expected
Summary

- SK-I has measured precisely $^8$B flux (1496 days, 5.0-20 MeV)
  \[ 2.35 \pm 0.02 \text{(stat.)} \pm 0.08 \text{(syst.)} \pm 10^6 \text{ cm}^{-2}\text{s}^{-1} \]
- Solar neutrino oscillation is established by SK and SNO
- No large energy distortion nor D/N asymmetry
  - Day/Night flux asymmetry: $A_{DN} = -0.021 \pm 0.020 \pm 0.013$
  - Energy spectrum: $\chi^2$ for flat 20.2/20 d.o.f. (44.3% C.L.)
- Oscillation analysis
  - Large angle solutions are preferred by zenith spectrum analysis
  - LMA is most preferable (98.9% C.L.) to solve all experimental results
- Solar $\nu_e$ flux limit is obtained by 0.8% of SSM prediction (90% C.L.)
- Reconstruction was done, and now running since Dec. 2002 with ~5500 PMTs
- Full reconstruction is planned to be 2005/2006.