Super-Kamiokande Low Energy Results
-Solar neutrinos & SN neutrinos-
NOW2012 @Conca Specchiulla
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for the Super-K Collaboration
Super-Kamiokande

- 50kton pure water Cherenkov detector
- 1km (2.7km w.e) underground in Kamioka
- 11129 50cm PMTs in Inner Detector
- 1885 20cm PMTs in Outer Detector

Physics targets of Super-Kamiokande

- Solar $\nu$
- Relic SN $\nu$
- Proton decay
- WIMPs
- Atmospheric $\nu$

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Corresponding Physics Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>~3.5</td>
<td>Low energy</td>
</tr>
<tr>
<td>~1</td>
<td>Solar $\nu$</td>
</tr>
<tr>
<td>~100</td>
<td>Relic SN $\nu$</td>
</tr>
<tr>
<td>~1 GeV</td>
<td>Proton decay</td>
</tr>
<tr>
<td>TeV</td>
<td>WIMPs</td>
</tr>
</tbody>
</table>

Hiroyuki Sekiya
Solar neutrinos observation

\[ \nu_e + e^- \rightarrow \nu_e + e^- \]

Neutrino Flux (cm\(^{-2}\) sec\(^{-1}\) MeV\(^{-1}\))

Neutrino energy (MeV)

(Bahcall-Pena-Garay-Serenelli 2008)

\[ \nu_e \pm 0.5\% \]

\[ ^{7}\text{Be} \pm 5.8\% \]

\[ ^{13}\text{N} \pm 15\% \]

\[ ^{15}\text{O} \pm 16\% \]

\[ ^{17}\text{F} \pm 19\% \]

\[ ^{8}\text{B} \pm 11.3\% \]

\[ \text{pp} \]

\[ \text{pp} \]

\[ \text{pep} \pm 1.1\% \]

\[ \text{hep} \pm 15.5\% \]
Current motivation

- Check the direct signal of the MSW effect

Solar matter effect
Energy spectrum up-turn

Earth matter effect
Flux day/night asymmetry

Neutrino survival probability

See this up-turn!

Night > Day: about 2% level
New SK-IV results are added

- First results from SK-IV (1069.3 days of data)
  - Better water quality control
    - Lowered threshold (~3.5MeV (kin.))
    - Large statistics with lower backgrounds.
  - New electronics
    - Better timing determination
    - Better MC model of trigger efficiency.
  - Introduce multiple scattering goodness
    - Although the $^{214}$Bi decay-electrons (majority of low energy BG) fluctuate up above 5.0 MeV, they truly have energy <3.3 MeV and should have more multiple scattering than true 5.0 MeV electrons, and therefore a lower MSG
  - Reduced systematic error
    - 1.7% for flux  cf. SK-I: 3.2%  SK-III: 2.1%
Lowered background

Event rates
4.0-4.5 MeV (kin.)

Solar angular distribution
3.5~4.0 MeV (kin.)

Stable low background level

Clear Solar peak ~7σ level
3.5 MeV threshold is achieved!

8B ν signal
763^{+113}_{-111}
Solar angle distributions with MSG in low energy

- MSG < 0.35
- 0.35 < MSG < 0.45
- 0.45 < MSG

- 3.5-4.0 MeV
- 4.0-4.5 MeV
Recoil electron spectrum

SK-I spectrum

SK-II spectrum

SK-III spectrum

New SK-IV spectrum

DATA/Unoscillated MC

stat. + uncor. syst. uncertainties

energy correlated error
Recoil electron spectrum

SK-I,II,II,IV
DATA/Unoscillated MC

\[ \sin^2 \theta_{13} = 0.025 \]

\[ \sin^2 \theta_{12} = 0.304, \Delta m^2 = 7.41 \times 10^{-5} \text{eV}^2 \]

\[ \sin^2 \theta_{12} = 0.314, \Delta m^2 = 4.8 \times 10^{-5} \text{eV}^2 \]

Flat probability

Flat prob., \( d\sigma / d\sigma \)

Distortion due to E dependence of
1) Oscillation survival probability
2) \( d\sigma_{\mu} / d\sigma_e \)

Unoscillated shape is favored \( \sim 1.1 \) to \( 1.9 \) \( \sigma \)

\[ \phi^B = 5.25 \times 10^6 / (\text{cm}^2 \cdot \text{sec}) \]
\[ \phi_{\text{hep}} = 7.88 \times 10^3 / (\text{cm}^2 \cdot \text{sec}) \]
Comparison with others

Super-K spectrum is the most precise!
Day-Night amplitude

$\sin^2 \theta_{12} = 0.314$  
$\Delta m_{21}^2 = 4.8 \cdot 10^{-5} \text{eV}^2$

Day-Night amplitude

$-2.8 \pm 1.1 \text{(stat)} \pm 0.5 \text{(sys)} \%$

Non-zero @2.3$\sigma$ level
Allowed oscillation parameter region from Day/Night data

The best constraint of $\Delta m^2_{12}$ among all solar neutrino measurements
Neutrino oscillation analysis
\( \theta_{13} \) analysis

Solar+KamLAND
Best fit
\( \sin^2 \theta_{13} = 0.030^{+0.017}_{-0.015} \)

Constraint to the following oscillation analyses
Consistent with reactor experiments (0.025)

Combined
Solar Data
KamLAND
Daya Bay/Reno
$(\Delta m_{12}^2, \theta_{12})$ from Only Super-K

SK (Day/Night) picks best-fit solar $\Delta m_{21}^2$

$\nu$ flux constraint

$\phi^8B = (5.25 \pm 0.20) \times 10^6/(\text{cm}^2 \cdot \text{sec})$
$(\Delta m^2, \theta_{12})$ from all solar data

$\Delta m^2_{21}$ in $\text{eV}^2$

$\sin^2(\theta_{12}) = 0.309^{+0.049}_{-0.029}$

$\Delta m^2_{21} = (7.49_{-0.19}^{+0.21}) \times 10^{-5}$ $\text{eV}^2$

$\sin^2(\theta_{12}) = 0.310^{+0.14}_{-0.015}$

$\Delta m^2_{21} = (4.86_{-0.50}^{+1.44}) \times 10^{-5}$ $\text{eV}^2$

$\sin^2(\theta_{12}) = 0.304 \pm 0.013$

$\Delta m^2_{21} = (7.44_{-0.19}^{+0.25}) \times 10^{-5}$ $\text{eV}^2$

KamLAND
Search for SN relic neutrinos

- All of the core collapse supernovae that have exploded throughout the history of the Universe have released neutrinos, which should still be in existence.

- Many SRN models that predict both the flux and the spectrum of anti-neutrino have been constructed.

![SN1987a Credit: X-ray: NASA/CXC/PSU/S.Park & D.Burrows.; Optical: NASA/STScI/CfA/P.Challis](image-url)
Super-K sensitivity

- SK-I+II+III result is only factor 2 higher than models!


SK 1497+794+562 Days
Excluded (E>16MeV)
\( \bar{\nu}_e e^+ \) (90% C.L.)

Models are parameterized in \( T_\nu \) of Fermi-Dirac emission

For LMA model Ando et al., (2005)
Combined 90% C.L.:
< 5.1 ev / yr / 22.5 ktons
< 2.7 /cm2/s (>16 MeV)

Current SK BG (spallation + solar \( \nu \))

BG should be reduced \(~O(10^4)\)
GADZOOKS! Project

Beacom and Vagins, PRL, 93:171101, 2004

- 0.2% Gadolinium sulfate in SK
- Neutron tag (signal) efficiency : 90%
- Background reduction : $2 \times 10^{-4}$

\[ \bar{\nu}_e \rightarrow p + \gamma \quad 2.2\text{MeV} - \gamma\text{-ray} \]

\[ n + p \rightarrow d + \gamma \]

\[ n + \text{Gd} \rightarrow \sim 8\text{MeV} \gamma \]

\[ \Delta T = \sim 30 \mu\text{sec} \]

\[ \bar{\nu}_e \] can be identified by the delayed coincidence technique.
EGADS
Evaluating Gadolinium’s Action on Detector Systems

R&D items

✓ Water purification with gadolinium sulfate
✓ Keep water transparency with gadolinium sulfate
• Effects on Super-K components/materials
• Neutron background and its effects
• Detection efficiency

Done

From Dec.

Main water circulation system
Pre-treatment system

240 PMTs

Transparency measurement
Hiroyuki Sekiya
NOW2012  Sep. 14 2012  @ Conca Specchiulla, Lecce, Italy

pre-treatment system

200 ton tank

15 ton tank for pre-treat

UDEAL

Gd water Circulation system
Status

- Aug. 2011 - Present

Long term stability and quality check

- 0.2% Gd-loaded water circulation (w/o 200t tank)

Selective filtration system uses a molecular size band-pass scheme to filter the water.

Confirmed Gd-kept eff. > 99.9%
Conclusion

- Solar neutrino measurement in Super-K keeps improving.
  - lower threshold, lower BG, smaller errors, and larger statistics
- No significant spectrum distortion.
- Asymmetry in day/night flux @2.3σ, hint of non-zero?
- Neutrino oscillation parameters are updated from global fit;
  - \(\Delta m^2_{12} = 7.44^{+0.2}_{-0.19} \times 10^{-5} \text{eV}^2\), \(\sin^2 \theta_{12} = 0.304 \pm 0.013\),
  - \(\sin^2 \theta_{13} = 0.030^{+0.017}_{-0.015}\)
- Adding 0.2% Gadolinium sulfate to SK, SRN event rate is expected to be 0.8 – 5.0 events/year/22.5kt (10 – 30 MeV)
  - EGADS, the R&D project is ongoing.
  - Neutron tagging efficiency measurement with 200t test tank and 240 PMTs will be done.
Extra slides
Solar neutrinos observation

- Neutrino-electron elastic scattering: $n + e^- \rightarrow n + e^-$
- Solar direction sensitive
- Realtime measurements
  - Energy spectrum
  - Day/night flux differences
  - Seasonal variation

Nuclear fusion reaction deep inside the Sun:

$$4p \rightarrow ^2\text{He} + 2e^+ + 2\nu_e$$
Solar neutrino spectrum

(Bahcall-Pena-Garay-Serenelli 2008)

±X% is theoretical uncertainties

$^7\text{Be}$, pep : integrated flux

$^7\text{B}$ ±5.8%

Super-Kamiokande target

$^{13}\text{N}$ +15% -14%

$^{15}\text{O}$ +16% -15%

$^{17}\text{F}$ +19% -17%

$^8\text{B}$ ±11.3%

hep ±15.5%

Neutrino energy (MeV)

Neutrino Flux (cm$^{-2}$/sec/MeV)
Total solar neutrino event

- best fit: $0.451 \pm 0.007$

- about 19,000 events more than from pure $\nu_e$
- small systematic uncertainty
- rate is consistent between all the SK phases
Allowed oscillation parameter region from Day/Night data

The best constraint of $\Delta m^2_{12}$ among all solar neutrino measurements
Day/Night amplitude fits as a function of $\Delta m^2$
Day/Night variation

Expected rate variation
Earth “matter” model

we assumed this kind of zenith angle shape from the neutrino oscillation parameter, and fit to the data.

Day/Night Asym.:
$$A_{DN} = 2(\varphi_D - \varphi_N)/(\varphi_D + \varphi_N)$$

<table>
<thead>
<tr>
<th>Phase</th>
<th>D/N amplitude</th>
<th>$A_{DN}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>-2.0±1.7±1.0%</td>
<td>-2.1±2.0±1.3%</td>
</tr>
<tr>
<td>SK-II</td>
<td>-4.3±3.8±1.0%</td>
<td>-6.3±4.2±3.7%</td>
</tr>
<tr>
<td>SK-III</td>
<td>-4.3±2.7±0.7%</td>
<td>-5.9±3.4±1.3%</td>
</tr>
<tr>
<td>SK-IV</td>
<td>-2.8±1.9±0.7%</td>
<td>-5.2±2.3±1.4%</td>
</tr>
<tr>
<td>SK comb.</td>
<td>-2.8±1.1±0.5%</td>
<td>-4.0±1.3±0.8%</td>
</tr>
</tbody>
</table>

from Phys.Rev. D69 011104 (2004): $\Delta m_{21}^2 = 6.3 \times 10^{-5} \text{eV}^2$
Only SNO

\[ \Delta \chi^2 \]

\[ \Delta m^2_{21} \text{ in eV}^2 \]

\[ \sin^2(\Theta_{12}) = 0.309_{-0.029}^{+0.040} \]
\[ \sin^2(\Theta_{12}) = 0.321_{-0.027}^{+0.017} \]
\[ \sin^2(\Theta_{12}) = 0.309 \pm 0.016 \]
\[ \Delta m^2_{21} = (7.49_{-0.19}^{+0.27}) \times 10^{-5} \text{eV}^2 \]
\[ \Delta m^2_{31} = (4.93_{-0.03}^{+0.02}) \times 10^{-5} \text{eV}^2 \]
\[ \Delta m^2_{31} = (7.48_{-0.02}^{+0.02}) \times 10^{-5} \text{eV}^2 \]

KamLAND
Super-K + SNO

\[ \sin^2(\theta_{12}) = 0.309^{+0.040}_{-0.029} \]
\[ \sin^2(\theta_{12}) = 0.317^{+0.016}_{-0.014} \]
\[ \sin^2(\theta_{12}) = 0.309^{+0.014}_{-0.014} \]

\[ \Delta m_{21} = (7.49^{+0.21}_{-0.19}) \times 10^{-5} \text{eV}^2 \]
\[ \Delta m_{31} = (4.85^{+1.44}_{-0.54}) \times 10^{-5} \text{eV}^2 \]
\[ \Delta m_{31} = (7.44^{+2.26}_{-0.18}) \times 10^{-5} \text{eV}^2 \]

allowed regions much smaller
$(\Delta m^2_{12}, \theta_{12})$ from Only Super-K

$\phi^8B = (5.25 \pm 0.20) \times 10^6/(\text{cm}^2 \cdot \text{sec})$
For each PMT hit pair, the vectors to the Cherenkov ring cross points are the direction candidates.

- MSG = vector sum of the candidates/ scalar sum of the candidates
- MSG of multiple scattering events should be small
Super-K water transparency

@ Cherenkov light wavelength
Measured by decay $e^-e^+$ from cosmic $\mu^-\mu^+$

- anti-correlated with Supply water temperature
- Started automatic temperature control

SK-III  SK-IV
Convection suppression in SK

- Very precisely temperature-controlled (±0.01°C) water is supplied to the bottom.

![Diagram showing convection suppression and event distribution](image)

3.5MeV-4.5MeV Event distribution

Temperature gradation in Z
The difference is only 0.2 °C
Current SK situation

- Stagnation and top-bottom asymmetry.
SRN models

- Cosmology (cosmic star formation history, initial mass function, Hubble expansion, etc) is established, so we can simply parameterize with:
  - $\bar{\nu}_e$ luminosity of typical supernova
  - Average $\bar{\nu}_e$ energy $\rightarrow \bar{\nu}_e$ Temp. (Fermi-Dirac emission)
BG Cherenkov angle distribution

- Dominant BGs are atmospheric $\nu_e \nu_\mu$ CC

  **Low angle events**

  $\mu, \pi$

  25-45°

  **Signal region**

  $\nu_e p \rightarrow e^+ n$ (invisible)

  42°

  **Isotropic region**

  reconstructed angle near 90°

- SK-I data/MC

- Signal+BG fitting

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NOW2012 Sep. 14 2012 @Conca Specchiulla, Lecce, Italy
Gd-loaded water transparency

Cherenkov light left at 15m

Usual SK pure water quality

Worst SK pure water quality used for physics analysis

0.2% Gd-loaded water is OK for Cherenkov detector