Solar Neutrino Results from Super-Kamiokande

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Super-Kamiokande

Features of SK detector

- Large water Cherenkov detector with **50kt ultra pure water**.
- **22.5 kt fiducial volume**.
- **1 km** under the Ikenoyama mountain in Japan (**2700 mwe**).

- **~11,000 of 20” PMT** for inner detector (ID).
  - 40% photocathode coverage
  - SK-II: Half PMT and coverage
- **1885 of 8” PMT** for outer detector (OD).
- Reconstruction of energy, direction and PID is possible.
From April of 1996, the Super-K accumulated atm./solar $\nu$ events, searched for nucleon decay, cooperated with $\nu$ beam exp., and made improvement over 20 years.

Further detector upgrade by loading Gd is planned for SRN (DSBN) discovery (SK-Gd talk at $13^{\text{th}}$, by L. M. Magro).

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Typical low-energy event

Super-Kamiokande
Run 1742 Event 102496
96-05-31:07:13:23
Inner: 103 hits, 123 pE
Outer: -1 hit, 0 pE (in-time)
Trigger ID: 1e03
E= 9.086 GeV-0.77 C0SsUN- 0.949
Solar Neutrino

\[ \nu + e^- \rightarrow \nu + e^- \]
(for solar neutrinos)

- Timing information
- Ring pattern
- Number of hit PMTs
- Energy

Time(ns)
- < 815
- 815 - 835
- 835 - 855
- 855 - 875
- 875 - 895
- 895 - 915
- 915 - 935
- 935 - 955
- 955 - 975
- 975 - 995
- 995-1015
- 1015-1035
- 1035-1055
- 1055-1075
- 1075-1095
- \( >1095 \)

(color: time)

\( E_{e, total} = 9.1 \text{ MeV} \)
\( \cos \theta_{\text{sun}} = 0.95 \)

Resolutions (for 10MeV electrons)

Energy: 14%  Vertex: 87cm  Direction: 26° SK-I
Energy: 14%  Vertex: 55cm  Direction: 23° SK-III

~6 hit / MeV (SK-I, III, IV)

(software improvement)
Solar Neutrino

- The Sun is burning with nuclear fusion reactions, called pp-chain and CNO-cycle, emitting neutrinos.
- Only neutrinos can bring out the information of “today’s” status of solar center.

- Their fluxes are predicted by the standard solar model (SSM).
- Super-K is sensitive to $^8B$ (and hep) neutrinos. ~18 events/day (SK-IV)
Physics of Solar Neutrino

Spectrum distortion

Super-K can search for the spectral upturn expected by neutrino oscillation MSW effect. New physics beyond SM can exist. e.g. sterile $\nu$, NSI

\[
\frac{d}{dt} \left( \frac{\nu_e}{\nu_\mu} \right) = \left( -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2} G_F N_e \frac{\Delta m^2}{4E} \sin 2\theta \right) \left( \frac{\Delta m^2}{4E} \sin 2\theta \right) \left( \frac{\Delta m^2}{4E} \cos 2\theta \right) \left( \frac{\nu_e}{\nu_\mu} \right)
\]

Day/Night flux asymmetry

Due to the earth matter effect, electron neutrino is regenerated. The $^8$B flux during night is higher than that during day.

Recent progress in solar \(\nu\) analysis

- **Solar neutrino observation**
  - Flux measurement, Yearly plot
  - Total live time 5200 days (May 1996 - March 2016)
  - SK-I (1496 days), SK-II (791 days), SK-III (548 days), SK-IV (2365 days (- Mar. 2016), PRD94, 052010: 1664 days)

- **Updated spectrum analysis (preliminary)**
  - + 280 days until March 2017. Total live time 5480 days.
  - SK-I to III and **2645 days (-Mar. 2017)** of SK-IV

- **Preliminary periodic modulation analysis in SK-IV**
  - Using same data set as PRD94, 052010
Observed solar $\nu$ signal

<table>
<thead>
<tr>
<th>SK phase</th>
<th>Energy threshold [MeV(kin)]</th>
<th>Live time [day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK I</td>
<td>4.5-19.5</td>
<td>1496</td>
</tr>
<tr>
<td>SK II</td>
<td>6.5-19.5</td>
<td>791</td>
</tr>
<tr>
<td>SK III</td>
<td>4.0-19.5</td>
<td>548</td>
</tr>
<tr>
<td>SK IV</td>
<td>3.5-19.5</td>
<td>2365 (- '16)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2645 (- '17)</td>
</tr>
</tbody>
</table>

- Data/MC (un-oscillated) = 0.4486±0.0062 (- March 2016).
- Super-K solar rate measurements are consistent with a constant solar neutrino flux emitted by the Sun in all SK phases.
$^8$B solar $\nu$ flux yearly plot

For the constant flux assumption, $\chi^2 = 15.52/19$ D.O.F (Mar. 2016).
The probability is 68.9%. (preliminary).
No significant correlation with the solar activity is seen.

Solar activity cycle
The solar activity cycle of ~11 years is observed with sun spot numbers.

SK has observed the solar neutrino for ~19 years, i.e. > 1.5 cycles.
Data set for oscillation analysis

- **SK:** PRD94,052010(2016) + preliminary SK-IV spectrum data
  - SK-I 1496 days, spectrum 4.5-19.5MeV(kin) + D/N : E ≥ 4.5MeV(kin)
  - SK-II 791 days, spectrum 6.5-19.5MeV(kin) + D/N : E ≥ 7.0MeV(kin)
  - SK-III 548 days, spectrum 4.0-19.5MeV(kin) + D/N : E ≥ 4.5MeV(kin)
  - SK-IV 2645 days, spectrum 3.5-19.5MeV(kin) (-Mar. 2017) + D/N (1664days) : E ≥ 4.5MeV(kin)

- **SNO:** PRC88,025501 (2013)

- Radiochemical : Cl, Ga
  - Cl rate: 2.56+/-0.23 SNU (Astrophys. J. 496, 505 (1998))

- Borexino : \(^7\)Be flux (PRL107, 141302 (2011))


- \(^8\)B spectrum : Winter 2006 (PRC73, 025503 (2006))

- \(^8\)B and *hep* flux free, if not mentioned.
All SK phases are combined without regards to energy resolution or systematics in this figure.

**SK spectrum is consistent within ~1 sigma with the MSW upturn for the solar best fit parameters, and marginally consistent within ~2 sigma with the MSW upturn for the solar+KamLAND best fit parameters.**
Periodic modulation analysis in SK-IV

- SK-I 1496 days, 4.5-19.5 MeV(kin)
- Used Lomb-Scargle (LS) and 5-day long samples
- It is pointed out that a maximum peak is observed at around 9.43/year from several researchers.
- Analysis techniques are improved
- We have reanalyzed SK-I data with Generalized LS method in astroML.
- A preliminary search in SK-IV in 5~15/year region is also done.

false alarm probability (FAP) = 0.015
Periodic modulation analysis in SK-IV

- Data set:
  - SK-I: 1496 days, 5-day long sample, 4.5-19.5 MeV(kin)
  - SK-IV: 1664 days, 5-day long sample, 4.5-19.5 MeV(kin)
  - Generalized LS method (with symmetric error)
  - Search region: 5 – 15 [/year]

Lomb power

- Maximum peak at around 9.43 /year is not found in SK-IV.

Frequency [/year]
Summary

- Solar (and Supernova) neutrinos are main astrophysical targets in low-energy region in SK.
- Partial preliminary results are reported.
  - SK-IV 2365 days (-2016), 2645 days (-2017) observation
  - SK-IV 2645 days spectrum
  - SK-IV 1664 days periodic modulation analysis
- Improvements of analysis are on going.
  - PMT-dependent gain correction in energy scale
  - Improved cuts for spallation BG
- Detector upgrade work for SK-Gd at 2018.
  - “SuperK-Gd” presented by L. Marti-Magro, at 13th July.
Super-Kamiokande Experiment

1996, Start of Super-K experiment
(Energy threshold 4.5 MeV_{kin} for solar \nu)

From April of 1996, the Super-K accumulated atm./solar \nu events, searched for nucleon decay, cooperated with \nu beam exp. and made improvement over 20 years!

2002, SK-II reconstruction.
FRP + acryl case installed.
(threshold 4.0 MeV_{kin})

2006, SK-III fully recon.
(threshold 4.5 MeV_{kin})

2008, SK-IV DAQ electronics update.
(threshold 3.5 and 2.5 MeV_{kin})

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K2K far detector

SK-I

1996

SK-II

2001 ‘02

SK-III

2001 ‘05 ‘06

SK-IV

2001 ‘08

T2K far detector

Today

‘99 ‘04 ‘09

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Solar neutrino measurements in SK

**Figure 1:**
- **Expected Solar+KamLAND**
- **Expected Solar global**
- **Observed SK+SNO**

**Figure 2:**
- **Observed** vs. **Expected** Solar global and Solar+KamLAND
- **Recoil electron kinetic energy (MeV)**

**Figure 3:**
- **Expected Solar+KamLAND**
- **Expected Solar global**
- **Exponential** & **quadratic fit**
- **Cubic fit**

**Figure 4:**
- **Expected (MSW)**
- **Observed** SK D/N

**Figure 5:**
- **Solar +KamLAND**
- **Solar global**

**Figure 6:**
- **PRD94, 052010**
- **Amplitude** $|\sin^2(\theta_{12})| = 0.319 \pm 0.003$ 10^{-5} eV^2 $\Delta m_{s}^{2} = 7.5 \pm 1.5$ 10^{-5} eV^2 $\Delta m_{s}^{2} = 4.85 \pm 0.03$ 10^{-5} eV^2 $\Delta m_{s}^{2} = 7.46 \pm 0.03$ 10^{-5} eV^2

**Figure 7:**
- **PRD94, 052010**
- **Expected Solar global**

**Figure 8:**
- **PRL112, 091805**
- **Solar global**
- **Expected (MSW)**
- **Observed SK D/N**

**Figure 9:**
- **PRD94, 052010**
- **Expected Solar global**
- **Expected Solar+KamLAND**
- **Recoil electron kinetic energy (MeV)**

**Figure 10:**
- **PRD94, 052010**
- **Expected Solar global**
Solar neutrino measurements in SK

**Expected (MSW)**
- Expected Solar+KamLAND
- Expected Solar global

**Observed SK+SNO**
- PRD94, 052010
- PRL112, 091805

**Statistical error dominates**
- Expected from Solar global
- Expected from Solar+KamLAND

**Flux in keVcm^2s**

**Recoil electron kinetic energy (MeV)**

**Data/MC (unoscillated)**

**Day/Night Asymmetry (%)**

**Δm^2_{21} (10^{-5} eV^2)**

**PP, 7Be, pep, CNO, 8B, Hep**
Whole area in these plots corresponds to 22.5 kton.

Above 5.0 MeV(kin), fiducial volume is 22.5kton.

Below 5.0 MeV tight fiducial volume cut is applied.

Water condition is controlled well.
SK-IV solar neutrino signal

Signal (in SK-IV): 51521 ±349 –347 events
(SK-I: 22404, SK-II: 7212, SK-III: 8148)
Total: 89285 events
SK-IV solar neutrino energy spectrum

Data/MC (unoscillated)

Recoil electron kinetic energy [MeV]

(MC flux = 5.25x10^6 cm^2/s from SNO NC)
Astrophysical neutrinos at SK (in Low-E)

- Solar neutrinos
  - Neutrino oscillation
    - Solar MSW
    - Terrestrial MSW
      - Tension among solar nue and reactor nue-bar
  - Solar astrophysics
    - Time variation
- Supernova neutrinos
  - Burst
  - Relic (DSNB)