RECENT RESULTS AND FUTURE PROSPECTS OF SUPER-KAMIOKANDE

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Inside of SK detector during refurbishment work (July 15, 2018)
Super-Kamiokande collaboration

10 nations, ~45 institutions, ~180 researchers (as of July 2018)

http://www-sk.icrr.u-tokyo.ac.jp/library/pamphlet.html (as of June 2016)
Toyama city

~30km

Office buildings
(~280m ASL)

~1km overburden

Ikeno-yama
(1369m ASL)

Under ground experimental area
(2700 m water equivalent (m.w.e.))

Atotsu entrance

Old Mozumi entrance

~30km

2km

3km

3km
**Kamioka Underground site**

- **A01/C02: KamLAND**
- **B01/C02: XMASS**
- **A02: CANDLES**
- **C02: Super-Kamiokande**
- **C01: SK-Gd water system**
- **B02: NEWAGE**
- **D01: Low-radioactivity R&D (LAB-A, 2015~)***

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**“Revealing the history of the universe with underground particle and nuclear research”**

- **A: Majorana ν**
  - A01: KamLAND, A02: CANDLES
- **B: Dark matter**
  - B01: XMASS, B02: NEWAGE, ...
- **C: Supernova ν**
  - C01: SK-Gd, C02: SN network
- **D01: Low BG techniques**
- **E01: Theory**

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**Related Websites**

- [http://www-sold.sold.st.kaikai.ac.jp/](http://www-sold.sold.st.kaikai.ac.jp/)
- [http://www.lowbg.org/ugnd/](http://www.lowbg.org/ugnd/)
Super-Kamiokande detector

- 50 kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt ID viewed by 20-inch PMTs
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- Refurbishment work is ongoing

Physics targets:
- Nucleon decay search
- Neutrino oscillation study
- Astrophysical neutrino search

Inner Detector (ID) PMT: ~11100 (SK-I, III, IV), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

http://www-sk.icrr.u-tokyo.ac.jp/sk/
History & Plan of Super-Kamiokande

**SK-I**
- 11146 ID PMTs (40% coverage)
- 4.5 MeV, 1496 days

**SK-II**
- 5182 ID PMTs (19% coverage)
- 6.5 MeV, 791 days

**SK-III**
- 11129 ID PMTs (40% coverage)
- 4.5 MeV, 548 days

**SK-IV**
- Electronics Upgrade
  - 3.5 MeV, 2860 days

- **Start upgrade for SK-Gd**

- **Neutron tagging with Gd**

- **Analysis energy threshold (recoil electron kinetic energy)**
- **Live time for solar neutrino analysis**

- Current total: 5695 days

- **Water system**
  - For SK-Gd

- **Acrylic (front) + FRP (back)**

- **Present**
  - **2022**
Summary of recent results

- **Nucleon decay search**
  - PRD96, 012003 (2017): SK 316 kt·yr
    - $\tau/B(p\rightarrow e^+ \pi^0) > 2.0 \times 10^{34}$ years (90%CL, preliminary)

- **Atmospheric $\nu$ oscillation analysis**
  - PRD97, 072001 (2018): SK 5326 days, 328 kt·yr
  - arXiv: 1711.09436: $\nu_\tau$ app. = 338.1 +/- 72.7 events (4.6 $\sigma$, 5326 d)

- **Solar $\nu$ oscillation analysis**
  - Current data set: SK 5695 days (SK-IV: until Dec. 2017, 2860 d)

- **Astrophysics**
  - Gravitational Wave source searches (GW170817)
  - WIMP searches (Sun, Earth, Galactic center)
  - Supernova neutrinos (burst, relic)
Atmospheric neutrino results
Typical high-energy events

Atmospheric $\nu$: Partially contained (PC)

Atmospheric $\nu$: Fully contained (FC)

(color: charge)

$\mu$-like $3.5\text{GeV/c}$

e-like $0.4\text{GeV/c}$
Zenith angle & lepton momentum distributions

m-like

\( \cos \) zenith

\( \text{Data/MC} \)

Oscillated MC (normal hierarchy, best fit)
Atm. $\nu$ oscillation results: mass ordering

SK + T2K(model) with $\sin^2 \theta_{13} = 0.0219 \pm 0.0012$

![Graphs showing $\Delta \chi^2$ vs. $|\Delta m_{32}^2|$, $|\Delta m_{31}^2|$, and $\sin^2 \theta_{23}$, with contours at 99%, 95%, and 68% confidence levels.]

FIG. 16. Constraints on neutrino oscillation contours from a combined fit of Super-K atmospheric neutrino data and a model of the T2K experiment assuming $\sin^2 \theta_{13} = 0.0219 \pm 0.0012$. Orange lines denote the inverted hierarchy result, which has been offset from the normal hierarchy result, shown in cyan, by the difference in their minimum $\chi^2$ values.

$$\Delta \chi^2 = \chi_{NH,min}^2 - \chi_{IH,min}^2 = -5.27$$

Over the range of parameters allowed at 90% confidence level, the normal mass hierarchy is favored by between 91.9% and 94.5% based on the combined Super-Kamiokande plus T2K result.

(CL_s technique [J. Phys. G 28, 2693 (2002)] is used)
Atm. $\nu$ oscillation results: parameters

**SK 5326 days**

PRD97, 072001 (2018)

$\Delta m_{32}^2$ [eV$^2$]

<table>
<thead>
<tr>
<th>$\sin^2 \theta_{23}$</th>
<th>Normal Hierarchy, 90% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Super-K</td>
</tr>
<tr>
<td></td>
<td>T2K</td>
</tr>
<tr>
<td></td>
<td>NOvA (2018 winter)</td>
</tr>
<tr>
<td></td>
<td>IceCube</td>
</tr>
<tr>
<td></td>
<td>MINOS</td>
</tr>
</tbody>
</table>

**SK only, normal hierarchy, $\theta_{13}$ constrained**

\[
\sin^2 \theta_{23} = 0.588^{+0.031}_{-0.064}
\]

\[
|\Delta m_{32}^2| = (2.50^{+0.13}_{-0.20}) \times 10^{-3} \text{eV}^2
\]

**TABLE V.** Summary of parameter estimates for each analysis and hierarchy hypothesis considered. Here NH (IH) refers to the normal (inverted) hierarchy fit. The terms “free” and “constrained” refer to fits without and with a constraint on $\sin^2 \theta_{13}$, respectively, as described in the text. The expected absolute $\chi^2$ value for the SK (SK + T2K) fits is 559.9 (636.2). The p-value for obtaining a smaller $\chi^2$ than the data is 0.439 (0.482) in the NH $\theta_{13}$-constrained fits.

| Fit                  | Hierarchy | $\chi^2$ | $\sin^2 \theta_{13}$ | $\sin^2 \theta_{23}$ | $|\Delta m_{32,31}^2| \times 10^{-3} \text{eV}^2$ | $\delta_{CP}$ |
|----------------------|-----------|----------|-----------------------|-----------------------|-----------------------------------------------|--------------|
| SK $\theta_{13}$ Free | NH        | 571.29   | 0.018$^{+0.029}_{-0.013}$ | 0.587$^{+0.036}_{-0.069}$ | 2.50$^{+0.13}_{-0.31}$                         | 4.18$^{+1.45}_{-1.66}$ |
|                      | IH        | 574.77   | 0.008$^{+0.017}_{-0.007}$ | 0.551$^{+0.044}_{-0.075}$ | 2.20$^{+0.33}_{-0.13}$                         | 3.84$^{+2.38}_{-2.12}$ |
| SK $\theta_{13}$ Constrained | NH | 571.33 | - | 0.588$^{+0.031}_{-0.064}$ | 2.50$^{+0.13}_{-0.20}$ | 4.18$^{+1.41}_{-1.61}$ |
|                      | IH        | 575.66   | - | 0.575$^{+0.036}_{-0.073}$ | 2.50$^{+0.08}_{-0.37}$ | 4.18$^{+1.52}_{-1.66}$ |
| SK + T2K $\theta_{13}$ Constrained | NH | 639.43 | - | 0.550$^{+0.039}_{-0.057}$ | 2.50$^{+0.05}_{-0.12}$ | 4.88$^{+0.81}_{-1.48}$ |
|                      | IH        | 644.70   | - | 0.550$^{+0.035}_{-0.051}$ | 2.40$^{+0.13}_{-0.05}$ | 4.54$^{+1.05}_{-0.97}$ |
Solar neutrino results
Typical low-energy event

Super-Kamiokande

Run 1742 Event 102496
96-25-31 07:13:13
Insc: 109 hits, 121 pE
Outer: 4 hits, 0 pE [in-time]
Trigger ID: 0x03
E = 9.08 eV EGM=0.77 EGSUN= 0.949
Solar Neutrino

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

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

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

\( \approx 6 \text{ hit / MeV} \)
(SK-I, III, IV)

Resolutions (for 10 MeV electrons)

<table>
<thead>
<tr>
<th>Component</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>14%</td>
</tr>
<tr>
<td>Vertex</td>
<td>87 cm</td>
</tr>
<tr>
<td>Direction</td>
<td>26° SK-I</td>
</tr>
<tr>
<td>Energy</td>
<td>14%</td>
</tr>
<tr>
<td>Vertex</td>
<td>55 cm</td>
</tr>
<tr>
<td>Direction</td>
<td>23° SK-III, IV</td>
</tr>
</tbody>
</table>

(color: time)

Time(ns)
- < 815
- 815-835
- 835-855
- 855-875
- 875-915
- 915-935
- 935-965
- 955-975
- 975-995
- 995-1015
- 1015-1035
- 1035-1055
- 1055-1075
- 1075-1095
- >1095

 OD
 ID

Software improvement
Signal (in SK-IV): 55729 +363 –361 events
Total: ~93000 solar $\nu$ events (in SK-I~IV)
Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.

$\chi^2 = 21.57 / 21$ d.o.f. $\Rightarrow$ Confidence level = 41.4%

Averaged $^8\text{B}$ flux with no oscillation
= (2.33+/-0.04) x10$^6$/cm$^2$/s
# Solar ν oscillation results

- Quadratic fit of SK spectrum is consistent with solar $\Delta m_{21}^2$ within ~1.2 $\sigma$ and disfavors KamLAND $\Delta m_{21}^2$ by ~2.0 $\sigma$.
- ~2.0 $\sigma$ level tension in $\Delta m_{21}^2$ between solar global analysis and KamLAND is still remaining.

## Solar ν energy spectrum

### SK I/II/III/IV LMA Spectrum

- **Solar+KamLAND parameter**
- **Solar global parameter**
- **Quadratic spectrum best-fit**
- **Exponential spectrum best-fit**

### Recoil electron kinetic energy [MeV]

<table>
<thead>
<tr>
<th>Data/Simulation (with no oscillation)</th>
<th>$\Delta m_{21}^2$ in $10^{-5}$eV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 - 6</td>
<td>5 - 10</td>
</tr>
<tr>
<td>6 - 8</td>
<td>10 - 15</td>
</tr>
<tr>
<td>8 - 10</td>
<td>15 - 30</td>
</tr>
<tr>
<td>10 - 12</td>
<td></td>
</tr>
<tr>
<td>12 - 14</td>
<td></td>
</tr>
<tr>
<td>14 - 16</td>
<td></td>
</tr>
<tr>
<td>16 - 18</td>
<td></td>
</tr>
</tbody>
</table>

## Solar ν oscillation parameters

### Solar + KamLAND:

- $\sin^2 \theta_{12} = 0.310 \pm 0.012$
- $\Delta m_{21}^2 = (7.49^{+0.19}_{-0.17}) \times 10^{-5}$eV$^2$

### Solar + KamLAND

- Filled region: 3$\sigma$

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**Very Preliminary**

Apr 2018

Preliminary

SK 5695 days
Future prospects (SK-Gd)
Next step: SK-Gd Phase

SK-Gd Phase:
Add gadolinium (Gd) to enhance neutron tagging efficiency of the SK detector.

Physics targets:
- Detect the world’s first Supernova Relic Neutrinos (SRN) (or Diffuse Supernova Neutrino Background, DSNB)
- Improve pointing accuracy for supernova
- Early warning of nearby supernova from pre-burst signal (silicon burning)
- Enhance $\nu$ or $\bar{\nu}$ discrimination in atmospheric $\nu$ & T2K analysis
- Reduce backgrounds in proton decay search

SK refurbishment is ongoing since June 2018
- Fix water leakage
- Replace dead PMTs
- Improve water piping in the SK detector

Capture efficiencies in water
- 0.01% Gd $[\text{Gd}_2(\text{SO}_4)_3$ 10t] : $\sim$50%
- 0.1% Gd $[\text{Gd}_2(\text{SO}_4)_3$ 100t] : $\sim$90%
SK-Gd: Expected sensitivity

DSNB flux:

- It depends on typical/actual SN emission spectrum

DSNB events number with 10 years observation

<table>
<thead>
<tr>
<th>HBD models</th>
<th>10-16MeV (evts/10yrs)</th>
<th>16-28MeV (evts/10yrs)</th>
<th>Total (10-28MeV)</th>
<th>significance (2 energy bin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{eff}}$ 8MeV</td>
<td>11.3</td>
<td>19.9</td>
<td>31.2</td>
<td>5.3 $\sigma$</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ 6MeV</td>
<td>11.3</td>
<td>13.5</td>
<td>24.8</td>
<td>4.3 $\sigma$</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ 4MeV</td>
<td>7.7</td>
<td>4.8</td>
<td>12.5</td>
<td>2.5 $\sigma$</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ SN1987a</td>
<td>5.1</td>
<td>6.8</td>
<td>11.9</td>
<td>2.1 $\sigma$</td>
</tr>
<tr>
<td>BG</td>
<td>10</td>
<td>24</td>
<td>34</td>
<td>----</td>
</tr>
</tbody>
</table>
## SK-Gd: Current plan

<table>
<thead>
<tr>
<th>FY2018</th>
<th>FY20XX</th>
<th>FY20XX</th>
<th>FY201XX</th>
<th>FY201XX</th>
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<tbody>
<tr>
<td><img src="image1" alt="T0" /></td>
<td><img src="image2" alt="T0" /></td>
<td><img src="image3" alt="T0" /></td>
<td><img src="image4" alt="T0" /></td>
<td><img src="image5" alt="T0" /></td>
</tr>
<tr>
<td>Water filling &amp; purification</td>
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<td>Water filling &amp; purification</td>
</tr>
<tr>
<td><img src="image6" alt="T1" /></td>
<td><img src="image7" alt="T1" /></td>
<td><img src="image8" alt="T1" /></td>
<td><img src="image9" alt="T1" /></td>
<td><img src="image10" alt="T1" /></td>
</tr>
<tr>
<td>Pure water Observation</td>
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<td>Pure water Observation</td>
<td>Pure water Observation</td>
</tr>
<tr>
<td><img src="image11" alt="T2" /></td>
<td><img src="image12" alt="T2" /></td>
<td><img src="image13" alt="T2" /></td>
<td><img src="image14" alt="T2" /></td>
<td><img src="image15" alt="T2" /></td>
</tr>
<tr>
<td>Normal run</td>
<td>Normal run</td>
<td>Normal run</td>
<td>Normal run</td>
<td>Normal run</td>
</tr>
</tbody>
</table>

- **T₀**: Start SK detector refurbishment (May 31, 2018)
  - Jan. 2019 ~: pure water run
- **T₁**: Load first 10 ton Gd$_2$(SO$_4$)$_3$ [0.01% Gd, 50% eff.]
  - First possible T₁ is late 2019 (will be decided with T2K/J-PARC ν beam)
- **T₂**: Load additional 90 ton Gd$_2$(SO$_4$)$_3$ [0.1% Gd, 90% eff.]
Refurbishment of SK detector: 1/2

May 31, 2018
Open ID inspection hole

Use a gondola to access inside SK detector

Inner Detector (ID) Top

Replacement of ID PMTs at Detector Barrel
Refurbishment of SK detector: 2/2

Improvement of water piping in Outer Detector (OD)

Replacement of OD PMTs

Improvement of water sealing in OD

Inner Detector
July 15, 2018
Super-Kamiokande (SK) is a 50-kton water Cherenkov detector located 1,000 m underground in Japan.

SK is providing various unique results since 1996, for more than 20 years.

- neutrino oscillation parameters, nucleon decay searches, astrophysical neutrino searches, ...

The refurbishment of the SK detector for the next phase (SK-Gd) is started in June 2018.

The main physics target in SK-Gd phase is the first observation of supernova relic neutrinos.