SK RESULTS ON SOLAR NEUTRINO AND PROSPECTS WITH HK

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Inside of SK detector during refurbishment work (July 15, 2018)
Outline

- SK detector
- Solar neutrinos
- Recent results from SK
- Prospects with HK
- Summary
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~
- SK-V is running
- For Solar $\nu$: $\nu_x + e^- \rightarrow \nu_x + e^-$

**Inner Detector (ID) PMT:** ~11100 (SK-I,III,IV,V), ~5200 (SK-II)

**Outer Detector (OD) PMT:** 1885
**History & Plan of Super-Kamiokande**

**SK-I**
- 11146 ID PMTs (40% coverage)
- 4.5 MeV
- 1496 days
- Analysis energy threshold (recoil electron kinetic energy)
- Live time for solar neutrino analysis

**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 (~Dec. 2017)

**SK-V → SK-Gd**
- Neutron tagging with Gd
- Current total: 5695 days

- SK-I: Acrylic (front) + FRP (back)
- SK-II: Aug-2002
- SK-III: Apr-2006
- SK-IV: Water system For SK-Gd

- E$_\nu$ → p, n, p, γ, 2.2 MeV
- E$_{γ}$ → γ, 8 MeV
Typical low-energy event

Super-Kamiokande
Run 1E42 Event 102496
E=35-41:13:33
Inner: 103 hits, 123 pE
Outer: 1 hit, 0 pE (in-time)
Trigger ID: 1e03
E = 9.046 GER=0.77 XSSUN= 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

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

Resolutions (for 10 MeV electrons)

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

- Energy: 14%
- Vertex: 55cm
- Direction: 23° SK-III, IV, V

(software improvement)
Low-energy backgrounds in SK-I

Spallation is dominant BG source in ~6.5-20MeV

Solar ν data reduction in SK-I (in 2m fiducial volume, 22.5kt)

○ After noise reduction
△ After spallation cut
▼ After ambient BG reduction
■ Final data sample

SK-I: PRD73, 112001

2m from wall

Low-e vertex dist.

Solar ν signal

Removal of spallation products

Number of events/day/22.5kt/0.5MeV

Recoil electron total energy (MeV)
Vertex distribution in SK-IV

- Whole area in these plots corresponds to 22.5kton
- Above 5.0MeV(kinetic energy), fiducial volume is 22.5kton
- Below 5.0 MeV(kinetic), tight fid. vol. cut is applied.

Color: Events/day/bin low→high

- Z>[7.5[m] (16.5kt)
- 4.5-5.0MeV(kinetic)
- 4.0-4.5MeV(kinetic)
- 3.5-4.0MeV(kinetic)
- (8.8kt)

SK-IV 2645 days

Preliminary

June 2017
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Solar neutrino

4p $\rightarrow$ $^4$He + 2e$^+$ + 2$\nu_e$ + 25MeV

- Standard Solar Model (SSM) predicts neutrino fluxes
- Most strong $\nu$ source on Earth at Earth: $\sim$66 billion $\nu$/sec/cm$^2$
- Photon: only surface
- $\nu$: direct observation of interior of the present Sun

The Sun seen with neutrinos in SK. The coordinate system in which the Sun is places at the center is used. Color means event rates.
**Solar neutrinos in SSM**

**Overall reaction:** \( 4p \rightarrow ^4He + 2e^+ + 2\nu_e + 25\text{MeV} \)

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**p-p chain**

\[
p^+ + p^- \rightarrow ^2H + e^- + \nu_e \quad \text{99.77\%} \\
^2H + p^- \rightarrow ^3He + \gamma \quad \text{15.08\%} \\
^3He + p^+ \rightarrow ^4He + e^+ + \nu_e \quad \text{0.23\%} \\
^7Be + e^- \rightarrow ^7Li + \nu_e \quad \text{99.9\%} \\
^7Li + p^+ \rightarrow ^4He + ^4He + 2p^+ \quad \text{84.92\%} \\
^3He + ^3He \rightarrow ^4He + 2p^+ \\
^7Be + ^7Be \rightarrow ^8B + ^8B \\
^8B \rightarrow ^8Be^* + e^- + \nu_e \\
^8Be^* \rightarrow ^4He + ^4He \\
\]

**CNO cycle**

\[
15N + p^+ \rightarrow ^{12}C + ^4He \\
^15O \rightarrow ^{15}N + e^+ + \nu_e \\
^15N + p^+ \rightarrow ^{16}O + \gamma \\
^16O + e^- \rightarrow ^{15}N + \nu_e \\
^{13}C + p^+ \rightarrow ^{13}N + \gamma \\
^{13}O \rightarrow ^{13}C + e^+ + \nu_e \\
^{16}O + p^+ \rightarrow ^{17}F + \gamma \\
^{17}F \rightarrow ^{17}O + e^+ + \nu_e \\
^{17}F + e^- \rightarrow ^{17}O + \nu_e \\
^{13}C + p^+ \rightarrow ^{14}N + \gamma \\
^{14}N + p^+ \rightarrow ^{15}O + \gamma \\
^{17}O + p^+ \rightarrow ^{14}N + ^4He \\
\]

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**Solar fusion cross sections:** SF-II (Rev. of Mod. Phys. 83 (2011) 195)


**Problem:** Solar abundances: GS98 (High metallicity), AGSS09 (Low metallicity)

http://upload.wikimedia.org/wikipedia/commons/a/a5/Proton_proton_cycle.png
http://upload.wikimedia.org/wikipedia/commons/f/fe/Cno_cycle.png
FIG. 7 (color online). Solar neutrino fluxes based on the “OP” calculations of Bahcall et al. (2005), with the addition of the new line features from CNO reactions. Line fluxes are in cm$^{-2}$ s$^{-1}$ and spectral fluxes are in cm$^{-2}$ s$^{-1}$ MeV$^{-1}$. From Stonehill et al., 2004.
Solar neutrinos at SK/HK

- High statistics measurement of $^8$B solar neutrinos
- Possible time variation of the flux
- Energy spectrum distortion due to solar matter effect
- Day-night flux asymmetry due to earth matter effect

\[ A_{DN} = \frac{(Day - Night)}{(Day + Night)/2} \]

### Spectrum distortion

\[ P(\nu_e \rightarrow \nu_e) \]

\[ \text{Flux} \quad [\text{/cm}^2\text{/s}] \]

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

\[ \sin^2(\theta_{12}) \]

\[ \text{Flux in keVcm}^2\text{/s} \]

Vacuum oscillation dominant
Matter oscillation dominant
Expected Solar+KamLAND
Expected Solar global
Observed SK+SNO

### Day-Night flux asymmetry

Regenerate $\nu_e$ by earth matter effect

Expected $A_{DN}$
- $1\%$
- $2\%$
- $3\%$
- $4\%$

Solar+KamLAND
KamLAND
Solar global
A theoretical expectation

\[
\langle P_{\text{ee}} \rangle = \frac{\Phi_{\text{CC}}}{\Phi_{\text{NC}}}
\]

![Graph showing theoretical expectation and experimental data points for neutrino oscillations.](image)

- **Borexino (\(^8\text{B}\))**
- **Super-K**
- **SNO**

**Graph Details**
- **Axes:**
  - Y-axis: \(\langle P_{\text{ee}} \rangle = \Phi_{\text{CC}}/\Phi_{\text{NC}}\)
  - X-axis: \(E_{\nu} \, [\text{MeV}]\)

**Legend:**
- **Standard**
- **NSI-up**
- **Sterile**
- **NSI-dw**

**Source:**
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Recent activities on solar \( \nu \) analysis

- **Energy scale improvements**
  - Taking into account PMT gain & dark rate effects

- **Preliminary update of spectrum analysis**
  - Total live time 5695 days (May 1996 - Dec. 2017)
  - SK-I (1496 days), SK-II (791 days), SK-III (548 days), SK-IV (1664 days \( \rightarrow \) 2860 days)

- **Update of day/night analysis**: On going (1664 days \( \rightarrow \) ?)

- **Preliminary periodic analysis in SK-IV**
  - Using same data set as PRD94, 052010

- **NSI analysis**: On going

- **Solar nu-e-bar**: On going

- **Study of spallation BG**
  - Using neutron events (2.2 MeV \( \gamma \) from \( n+p \)) in SK-IV

- **Study of radon BG**
Preliminary

- PMT gain and PMT dark rate are changing, and it caused a slight drift of energy scale as a function of time.
- A new energy scale with gain and dark rate correction is implemented.
- It enables low-energy analysis of whole SK-IV period with a same systematic uncertainty.

- **Relative gain**
- **Dark rate**
- **Decay electron peak before correction**
- **Decay electron peak after correction**

<table>
<thead>
<tr>
<th>Year</th>
<th>Effective # of hit PMT</th>
<th>Decay electron peak before correction</th>
<th>Decay electron peak after correction</th>
<th>Used data for PRD94,052010</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td></td>
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<td></td>
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<tr>
<td>2017</td>
<td></td>
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<td></td>
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</tbody>
</table>
SK-IV solar neutrino signal

SK-IV 3.5-19.5 MeV (kinetic)

Signal (in SK-IV): 55729 +363 -361 events
Total: ~93000 solar v events (in SK 5695 days)
$^8$B solar neutrino flux: Yearly plot

**Averaged $^8$B flux with no oscillation**

$= (2.33+/-0.04) \times 10^6 / \text{cm}^2 / \text{s}$

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

Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.
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

Solar ν oscillation parameters

$\Delta m_{21}^2 = (7.49^{+0.19}_{-0.17}) \times 10^{-5} \text{eV}^2$

$\sin^2 \theta_{12} = 0.310 \pm 0.012$

SK 5695 days
Super-K Spectral Data

$\nu_e$ survival probability
$P(\nu_e \rightarrow \nu_e)$

- Expected Solar+KamLAND
- Expected Solar global
- All solar (pp)
- Borexino (pp)
- Borexino ($^7$Be)
- Borexino (pep)
- Borexino ($^8$B)

SK+SNO

Expected Solar+KamLAND

Expected Solar global

Borexino (pp)

Borexino ($^7$Be)

Borexino (pep)

Borexino ($^8$B)

Homestake +SK+SNO (CNO)

SK-I~IV 4499 days

PRD94, 052010

Neutrino energy [MeV]

$\nu$ Energy in MeV

$P_e$
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Hyper-Kamiokande (HK)

- Gigantic neutrino and nucleon decay detector in Kamioka, Japan
- **187 kton fiducial mass**: ~8 x SK
- **x 2 higher photon sensitivity** than SK
- MW-class world-leading ν-beam by upgraded J-PARC

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

**Current status:**
- HK is a priority project by MEXT’s Roadmap 2017
- MEXT allocated a seed budget of HK in FY2019. (In SK, after the one-year seed budget, full budget was allocated)
- U. Tokyo decided to start HK constriction in April 2020.
- To enhance neutrino oscillation physics, a 2nd detector in Korea is under study

Solar neutrinos in HK

- **Expected event rate**
  - $^8$B solar neutrino: $\sim 130$ events/day
  - 4.5 MeV threshold (visible energy)
  - with oscillation, scaled from SK rate

- **Neutrino physics**
  - Oscillation parameters
  - NSI analysis

- **Solar physics**
  - *Hep* solar neutrino
  - Core temperature monitor
  - Solar g-mode oscillation
  - Neutrino from solar flare

An estimation of Rn background

Radon events could be reduced in HK thanks to better energy resolution.

$^{214}\text{Bi}$ beta spectrum
With SK-IV energy resolution
With HK energy resolution

~factor 10 at 4.5 MeV

(Simulation)
8B Solar neutrino measurements

Day/Night sensitivity
- Sensitivity to no asymmetry
- Sensitivity to KamLAND

Spectrum upturn
- Solid: 0.3% syst. err.
- Dotted: 0.1% syst. err.
- Solid: 4.5 MeV threshold
- Dotted: 3.5 MeV threshold

- Day/Night (solar vs reactor): 4~5 sigma in 10 years
- Spectrum upturn: ~3 sigma in 10 years

Hep solar neutrino

- The last piece of the solar neutrinos in pp-chain.
- Theoretical calculation is difficult.
- → Better understanding of solar physics
- Production area is different.
- → A new probe of the solar interior around core region
- Non-standard solar models predict the potential enhancement of the hep neutrino flux.
- Could be additional input to the solar chemical composition problem.
**Hep solar neutrino at HK**

**Integrated # of expected solar neutrino events**

- **8B+hep (BP2004 SSM)**
- **only 8B**

(No spallation background)

**Expected non-zero significance**

- No spallation BG
- Mozumi site spa. BG level
- Tochibora site spa. BG level

(considering major syst. uncertainties)

<table>
<thead>
<tr>
<th></th>
<th>E_{total} [MeV]</th>
<th>(^8\text{B} [/1.9\text{Mton year}]</th>
<th>\text{Hep} [/1.9\text{Mton year}]</th>
<th>\text{Hep} / (^8\text{B} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK</td>
<td>19.5-25.0</td>
<td>0.77</td>
<td>3.03</td>
<td>3.9</td>
</tr>
<tr>
<td>HK</td>
<td>18.0-25.0</td>
<td>0.56</td>
<td>6.04</td>
<td>10.6</td>
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</table>

- First direct observation.
- Energy resolution & spallation BG reduction are essential.
Temperature dependences of $\nu$ flux from SSM


$^8$B flux is very sensitive to solar core temperature (flux $\propto T^{24}$)

$\Rightarrow$ study of possible time variation of $^8$B flux (Solar physics)

(Accuracy of core temperature measurement: $\sim0.8\%$ day by day at HK)
Summary

- Solar neutrino has been observed since 1970’s
  - It could be used as a probe of solar physics
- Agreement between SSM + ν oscillation and solar neutrino experiments looks good, but there is some room for new physics
- Tension between solar and reactor experiments
- Energy spectrum in vacuum-matter transition region
- A very precise solar neutrino measurements could be done with HK for both ν properties and solar physics
- Oscillation parameters, hep neutrinos, short time variations, solar flares, ...