Experimental determination of neutrino oscillation in atmospheric neutrinos / solar neutrinos

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The Univ. of Tokyo for
Super-Kamiokande collaboration

Three neutrinos and beyond
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Qui Nhon, Vietnam
Neutrinos from natural sources

- Neutrino sources in nature
  - Astrophysical objects (Solar, Super-Nova, DM..)
  - Radioactivities in the earth
  - High energy CR interactions in atmosphere (atmospheric neutrino) ...

- Big roles to discover neutrino oscillations and parameter determination in last two decades.
- Also unique channels to probe the objects.

- Many experiments.
- My talk focused on an experiment, Super-Kamiokande
Super-Kamiokande

- Ring-imaging Water Cherenkov Detector, @1000m underground, Kamioka, Japan
- Multi-Purpose experiment (Atm.ν, WIMP, Proton decay, solar-ν, beam ν)
- Wide dynamic range
  A few MeV ~ over TeV

- 4π acceptance, very efficient π⁰/e separation.
- High Particle ID (μ/e) power (~99% at 600MeV/c)

Four periods in above 20yrs
→ total ~5300 livetime-days data
5th period started from Feb.2019.
A key: stability of the detector

- Detailed calibrations with various sources.
  - *in-situ* laser for water transparency.
  - Neutron sources (DT generator)
  - Monochromatic electron (LINAC)
  - Gamma ray sources (Ni+Cf)
  - CR muons, …

- Water transparency is a key of Water Cherenkov detector.
- Measurement & modeling in full MC simulation.
- Also, gain drift of PMTs are considered.

Relative Gain

<table>
<thead>
<tr>
<th>Date</th>
<th>Gain</th>
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<tbody>
<tr>
<td>01/01/09</td>
<td>1.05</td>
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<tr>
<td>01/01/10</td>
<td>1.10</td>
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<tr>
<td>01/01/11</td>
<td>1.15</td>
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<tr>
<td>01/01/12</td>
<td>1.20</td>
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Stop Muon Momentum / Range [MeV/cm]

- SK-III
- SK-IV

Stop Momentum (MeV/cm)

<table>
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<tr>
<th>Date</th>
<th>Momentum</th>
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<tbody>
<tr>
<td>01/01/09</td>
<td>2.25</td>
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<tr>
<td>01/01/10</td>
<td>2.30</td>
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<tr>
<td>01/01/11</td>
<td>2.35</td>
</tr>
<tr>
<td>01/01/12</td>
<td>2.40</td>
</tr>
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Water temperature (deg.)

- April 2009
- April 2010
- April 2011
- April 2012
- April 2013
- April 2014
- April 2015
- April 2016
- April 2017
- April 2018

Dark noise charge peak w.r.t. April 2009

- 1992-1995 PMT
- 1996-1997 PMT
- 2003 PMT
- 2004 PMT
- 2005 PMT

~2% drift / year
Atmospheric neutrinos

= Secondary products of primary cosmic rays in the atmosphere

- First observation in 1965 in two deep underground experiments.
- Several Flux calculations on the market:
  - Primary CR fluxes, p+A cross sections,
  - π’s production, Geo-magnetic field,..

- Calculated fluxes are well tested (calibrated) by Cosmic Ray muons.

\[ p + A \rightarrow \pi^\pm, \ldots \]

\[ \pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \]

\[ \rightarrow e^\pm + \nu_e (\bar{\nu}_e) + \bar{\nu}_\mu (\nu_\mu) \]
- Wide energy range, wide range of flight length.
- Passing through dense matter inside the Earth (matter effect is expected).
- Mixture of $\nu_\mu$, $\nu_e$, and their anti-neutrinos.
- Up/Down symmetric (> a few GeV)
- DC-like continuous beam, FREE!

$\nu_\mu/\nu_e \sim 2$ @ $E_\nu < a$ few GeV

Flux $\sim E^{-2.71}$ at high energy region
<10% uncertainty @1GeV region

Symmetric for $E_\nu > a$ few GeV
Event topologies of Super-K events

- Fully Contained (FC)
- Partially Contained (PC)
- Upward Stopping-mu
- Upward Through-going mu

Energy spectrum of neutrinos

- ~100MeV – over TeV neutrinos
Totally 19 Sub-divided samples. They further binned by:
- zenith angle
- energy (momentum)
- SK period

- Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillation, $\nu_e$ oscillation is sub-dominant effect.
- Fit MC expectation by modifying within the estimated systematic errors (~150 systematic errors from SK detector, flux, $\sigma$ int.).
Neutrino oscillation in atmospheric $\nu$

- "Solar term" $\rightarrow$ \[ \sin^2 \theta_{23} \text{ octant} \]
- Interference term $\rightarrow$ CP violation phase
- Resonance term $\rightarrow$ mass hierarchy

- "Solar term" $\rightarrow$ \[ P_2(r \cdot \cos^2 \theta_{23} - 1) \]
- Interference $\rightarrow$ \[ -r \cdot \sin^2 \tilde{\theta}_{13} \cdot \cos^2 \tilde{\theta}_{13} \cdot \sin 2\theta_{23} (\cos \delta_{CP} \cdot R_2 - \sin \delta_{CP} \cdot I_2) \]
- Resonance $\rightarrow$ \[ +2\sin^2 \tilde{\theta}_{13} (r \cdot \sin^2 \theta_{23} - 1) \]
Results of analysis of $\nu$ oscillation
Evidence for $\nu_\tau$ appearance at Super-K


- Search for events consistent with hadronic decay of $\tau$ leptons.
- Neural networks to discriminate from B.G. mainly multi-hadronic production.
- Prompt $\nu_\tau$ is negligible.
- 2D Un-binned maximum likelihood method is employed using a PDF:

\[
PDF = PDF(b.g) + \alpha \times PDF(\tau) + \sum \epsilon_i \times \Delta PDF_i
\]

$\alpha = 1.47 \pm 0.32$

4.6 $\sigma$ excess from no-$\tau$
( Expected 3.3 $\sigma$ significance)
Allowed regions on \((\sin^2 \theta_{23}, \Delta m^2_{32})\)

Consistent with other experiments, weak preference for second octant \((< 1\sigma)\)

Super-K results:

\[
\Delta m^2_{32} = 2.5^{+0.13}_{-0.20} \times 10^{-3}\text{eV}^2
\]

\[
\sin^2 \theta_{23} = 0.588^{+0.031}_{-0.064}
\]
• Driven by excess of upward-going e-like events:
  • Primarily in SK-IV data
  • Consistent with the effects of $\theta_{13}$ driven $\nu$ oscillation.

Upward/Downward asymmetry in energetic electron samples ($\nu e$/anti-$\nu e$ enriched)

- Muti-GeV $e$-like $\nu_e$
- Muti-GeV $e$-like anti-$\nu_e$
- Muti-GeV $e$-like anti-$\nu_e$
- Muti-Ring $e$-like $\nu_e$
- Muti-Ring $e$-like anti-$\nu_e$
- Muti-Ring others

(Upward - Downward)

(Upward + Downward)
SK atm.ν + constraint from T2K ν_μ, ν_e published results

- Add constraint from T2K by mimic data reproducing published results.
- $\chi^2_{NH} - \chi^2_{IH} = -5.2$ (-4.3 SK only)
- Significance of IH is disfavored by 91.9% ~ 94.5% (81.9% ~ 96.7% SK only) at allowed 90% CL region, based on psudo-experiments.
Test of Matter effect

- Atmospheric neutrino data in SK prefer the matter effect hypothesis or not?
- Introduce a phenomenological scaling factor $\alpha$ to electron potential:

$$H = U M U^\dagger + \alpha \cdot V_e \quad (\alpha = 1 \text{ is nominal matter})$$

- Best fit is at $\alpha = 1$.
- Significance to reject $\alpha=0$ (no matter effect) is $1.6\sigma$ level, based on toy MC estimation.
Solar neutrinos

Nuclear fusion yields energy and neutrinos:

\[ 4p \rightarrow {}^4\text{He} + 2e^- + 2\nu_e + 25\text{MeV} \]

- Most intensive source of neutrino on the earth.
- Well described by a standard solar model (SSM) and fluxes prediction available.
- A chain reaction starting from \( p+p \) fusion is the main source of the power (called "pp chain"). Alternative reaction cycle ("CNO" cycle) is predicted but not observed yet.
- Metallicity problem: Composition of relative heavy materials
Determination of neutrino parameters of 12 sector and the mechanism of the neutrino oscillation

Spectrum distortion due to neutrino oscillation effect. (test non-standard scenario).

Day/night difference due to matter effect in the earth

![Graph showing neutrino oscillation probabilities and energies](image)

Expected
Solar global
Vacuum oscillation dominant
Matter effect dominant
Super-K
Solar+KamLAND
Expected
Solar+KamLAND
KamLAND
Solar global

Regenerate $\nu_e$ by earth matter effect

Expected $A_{DN}$
-1% -2% -3% -4%
Solar neutrino signals in Super-Kamiokande

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

- Realtime measurements yields solar direction and path in the earth.
- Energy determination is crucial for spectrum study. Detailed calibration yields 0.5% level energy scale calibration.

Event display of solar \( \nu \) candidate

Detector performance

<table>
<thead>
<tr>
<th>Resolution (10 MeV)</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>vertex</td>
<td>55 cm</td>
</tr>
<tr>
<td>direction</td>
<td>23 deg.</td>
</tr>
<tr>
<td>energy</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td># of hits.</td>
</tr>
</tbody>
</table>

\( E_e = 8.6 \text{ MeV (kin.)} \)
\( \cos \theta_{\text{sun}} = 0.95 \)

\( \sim 6 \text{ hits}/\text{MeV} \)
well calibrated by LINAC and DT within 0.5% precision
Recoil electron direction / spectrum

Clear sun directions. It provides a good signal estimation by fitting background and signal models.

SK spectrum data is consistent within $1\sigma$ for the Solar best fit parameters, while marginally consistent within $2\sigma$ for the Solar+KamLAND best fit parameters.
Neutrino oscillation analysis

The unit of $\Delta m_{21}^2$ is $10^{-5}$ eV$^2$.

Solar global

KamLAND

$\sin^2 \theta_{12} = 0.316^{+0.034}_{-0.026}$

$\Delta m_{21}^2 = 7.54^{+0.19}_{-0.18}$

$\sin^2 \theta_{12} = 0.310 \pm 0.014$

$\Delta m_{21}^2 = 4.82^{+1.20}_{-0.60}$

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

$\Delta m_{21}^2 = 7.49^{+0.19}_{-0.17}$

The unit of $\Delta m_{21}^2$ is $10^{-5}$ eV$^2$

$\sin^2 \theta_{13} = 0.0219 \pm 0.0014$

About 2$\sigma$ tension between Solar global and KamLAND in $\Delta m_{21}^2$. 

Very Preliminary
Probability of $\nu_e \rightarrow \nu_e$

Neutrino energy [MeV]
Day/Night asymmetry ($A_{DN}^{\text{fit}}$)

Rate dependence of the path in the earth

For solar global parameter:
\[ \Delta m_{21}^2 = 4.84 \times 10^{-5} \text{ eV}^2 \]
\[ \sin^2 \theta_{12} = 0.311 \]

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

\[ A_{DN} = -3.3 \pm 1.0 \pm 0.5\% \]

Non-zero significance is 3 $\sigma$

in SK-I to IV (4499 days)
Time variation of the $^8$B neutrino flux

Averaged $^8$B flux with no oscillation is $(2.33+/-0.04) \times 10^6$/cm$^2$/s

$\chi^2 = 19/28 / 22$ d.o.f (62.8 C.L.)

Super-K covers two interval of solar cycle. $^8$B neutrino rate are consistent with a constant flux.

Sun spot number: WDC-SILSO, Royal Observatory of Belgium, Brussels
Status and future of Super-Kamiokande

• Super-Kamiokande was stopped for refurbishment toward new phase with Gd-loaded water from June 2018 to Feb. 2019.

• Replacing materials with Gd water compatible materials.

• Water leakage repair.

• Water system upgrades for Gd loading.

• Detailed magnetic field measurements / dynode direction recording for understanding of systematic errors.

• About 100 dead PMTS are replaced for a newly developed 20 inch PMTs for Hyper-Kamiokande. (x2 QE/CE, better time resolution)

• Refurbishment is done successfully. No water leak.

• Restarted data taking from Feb. 2019. Plan to start Gd loading in this FY.
Status and future of Super-Kamiokande (2)

• Atmospheric neutrino (and nucleon decay)
  • New algorithm of event reconstruction
  • Expanding the fiducial volume (22.5kton to 29.7kton)
  • Neutron tagging is expected to improve separation of n / anti-n, and energy reconstruction. Gd loading is in preparation.

• Solar neutrino
  • Lowering threshold : WIT system, which applies reconstruction and reduction just after front-end.
  • Reduction of spallation event will be improved.
  • Keep continuing solar neutrino analysis in Super-K Gd era.
  • Non standard interaction (NSI) study is on-going.
Summary

• Neutrino oscillation studies in Super-Kamiokande, based on atmospheric neutrinos and solar neutrinos are presented.
• Refurbishment is done last year.
• New phase of the Super-Kamiokande started from Feb.2019, and calibration works are ongoing.
Atmospheric neutrino flux measurement in Super-K

- Neutrino fluxes ($\nu_\mu$+anti-$\nu_\mu$, $\nu_e$+anti-$\nu_e$) by an unfolding method with Bayesian theory: No bias, mathematically robust.
- Systematic errors from SK, neutrino interactions are considered.
- Super-K gives good measurement especially in low energy region.
Super-Kamiokande collaboration

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
University of British Columbia, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
Imperial College London, UK
NFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
KEK, Japan
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
The University of Tokyo, Japan
Tokai Institute of Technology, Japan
Tokyo University of Science, Japan
University of Toronto, Canada
TRIUMF, Canada
Tsinghua University, Korea
The University of Winnipeg, Canada
Yokohama National University, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
Osaka University, Japan
University of Oxford, UK
Queen Mary University of London, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tokai University, Japan

178 collaborators from 45 institutes
10 countries
External Constraint from other Experiments

- Adding external data set to atmospheric neutrinos improve the sensitivity to the mass hierarchy: Sensitivity depends on values of $\Delta m^2$ and $\sin^2 \theta_{23}$.
- Fit the T2K $\nu_\mu$ and $\nu_e$, and anti-neutrino data sets simultaneously.
- Fit is based on **publicly available** T2K information and results
  - Make a mimic T2K data, and analyzed with SK atm. $\nu$ data.
  - (not a joint result of the T2K and SK collaborations)

MINOS constraint is similarly important but harder to model accurately (so far...)

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Hierarchy Sensitivity NH True

$\delta_{cp}$ Uncertainty

$\Delta \chi^2 = 2$  
$\Delta \chi^2 = 1$

SK + T2K $\nu_\mu, \nu_e$

SK Alone

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T2K $\nu_\mu$

External Constraint

90% C.L. External Fit
90% C.L. T2K Official
Energy spectrum

SK-I Spectrum
SK-I 1496 days
Solar+KamLAND parameter
Solar global parameter
Quadratic spectrum best-fit
Exponential spectrum best-fit

SK-II Spectrum
SK-II 791 days

SK-III Spectrum
SK-III 548 days

SK-IV Spectrum
SK-IV 2970 days
Preliminary

May 2019
Survival probabilities

M. Ikeda, Neutrino 2018
DOI: 10.5281/zenodo.1286857
The total energy scale uncertainty in each period has been estimated as 3.3% in SK-I, 2.8% in SK-II, 2.4% in SK-III, and 2.1% in SK-IV. The total systematic error is assigned taking this value.

The stability seen in the SK-IV period is a result of improvements in the water purification system and in scale. The stability since SK-I appears in Fig. 3. Absolute energy scale measurements for each SK period. Vertical error bars denote the statistical uncertainty and horizontal error bars the momentum range spanned by each analysis.

Sub-GeV stopping cosmic ray muon data in each bin. The vertical axis shows the deviation of this parameter from the mean value for stopping cosmic ray muon data in each bin. The average energy scale variation in the stopping muon momentum divided by reconstructed momentum of Michel electrons and the scale, which is measured using the variation in the average summed in quadrature with the time variation of the energy.

The momentum range is 10 MeV to 1330 MeV. For the SK-I, -II, and -III data periods the latter selection is based on consistent with radiative losses are separated into a subsample. The 19 analysis samples defined for each run period are summarized in Table 1. After all selections there are a total of 14 FC analysis samples. Fully contained events have a reconstructed vertex within the 22.5 kton fiducial volume, and visible energy or momentum into combinations of single- or multi-ring, electron-like, and sub-GeV (E<1330 MeV) or multi-GeV (E>1330 MeV) or muon-like (E>1330 MeV). Additional selections are made based on the number of observed Cherenkov rings, the particle ID (PID) of the most energetic ring, and the energy deposition in both the OD and ID is expected and the surrounding SK or in the OD water. Accordingly, light events produced by neutrino interactions in the rock are classified as OD. For the SK-I, SK-II, and SK-III periods the latter selection is based on a single- or multi-ring, electron-like, or sub-GeV event categories appear in Fig. 4. Energy scale stability measured as a function of date range. An example of the latter showing the energy scale variation in the stopping muon momentum divided by reconstructed momentum of Michel electrons and the energy scale is taken as the average value for the most discrepant sample from this study in each run period.

The current analysis utilizes atmospheric neutrino data since the start of SK operations. The energy scale is taken as the mean value for stopping cosmic ray muon data in each bin. The vertical axis shows the deviation of this parameter from the mean value for stopping cosmic ray muon data in each bin. The average energy scale variation in the stopping muon momentum divided by reconstructed momentum of Michel electrons and the scale, which is measured using the variation in the average summed in quadrature with the time variation of the energy.

The energy scale is taken as the average value for the most discrepant sample from this study in each run period. Note the SK-III data correspond to a total livetime of 5,326 days, 2,519 of which are from SK-IV. Super-Kamiokande was subject to poor and volatile water transparency conditions, resulting in a comparatively turbulent energy scale. The stability seen in the SK-IV period is a result of improvements in the water purification system and in scale. The stability since SK-I appears in Fig. 3. Absolute energy scale measurements for each SK period. Vertical error bars denote the statistical uncertainty and horizontal error bars the momentum range spanned by each analysis.
Solar $\nu$ Angle $\theta_{12}$ & Mass$^2$ Difference

- Super-K data best constrains $\Delta m_{21}^2$
- SNO data best constrains $\sin^2 \theta_{12}$
- Complementarity makes combined fit beneficial
- Correlation via $^8$B flux further tightens constraints

Very Preliminary

Super-K

SK+SNO

SNO