Results and Prospects from Atmospheric and Solar Neutrinos

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Uppsala university, 25-30 September, 2017
Request from committee

This overview talk should cover all large neutrino detectors projects both for atmospheric and solar neutrino.
Atmospheric and solar neutrinos in neutrino oscillation

Mixing angle: Maki-Nakagawa-Sakata Matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{-i\delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Atm. and Acc.
\[\theta_{23} \sim 45 \pm 5^\circ\]
\[|\Delta m^2_{32}| = 2.4 \times 10^{-3}\text{eV}^2\]

Reactor and Acc.
\[\theta_{13} \sim 9^\circ\]

Solar and KamLAND
\[\theta_{12} \sim 34 \pm 3^\circ\]
\[\Delta m^2_{21} = +7.6 \times 10^{-5}\text{eV}^2\]

\[\delta_{cp}\] and Mass hierarchy of 2-3 are unknown

Atmospheric, Accelerator, Reactor

Atmospheric and solar neutrinos play crucial role for determining the neutrino oscillation parameters
Atmospheric neutrino
Atmospheric neutrinos

Cosmic rays strike air nuclei and the decay of the out-going hadrons gives neutrinos.

✓ Flux measurement by SK
✓ Model calculation is consistent with data.

Cosmic ray (p, He, ...)

\[ L = 10 \sim 20 \text{ km} \]

\[ L \sim \text{up to} 13000 \text{ km} \]
Super-Kamiokande

50000 tons of Water Cherenkov detector

Cherenkov light

Charged particle

Neutrino

Kamioka mine

~1km

~3km

~2km

(2700 mwe)

Japanese

<table>
<thead>
<tr>
<th>Phase</th>
<th>Period</th>
<th>Fiducial vol. (kton)</th>
<th># of PMTs</th>
<th>Energy thr. (MeV)</th>
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</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>1996.4 ~ 2001.7</td>
<td>22.5</td>
<td>11146 (40%)</td>
<td>4.5</td>
</tr>
<tr>
<td>SK-II</td>
<td>2002.10 ~ 2005.10</td>
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<td>5182 (20%)</td>
<td>6.5</td>
</tr>
<tr>
<td>SK-III</td>
<td>2006.7 ~ 2008.8</td>
<td>22.5 (&gt;5.5MeV) 13.3 (&lt;5.5MeV)</td>
<td>11129 (40%)</td>
<td>4.5</td>
</tr>
<tr>
<td>SK-IV</td>
<td>2008.9 ~</td>
<td>22.5 (&gt;5.5MeV) 16.5 (4.5&lt;E&lt;5.5) 8.9 (&lt;4.5MeV)</td>
<td></td>
<td>3.5</td>
</tr>
</tbody>
</table>

Running and improvements over 20 years
Super-Kamiokande
as an atmospheric neutrino detector

50000 tons of Water Cherenkov detector

Super-K Atmospheric Event Topologies

- Fully Contained (FC)
- Upward-going Muons (Up-$\mu$)
- Partially Contained (PC)

Average energies
- FC: ~1 GeV
- PC: ~10 GeV
- Up-$\mu$: ~100 GeV

Neutrino interactions in SK
- (quasi-)elastic scattering: $\nu + N \rightarrow l + N'$
- Single meson production: $\nu + N \rightarrow l + N' + \text{meson}$
- Deep inelastic interaction: $\nu + N \rightarrow l + N' + \text{hadrons}$
- Coherent pion production: $\nu + {}^{16}\text{O} \rightarrow l + {}^{16}\text{O} + \pi$

Parent neutrino spectra

Event topology
- Fully-contained
- Partially-contained
- Upward-going muon

Cherenkov light
- Single ring
- Multi ring
- e-like
- $\mu$-like
- Partly-contained single ring
- Partly-contained multi ring
3 flavor neutrino oscillation analysis

Consider all the sub-leading effects ($\Delta m^2_{21}$, matter)
- Mass hierarchy: resonance in multi-GeV $\nu_e$ or $\bar{\nu}_e$
- Octant $\theta_{23}$: magnitude of the resonance
- $\delta_{CP}$: interference btw two $\Delta m^2$ driven oscillation

Fractional change of upward $\nu_e$ flux ($\cos \theta_{\text{zenith}} = -0.8$)

![Graphs showing the fractional change of upward $\nu_e$ flux](image)

- (a) $\cos \theta_{13} = 0.8$, $\sin^2 \theta_{23} = 0.4$, $\sin^2 \theta_{13} = 0.025$, $\delta = 40^\circ$
- (b) $\cos \theta_{13} = 0.8$, $\sin^2 \theta_{23} = 0.4$ or 0.6, $\sin^2 \theta_{13} = 0.025$, $\delta = 40^\circ$
- (c) $\cos \theta_{13} = 0.8$, $\sin^2 \theta_{23} = 0.6$, $\sin^2 \theta_{13} = 0.025$, $\delta = 220^\circ$
- (d) $\cos \theta_{13} = 0.8$, $\sin^2 \theta_{23} = 0.6$, $\sin^2 \theta_{13} = 0.025$, $\delta = 40^\circ$

- $\delta_{CP} = 40^\circ$ or $220^\circ$

- Hierarchy is NH or IH

- Resonance in $\bar{\nu}_e$ (not shown) in the case of IH.
Parameter determination (SK+T2K)

| Fit (585 dof)    | $\chi^2$ | $\sin^2 \theta_{13}$ | $\delta_{CP}$ | $\sin^2 \theta_{23}$ | $|\Delta m_{32}^2|$/eV$^2$ |
|------------------|----------|----------------------|---------------|----------------------|---------------------------|
| SK+T2K (IH)      | 644.82   | 0.0219 (fix)         | 4.538         | 0.55                 | 2.5x10^{-3}              |
| SK+T2K (NH)      | 639.61   | 0.0219 (fix)         | 4.887         | 0.55                 | 2.4x10^{-3}              |

$\Delta \chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2$

Probability for IH is 0.024 ($\sin^2 \theta_{23}=0.6$) and 0.001 ($\sin^2 \theta_{23}=0.4$), while for NH is 0.43 ($\sin^2 \theta_{23}=0.6$)

Friday afternoon: F.d.M.Blaszczyk

26 Sep., 2017

NUFACT2017 9
**τ** neutrino appearance

Hard to identify event by event but can be statistically seen

![Multi-ring decay](image)

Search for events consistent with hadronic decays of tau lepton using neural network method

\[
data = \text{PDF(BG)} + \alpha \times \text{PDF}(\tau) + \sum \varepsilon_i \times \text{PDF}_i\]

PDF of i-th sys. error shifting by 1σ

**τ** fraction is found to be \(1.47 \pm 0.32\), which is \(4.6\,\sigma\) from 0.

Friday afternoon: F.d.M.Blaszczyk
Hyper-Kamiokande (future)

2 tanks x
with staging ~10 times larger volume than Super-K

Atm. and acc. $\nu$
measurements in
Hyper-K will make
much more precise
determination for
mass hierarchy,
octant $\theta_{23}$,
$\delta_{CP}$
be available.

See E. O’Sullivan and C. Bronner’s presentation in more detail
Atmospheric neutrino flux is very sensitive to matter effects, to both $D_{m_2}$ values, and covers a wide range of $L/E$.

MH with atmospheric neutrinos is nearly independent from the CP-violating phase.

Event rate: 14k e-like, 20k $\mu$-like fully contained for 350kt-year exposure
IceCube DeepCore

- 8 dedicated string fill \( \sim 10^7 \text{ m}^3 \) of ice with a typical spacing of 70m.
- Sensors are concentrated in the clearest deep ice, with a denser 7m vertical spacing.
- Energy range is 5.6 to 56 GeV, in which Deep Inelastic Scattering is dominant.

![Diagram of IceCube DeepCore]

- Neutrino directions of the initial neutrino. IceCube's optical sensors, Digital Optical Modules (DOMs), provide information about the direction of the initial neutrino. Their long tracks can be reconstructed and provide information about the direction and energy of the initial neutrino.
- Misreconstructed downward-going events, with a contribution of 5%.
- The angular resolution of the low-energy sample was 8\(^\circ\) and thus the effective housing with in-situ pulse digitization [4, 5].
- The IceCube DeepCore consists of eight dedicated distance of 125 m between neighboring strings. The sensors are arranged on 86 vertical strings, each holding up to 25 IceCube's optical sensors, Digital Optical Modules (DOMs), which can travel large distances in the ice.
- IceCube's optical sensors, Digital Optical Modules (DOMs), are used to detect muons produced in charged current interactions in the surrounding ice or the nearby bedrock. This analysis uses data taken while 79 detector strings were operational during 9 days of high-quality data were collected in this configuration, excluding some of the DeepCore strings. A total of 318 analysis uses data taken while 79 detector strings were operational during 9 days of high-quality data were collected in this configuration, excluding some of the DeepCore strings. A total of 318.

![Graph of neutrino energy distributions]

- The resolution of the reconstructed zenith angle is an essential parameter given that the neutrino propagation distance in km, and atmospheric uncertainties. The low-energy sample contained 719 events, while the high energy sample contained 39 events after final cuts.

![Graph of neutrino energy distributions]

- The variation in zenith angles alters the angular resolution of the low-energy sample. The dominant background in the low-energy sample was mis-reconstructed cosmic ray-induced muons contributing 5%.
- In 11 days of simulated cosmic ray air shower runs, the energetic reference sample provided high statistics and detector downtime. The high-energy reference sample provided high statistics and thus the atmospheric neutrinos in the low-energy (DeepCore) and in the high-energy (IceCube) samples according to simulations.

![Graph of neutrino energy distributions]

- The expected modification of the atmospheric neutrino zenith angle distribution due to oscillation-induced appearance due to atmospheric mixing angle, \( \theta_{23} \), which can travel large distances in the ice. The resolution of the reconstructed zenith angle is an essential parameter given that the neutrino propagation distance in km, and atmospheric uncertainties. The low-energy sample contained 719 events, while the high energy sample contained 39 events after final cuts.

![Graph of neutrino energy distributions]

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IceCube DeepCore

Cascade-like

Track-like

\( \frac{\text{Ratio to Best Fit}}{\text{Number of Events}} \)

\( \log_{10}(L_{\text{reco}}/E_{\text{reco}} \text{[km/GeV]}) \)

arXiv: 1707.07081
Friday afternoon: T. Ehrhardt, P. Eller

IC2017 [NO] (this work)  
SK IV 2015 [NO]  
MINOS w/atm [NO]  
NO\textsc{b}A 2017 [NO]  
T2K 2017 [NO]  

90\% CL contours

\( \Delta m^2 \) (10^{-3} eV^2)  
\( \sin^2 (\theta_{23}) \)  
\( \Delta \chi^2 \)
IceCube-Gen2 (future)

A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science

Multi-component observatory:
- IceCube-Gen2 High-Energy Array
- Surface air shower detector
- Sub-surface radio detector
- PINGU

Friday afternoon: T. Ehrhardt, P. Eller

IceCube-Gen2 Surface Veto

IceCube-Gen2 High-Energy Array
~10x IceCube volume

IceCube
DeepCore
PINGU
low energy
Science goals:

- $\nu_\mu$ disappearance
- $\nu_\tau$ appearance
- Precise calibration of IceCube optical properties and DOM response
IceCube-Gen2 (future)

Gen2 Phase 3 years

- IceCube 2017
- Super-K 2015
- MINOS w/atm
- NO\(\nu\)A 2017
- T2K 2017
- Gen2-Phase1 (3 yr proj.) [T2K 2016 assumed]

\[ |\Delta m^2_{32}| \left( 10^{-3} \text{ eV}^2 \right) \]

\[ \sin^2(\theta_{23}) \]

90% CL contours [NO] IceCube Preliminary

Phase 1 science: precision \(\nu_{\mu}\) disappearance

Precision significantly improved over DeepCore

DeepCore

Gen2 Phase 1
ANTARES

Mediterranean detector since 2008
- Studying the upgoing muon rate as a function of reconstructed muon energy
- Energy is above 20GeV

Sensitivity for 2236 days

863 days from 2007 to 2010

I. Salvadori
PoS(ICRC2017)1026
KM3NeT-ORCA (future)

2475m depth

- ~6 Mton instrumented
- 115 strings
- 18 DOMs / str
- 31 PMTs / DOM
- Total: 64k 3’’PMTs

- Study atmospheric neutrinos in 5-50GeV region which is unique for determination of the mass hierarchy.
- Sensitivity is 3σ in 4 years, or better

Friday afternoon: M. Circella
Summary of atmospheric $\nu$

- Full 3 flavor oscillation analysis is performed to extract mass hierarchy, Octant $\theta_{23}$, $\delta_{\text{CP}}$.
- Tests of various non-standard scenarios are possible.
- Several large detector experiments are proposed, and determine those parameters in near future.
Solar neutrino
Solar neutrinos

**pp-chain**

\[ p + p \rightarrow ^2H + e^+ + \nu_e \]

\[ p + e^- + p \rightarrow ^2H + \nu_e \]

\[ ^2H + p \rightarrow ^3He + \gamma \]

\[ ^3He + ^3He \rightarrow \alpha + 2p \]

\[ ^3He + \alpha \rightarrow ^7Be + \gamma \]

\[ 7Be + e^- \rightarrow ^7Li + \nu_e \]

\[ ^7Li + p \rightarrow 2\alpha \]

**CNO cycle**

\[ ^12C \rightarrow ^13C \]

\[ ^13C \rightarrow ^17O \]

\[ ^17O \rightarrow ^16O \]

\[ ^16O \rightarrow ^15N \]

\[ ^15N \rightarrow ^14N \]

\[ ^14N \rightarrow ^4He \]

\[ ^4He \rightarrow ^3He \]

\[ ^3He \rightarrow ^2H \]

\[ ^2H \rightarrow ^1H \]

\[ ^1H \rightarrow ^1H \]

Solar neutrino energy spectrum

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

Neutrino energy (MeV)

- **pp** ±0.6%
- **13N** ±14%
- **15O** ±15%
- **17F** ±17%
- **7Be** ±7%
- **8B** ±14%
- **hep** ±30%


Super-K (1996~)

SNO (1999~2006)

BOREXINO (2007~)

NuFACT2017
Super-Kamiokande
as a solar neutrino detector

- Find solar direction
- Realtime measurements
  - day-night flux differences
  - seasonal variation
- Energy spectrum

$\nu^+ + e^- \rightarrow \nu^+ + e^-$

50000 tons of Water Cherenkov detector

41.4 m

39.3 m

Neutrino

Cherenkov light

Charged particle

Neutrino-electron elastic scattering
Super-Kamiokande
as a solar neutrino detector

Typical event

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

✓ Find solar direction
✓ Realtime measurements
  - day-night flux differences
  - seasonal variation
✓ Energy spectrum

Detector performance

<table>
<thead>
<tr>
<th>resolution (10 MeV) information</th>
</tr>
</thead>
<tbody>
<tr>
<td>vertex</td>
</tr>
<tr>
<td>direction</td>
</tr>
<tr>
<td>energy</td>
</tr>
</tbody>
</table>

~ 6 hits/MeV
well calibrated by LINAC and DT within 0.5% precision

Super-Kamiokande
Run 1742 Event 102496
96-05-31; 07:13:33
Inner: 192 hits, 322 pE
Outer: -1 hits, 0 pE (in-time)
Trigger ID: 365
E = 9.086 GeV; 0.37 \text{ MSW}; 0.549
Solar Neutrino

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

26 Sep., 2017 NUFAC2017
Motivation of the measurement

See the neutrino oscillation MSW effect directly

Spectrum distortion

Day-Night flux asymmetry

Super-K can search for the spectrum “upturn” expected by neutrino oscillation MSW effect
Neutrino oscillation

~2σ tension between solar global and KamLAND in $\Delta m^2_{21}$

$\sin^2 \theta_{12} = 0.316^{+0.034}_{-0.026}$
$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$
$\sin^2 \theta_{12} = 0.308 \pm 0.014$
$\Delta m^2_{21} = 4.85^{+1.33}_{-0.59}$
$\sin^2 \theta_{12} = 0.307^{+0.013}_{-0.012}$
$\Delta m^2_{21} = 7.49^{+0.19}_{-0.18}$

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

$\sin^2 \theta_{13} = 0.0219 \pm 0.0014$
Day/Night asymmetry

expected time variation as a function of $\cos\theta_z$

Day/Night Amplitude was fitted to $-3.3\pm1.0\pm0.5\%$

Non-zero significance was $2.9\sigma$

in SK-I to IV (4499 days)

$\Delta m_{21}^2=4.84\times10^{-5}\text{ eV}^2$

$\sin^2\theta_{12}=0.311$

$\sin^2\theta_{13}=0.025$

KamLAND

Solar

SK-I,II,III,IV best fit

expected

$\Delta m_{21}^2=4.84\times10^{-5}\text{ eV}^2$

$\sin^2\theta_{12}=0.342$
Recoil electron spectrum

SK spectrum data is consistent within 1σ for the Solar best fit parameters, while marginally consistent within 2σ for the Solar+KamLAND best fit parameters.
Yearly solar neutrino flux

8B flux vs sun spot

No correlation with 11 years solar activity is observed

$\chi^2 = 15.52/19$ (dof)

Prob. = 68.9%

Solar neutrino rate measurement in SK is fully consistent with a constant solar neutrino flux emitted by the Sun
Borexino

Gran Sasso in Italy since 2007
(10th years anniversary)

https://agenda.infn.it/conferenceDisplay.py?confId=12485

- High light yield
- Lowering energy threshold
- Good energy resolution
- Realtime measurements
- No neutrino directional information
- Background reduction and understanding are critical

270 t PC+PPO (1.5g/l)
in nylon vessel (R=4.25m)

Liquid scintillator

2212 8” PMTs with light guide cone

ν+ e⁻ → ν+ e⁻
Borexino

Extract the each solar neutrino rate and the BG contribution from the spectrum

- $P_{ee}(pp) = 0.57 \pm 0.10$
- $P_{ee}(^{7}\text{Be}, 862\text{keV}) = 0.53 \pm 0.05$
- $P_{ee}(\text{pep}) = 0.43 \pm 0.11$


arXiv: 1707.09279
Borexino

Astrophysical point of view

![Graph showing B16 SSM (± 1σ): HZ (GS98) and LZ (AGSS09met) with allowed regions for 68.27%, 95.45%, and 99.73% C.L.](image)

arXiv: 1707.09279

BX results seem to give a hint towards the High Metallicity hypothesis in spite of the large theoretical error
Solar neutrinos in Hyper-K

$\sin^2 \theta_{13} = 0.0242 \pm 0.0026$

$\sin^2 \theta_{12} = 0.308 \pm 0.014$

$\Delta m_{21}^2 = 7.49^{+0.19}_{-0.18}$ eV$^2$

$\Delta m_{21}^2 = 7.50^{+0.19}_{-0.18}$ eV$^2$

$\Delta m_{21}^2 = 4.85^{+1.4}_{-0.59}$ eV$^2$

$\sin^2 \theta_{12} = 0.311 \pm 0.014$

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

$\sin^2 \theta_{12} = 0.312 \pm 0.033 - 0.025$

$\Delta m_{21}^2 = 7.50^{+0.19}_{-0.18}$ eV$^2$

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

~2σ tension with KamLAND in $\Delta m_{21}^2$

~4% at solar best

~2% at KamLAND

(E$_{th} = 6.5$ MeV)
Solar neutrinos in Hyper-K

Sensitivity of Day/Night flux asymmetry

- b/w zero D/N and Solar of $\Delta m^{21}$
- b/w Solar and KamLAND of $\Delta m^{21}$

E. O’sullivan, C. Bronner

Systematic error
- 0.3 %
- 0.1 %
- 0.3 %
Summary of solar $\nu$

- Current running detectors are Super-Kamiokande and Borexino.
  - Indication of Day-Night asymmetry has been found in Super-K at 3 $\sigma$ level.
  - Precise measurements of pp, $^7$Be, pep has succeeded in Borexino

- $2 \sigma$ tension between solar and KamLAND $\Delta m_{21}^2$ is seen. Day-night measurement in Hyper-K can determine the parameter.
Super-K Gd

Inverse beta decay

\( \bar{\nu}_e \rightarrow p + e^- \)  

(2.2 MeV)

\( n \rightarrow p + \gamma + e^- + \nu_e \)  

~8 MeV

Delayed coincidence

Dissolve Gadolinium into Super-K


WE ARE HERE.

First observation of neutrinos emitted from past supernovae

S. Ando

FACT2017
Super-K Gd

Tank open on June 1st, 2018

<table>
<thead>
<tr>
<th>Year</th>
<th>201X</th>
<th>201X+1</th>
<th>201X+2</th>
<th>201X+3</th>
<th>201X+4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fill water (~2 month)</td>
<td>Pure water circulation</td>
<td>Physics run</td>
<td>Stabilize water transparency</td>
<td>Physics run</td>
</tr>
</tbody>
</table>

**T₀** = Start leak stop work (~3.5 month)

**T₁** = Load first Gd₂(SO₄)₃ up to 10t = 0.02%

**T₂** = Load full Gd₂(SO₄)₃ 100t = 0.2%
Around this time next year

Open the Super-K tank since 2006
Around this time next year

Open the Super-K tank since 2006

Stay tuned!
Thank you for your attention