Atmospheric neutrino oscillations with Super-Kamiokande and prospects for SuperK-Gd

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The Super-Kamiokande (SK) Experiment

- Water-Cherenkov detector
- Located in Kamioka, Japan
- Under Mt. Ikenoyama
- Overburden 1km of rock
- Total of 50 kton of ultra-pure water, and **22.5 kton fiducial volume**
- Optically divided into inner (ID) and outer (OD) detectors, instrumented with
  - **ID:** ~11000 20”-PMTs → 40% photo-coverage
  - **OD:** ~2000 8”-PMTs mainly used as veto
The Super-Kamiokande Experiment

- More than 20 years of operation and data taking

<table>
<thead>
<tr>
<th>Period</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>1996 to 2001 Start</td>
</tr>
<tr>
<td>SK-II</td>
<td>2003 to 2005 20% PMT coverage after accident</td>
</tr>
<tr>
<td>SK-III</td>
<td>2006 to 2008 Resume 40% PMT coverage</td>
</tr>
<tr>
<td>SK-IV</td>
<td>2008 to 2018 Electronics upgrade</td>
</tr>
<tr>
<td>SK-V</td>
<td>2019 to 2020 Upgrade for Gd-loading</td>
</tr>
<tr>
<td>SK-Gd1</td>
<td>2020 to... Largest Gd-doped WC detector</td>
</tr>
</tbody>
</table>

- Wide variety of fundamental physics over a wide range of energies:
  - Solar, atm., LBL, SN and astrophysical vs, proton and exotic nucleon decays, dark matter
- Still at the forefront with its latest upgrade, SuperK-Gd
  - Will eventually reach a concentration of 0.2% of Gd, capturing 90% of the neutrons
- Even richer physics capabilities:
  - First measurement of DSNB
  - Search for solar antineutrinos
  - Background reduction for proton-decay
  - Improved distinction of $\nu$s and $\bar{\nu}$s at higher energies
The Super-Kamiokande Experiment

**e-like**

Super-Kamiokande IV
Run 65720 Sub 275 Event 51523895
09:10:19-19:55:15
Inner: 1453 hits, 199.1 ps
Outer: 3 hits, 3 ps
Trigger: 0x00000007
E_wall: 531.0 cm
E_vac: 234.0 MeV
n_e-like, p = 104.0 MeV/c

**μ-like**

Super-Kamiokande IV
Run 65718 Sub 22 Event 3976280
09:10:19-19:35:31
Inner: 9809 hits, 17985 ps
Outer: 1 hits, 1 ps
Trigger: 0x00000007
E_wall: 497.7 cm
E_vac: 2.8 GeV
m_μ-like, p = 105.1 MeV/c
Atmospheric Neutrinos

- Neutrinos produced due to the interaction of cosmic rays and Earth’s atmosphere

- Large statistics, but not enough yet
  - wide range of energies: $O(10^{-1})$ GeV to $O(10^2)$ GeV
  - wide range of baselines: $O(10)$ km to $O(10^4)$ km, half of them through the Earth

- Detailed and specific simulations are required to compute the neutrino flux

- SK discovered the **atmospheric neutrino oscillations** (Nobel 2015)
Atmospheric Neutrino Oscillations

Vacuum oscillations: neutrinos coming from above

$$|\bar{\nu}_i\rangle = \sum_{\ell} U_{\nu\nu}^{\ell\ell} |\bar{\nu}_\ell\rangle$$

$$U_{\nu\nu} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Neutrino coming from below, pass through the Earth changing the effective Hamiltonian and thus, the neutrino propagation

$$H_{\text{eff}} = H_0 + H_{CC} = H_0 \pm \sqrt{2}G_FN_e \text{diag}(1, 0, 0)$$

- matter potential is opposite for $\bar{\nu}_s$
- mass ordering changes the matter (MSW) effects between $\nu_s$ and $\bar{\nu}_s$
SK Atmospheric Neutrino Oscillation Analysis

Atmospheric neutrinos are sensitive to crucial oscillation parameters:

- **Neutrino mass ordering**: e-like, > 1 GeV
- **Leptonic $\delta_{CP}$ phase**: < 1 GeV
- **Octant of $\theta_{23}$**: > 1 GeV

\[ \textit{Separation of } \nu \textit{ and } \bar{\nu} \textit{ is crucial} \]

**Analysis updates since last publication** [Phys. Rev. D 97, 072001]

- SK-IV electronics allows for neutron tagging on hydrogen, with an efficiency of 25%
  - New samples in SKIV for better single-ring $\nu/\bar{\nu}$ separation
  - Usual sample scheme for SKI-III

- **New event selection for Multi-Ring** events based on Boosted Decision Tree
- New Monte-Carlo using **NEUT 5.4.0** with updated cross-section models and systematics
- Changed **zenith binning** to better target the **matter effects**
- Total of 3244.4 days
Neutron tagging improves the sensitivity to the mass hierarchy and the CP-phase.
SK Atmospheric Neutrino Oscillation Analysis

Neutron tagging improves the sensitivity to the mass hierarchy and the CP-phase.

Improved Multi-Ring event classification enhances the sensitivity to the ordering.
Results from the SK Atm. Neutrino Osc. Analysis

<table>
<thead>
<tr>
<th>930 bins</th>
<th>$\chi^2$</th>
<th>$\theta_{13}$ (reac.)</th>
<th>$\delta_{\text{CP}}$</th>
<th>$\theta_{23}$</th>
<th>$\Delta m_{23} \times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK (NH)</td>
<td>1037.5</td>
<td>0.0218</td>
<td>4.36$^{+0.88}_{-1.39}$</td>
<td>0.44$^{+0.05}_{-0.02}$</td>
<td>2.40$^{+0.11}_{-0.12}$</td>
</tr>
<tr>
<td>SK (IH)</td>
<td>1040.7</td>
<td>0.0218</td>
<td>4.54$^{+0.88}_{-1.32}$</td>
<td>0.45$^{+0.09}_{-0.03}$</td>
<td>2.40$^{+0.09}_{-0.32}$</td>
</tr>
</tbody>
</table>
Comparison with previous results

- Preference for normal mass ordering at C.L. 86%
- Stronger rejection of small values of CP-phase
- Data prefers first octant and the contours for $\theta_{23}$ are significantly more constraining
Explicit fit to the data (traditional SK atm. samples)
Explicit fit to the data *(neutron-tagging SK atm. samples)*

**Preliminary**
The hierarchy preference, a closer look

Significance resides mainly in the purity of $\nu_e$-like samples

→ Improved in Multi-Ring with new event selection

→ Improved in Single-Ring with new sample definition using neutrons

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Results in context

Preliminary
Prospects for the SuperK-Gd Atm. ν Osc. Analysis

The **SuperK-Gd** upgrade has finally started in July 2020.

The detector is fully operational and acquiring data with its present Gd concentration. **0.011% Gd**

- ~50% of neutron tagging efficiency (double the H-tagging eff.)

In addition to its impact to low energy physics, we have already seen the **importance of neutron tagging in the atm. ν analysis**

With greater neutron tagging efficiency:

- Much better classification of neutrinos and antineutrinos
- Improve the neutrino energy reconstruction, as they carry information about the invisible energy
- Provide additional power in discriminating CC events from NC events

Complementary studies and measurements will be needed, especially for the two last items as they rely on large neutron multiplicities (>10)
Conclusions

- After 25 years since the beginning, SK has rejuvenated once again to stay at the forefront of $\nu$ physics → **SuperK-Gd**

- Discovery of neutrino oscillations in 1998 and currently providing some of the most precise measurements of the oscillation parameters

- **Updated and upgraded atmospheric neutrino analysis**
  - Preference for large ($\sim 3\pi/2$) CP-phase values, agreeing with LBL experiments
  - Preference for normal mass ordering at 86% C.L.
  - Preference for first octant of $\theta_{23}$

- Expecting still improved performance and results from SuperK-Gd data and from the acquired experience over the years