Neutrino oscillation physics potential of Hyper-Kamiokande

Linda Cremonesi\textsuperscript{1},
for the Hyper-Kamiokande Collaboration

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\textsuperscript{1}currently at University College London
1. The Hyper-Kamiokande experiment

2. Tokai to Hyper-K

3. Physics sensitivity

4. Summary
Hyper-Kamiokande is a multi-purpose Water-Cherenkov detector with a variety of scientific goals:

- Neutrino oscillations (atmospheric, accelerator and solar);
- Neutrino astrophysics;
- Proton decay;
- Non-standard physics.
Hyper-Kamiokande: overview

- Total Volume: 0.99 Mton
- Inner Volume: 0.75 Mton
- Fiducial Volume: 0.56 Mton (0.056\times10)
- Photo sensors: SK-type PMTs
- Inner detector: 99,000 20” PMTs
- Outer detector: 25,000 8” PMTs
- Nominal site: Tochibora mine
- Reconstruction: fiTQun/BONSAI

- 2 tanks lying along-side, divided in 10 compartments;
- Compartments are optically separated;
- Egg-shape cross section;
- 20% photocathode-coverage;
- Fiducial volume: 25 times larger than Super-Kamiokande;
- Detector simulation studied with WCSim (Geant4, Water Cherenkov simulation programme);

Water Cherenkov: proved technology and scalability

- Excellent PID at sub-GeV region (> 99%);
- Large mass \rightarrow statistics always critical for any measurement
Tokai to Hyper-K long-baseline experiment

Natural extension of T2K experiment

- Upgraded facility at J-PARC will deliver a muon (anti-)neutrino beam towards Hyper-K ($\approx 0.75-1$ MW);
- $2.5^\circ$ off-axis narrow-band beam:
  - Suppresses high energy background;
  - $E_\nu \approx 0.6$ GeV peak at oscillation maximum;
- Pure $\nu_\mu$ beam with $< 1\% \nu_e$ contamination.
Near and intermediate detectors

- Different options for near detectors (at 280 m) are being investigated:
  - Upgraded INGRID (on axis detector for beam mean energy measurements) and ND280 (off axis detector for neutrino flux measurement and constraint of systematic uncertainties);
  - Addition of new detectors, like a 3D grid-like neutrino near detector with a water target (WAGASCI, see poster session), a high pressure TPC\(^2\) or a water-based liquid scintillation detector\(^3\).

- Add new water-based intermediate (1-2 km) detector to better constraint uncertainties on flux and cross-section.

  **nuPRISM**
  (arXiv:1412.3086 [physics.ins-det])

  Water column detector to minimise dependence on \(\nu\) interaction sampling the beam at several off-axis angles;

  **TITUS**
  (arXiv:1504.08272 [physics.ins-det])

  - A water Cherenkov detector Gd doped, surrounded by Muon Range Detector, to minimise systematic errors;

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Physics potential

- All results shown today are reported in *Prog. Theor. Exp. Phys. (2015) 053C02*.

- Assumptions:
  - Integrated beam power: $7.5 \text{ MW} \times 10^7 \text{ sec}$ (i.e. 0.75 MW for 10 years running) $\rightarrow 1.56 \times 10^{22}$ POT;
  - $\nu : \text{running/} \overline{\nu} \text{ running} \rightarrow 1:3$;
  - Normal mass hierarchy with $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$ are assumed.

- Physics potential evaluated with a simultaneous fit of the appearance and disappearance spectra;

- Realistic estimation of the systematic uncertainties (based on the experience of T2K);
Systematic uncertainties assumptions

1. **Flux and ND constrained uncertainties** → conservatively assumed to be the same as T2K;

2. **ND-independent cross-section uncertainties** → assumed improvements due to availability of water target and new samples in ND;

3. **Far detector uncertainties** → reduced due to availability of larger atmospheric sample for systematics studies.

<table>
<thead>
<tr>
<th></th>
<th>Flux &amp; ND-constrained</th>
<th>ND-independent cross section</th>
<th>Far detector</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ mode</td>
<td>App</td>
<td>3.0%</td>
<td>1.2%</td>
<td>0.7%</td>
</tr>
<tr>
<td></td>
<td>Disapp</td>
<td>2.8%</td>
<td>1.5%</td>
<td>1.0%</td>
</tr>
<tr>
<td>$\bar{\nu}$ mode</td>
<td>App</td>
<td>5.6%</td>
<td>2.0%</td>
<td>1.7%</td>
</tr>
<tr>
<td></td>
<td>Disapp</td>
<td>4.2%</td>
<td>1.4%</td>
<td>1.1%</td>
</tr>
</tbody>
</table>
**ν\textsubscript{e} appearance**

The expected number of ν\textsubscript{e} candidate events.

### Appearance τ mode

![Appearance τ mode graph](image)

### Appearance ¯ν mode

![Appearance ¯ν mode graph](image)

<table>
<thead>
<tr>
<th>ν mode</th>
<th>signal</th>
<th>ν\textsubscript{μ} → ν\textsubscript{e}</th>
<th>¯ν\textsubscript{μ} → ¯ν\textsubscript{e}</th>
<th>ν\textsubscript{μ}/¯ν\textsubscript{μ} CC</th>
<th>ν\textsubscript{e}/¯ν\textsubscript{e} CC</th>
<th>NC</th>
<th>BG Total</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν mode</td>
<td>3016</td>
<td>28</td>
<td>11</td>
<td>523</td>
<td>172</td>
<td>706</td>
<td>3750</td>
<td>3750</td>
</tr>
<tr>
<td>¯ν mode</td>
<td>396</td>
<td>2110</td>
<td>9</td>
<td>618</td>
<td>265</td>
<td>891</td>
<td>3397</td>
<td>3397</td>
</tr>
</tbody>
</table>
Effect of $\delta_{CP}$ at Hyper-K

**Neutrino mode: Appearance**

- **Number of events/50 MeV**
  - $0$
  - $50$
  - $100$
  - $150$
  - $200$
  - $250$
  - $300$
  - $350$
  - $400$

- **Reconstructed Energy $E_{\text{rec}}$ (GeV)**
  - $0$
  - $0.2$
  - $0.4$
  - $0.6$
  - $0.8$
  - $1$
  - $1.2$

**Antineutrino mode: Appearance**

- **Number of events/50 MeV**
  - $-150$
  - $-100$
  - $-50$
  - $0$
  - $50$
  - $100$
  - $150$

- **Reconstructed Energy $E_{\text{rec}}$ (GeV)**
  - $0$
  - $0.2$
  - $0.4$
  - $0.6$
  - $0.8$
  - $1$
  - $1.2$

**Difference of events/50 MeV**

- $(\delta=90) - (\delta=0)$
- $(\delta=-90) - (\delta=0)$
- $(\delta=180) - (\delta=0)$
The expected number of $\nu_\mu$ candidate events.

### $\nu_\mu$ Disappearance

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\nu_\mu$ CC</th>
<th>$\bar{\nu}_\mu$ CC</th>
<th>$\nu_e$ CC</th>
<th>$\bar{\nu}_e$ CC</th>
<th>NC</th>
<th>$\nu_\mu \rightarrow \nu_e$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ mode</td>
<td>17225</td>
<td>1088</td>
<td>11</td>
<td>1</td>
<td>999</td>
<td>49</td>
<td>19372</td>
</tr>
<tr>
<td>$\bar{\nu}$ mode</td>
<td>10066</td>
<td>15597</td>
<td>7</td>
<td>7</td>
<td>1281</td>
<td>6</td>
<td>26964</td>
</tr>
</tbody>
</table>
Sensitivity to $\delta_{CP}$

76% (58%) of $\delta_{CP}$ space covered at 3$\sigma$ (5$\sigma$) with better than 19 degrees uncertainty

- Assuming normal MH, $\sin^2 2\theta_{13} = 0.1$, $\sin^2 \theta_{23} = 0.5$ and $\Delta m^2_{32} = 0.0024$ eV
- (left) Fraction of $\delta_{CP}$ space for which $\sin \delta_{CP} = 0$ can be excluded with 3$\sigma$/5$\sigma$.
- (right) 1 $\sigma$ uncertainty as a function of the integrated beam power.
Sensitivity to $\theta_{23}$

Octant resolution w/ reactor $\theta_{13} \rightarrow$ wrong octant rejection for $\sin^2 \theta_{23} < 0.46$ or $> 0.56$.

- Expected 1$\sigma$ uncertainty of $\Delta m_{32}^2$ better than $1.5 \times 10^{-5}$ eV$^2$ for NH/IH.
- Expected 1$\sigma$ uncertainty of $\sin^2 \theta_{23}$:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NH</th>
<th>IH</th>
</tr>
</thead>
<tbody>
<tr>
<td>True $\sin^2 \theta_{23}$</td>
<td>0.45</td>
<td>0.50</td>
</tr>
<tr>
<td>NH</td>
<td>0.006</td>
<td>0.015</td>
</tr>
<tr>
<td>IH</td>
<td>0.006</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Without reactor

With reactor
Sensitivity to Mass Hierarchy

Significance of MH determination as a function of the Hyper-K lifetime

- Use atmospheric neutrinos to determine mass hierarchy;
- $3\sigma$ after 10 years data taking for $\sin^2 \theta_{23} > 0.42$ (0.43) for NH (IH)
The Hyper-Kamiokande experiment offers a variety of physics goals, in particular measurement of neutrino oscillation:

- **76% (58%) of $\delta_{CP}$ space covered at $3\sigma$ ($5\sigma$) with better than 19 degrees uncertainty;**

- If mass hierarchy is not known, Hyper-K can reject wrong hierarchy with more than $3\sigma$;

- Resolve $\theta_{23}$ octant degeneracy with help of reactor constraint on $\theta_{13}$;

- Very broad physics potential (solar neutrinos, supernova neutrinos, proton decay, etc.);

- Find out more during the Poster session → Mark Rayner “Status of the Hyper-Kamiokande Project”.

International proto-collaboration has been formed (13 countries, ≈250 members);

Work ongoing worldwide in all the aspects of the experiment;

Cooperation with KEK-IPNS/ICRR to develop the project;

Design Report being prepared in 2015;

Once the budget is approved, the construction can start in 2018 and data taking around 2025.
THANK YOU
Sensitivity studies

- Sensitivity to oscillation parameters evaluated using a binned likelihood based on the reconstructed neutrino energy distribution developed for the T2K experiment;
- Fit is performed using both $\nu_e (\bar{\nu}_e)$ appearance and $\nu_\mu (\bar{\nu}_\mu)$ disappearance samples simultaneously.
- Systematic uncertainties are implemented as a covariance matrix based on the experience and prospects of T2K experiment;
- Event selection is the same as T2K official selection for $\nu_e$ appearance and $\nu_\mu$ disappearance analysis.

- Integrated beam power: $7.5 \text{ MW} \times 10^7 \text{ sec}$ (i.e. 0.75 MW for 10 years running) $\rightarrow 1.56 \times 10^{22} \text{ POT};$
- Horn current: $\pm 320 \text{ kA};$
- $\nu : \bar{\nu} \rightarrow 1:3;$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\sin^2 2\theta_{13}$</th>
<th>$\delta_{CP}$</th>
<th>$\sin^2 \theta_{23}$</th>
<th>$\Delta m^2_{32}$</th>
<th>$\sin^2 2\theta_{12}$</th>
<th>$\Delta m^2_{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>0.10</td>
<td>0</td>
<td>0.5</td>
<td>$2.4 \times 10^{-3}$</td>
<td>0.8794</td>
<td>$7.6 \times 10^{-5}$</td>
</tr>
<tr>
<td>Treatment</td>
<td>Fitted</td>
<td>Fitted</td>
<td>Fitted</td>
<td>Fitted</td>
<td>Fixed</td>
<td>Fixed</td>
</tr>
</tbody>
</table>
Sensitivity to $\theta_{23}$

Table: Expected $1\sigma$ uncertainty of $\Delta m_{32}^2$ and $\sin^2 \theta_{23}$ for true $\sin^2 \theta_{23} = 0.45, 0.50, 0.55$. Reactor constraint on $\sin^2 2\theta_{13} = 0.1 \pm 0.005$ is imposed.

<table>
<thead>
<tr>
<th>True $\sin^2 \theta_{23}$</th>
<th>Parameter</th>
<th>$\Delta m_{32}^2$ (eV$^2$)</th>
<th>$\sin^2 \theta_{23}$</th>
<th>$\Delta m_{32}^2$ (eV$^2$)</th>
<th>$\sin^2 \theta_{23}$</th>
<th>$\Delta m_{32}^2$ (eV$^2$)</th>
<th>$\sin^2 \theta_{23}$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$0.45$</td>
<td></td>
<td>$0.50$</td>
<td></td>
<td>$0.55$</td>
<td></td>
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<td>NH</td>
<td>$1.4 \times 10^{-5}$</td>
<td>$0.006$</td>
<td>$1.4 \times 10^{-5}$</td>
<td>$0.015$</td>
<td>$1.5 \times 10^{-5}$</td>
<td>$0.009$</td>
<td></td>
</tr>
<tr>
<td>IH</td>
<td>$1.5 \times 10^{-5}$</td>
<td>$0.006$</td>
<td>$1.4 \times 10^{-5}$</td>
<td>$0.015$</td>
<td>$1.5 \times 10^{-5}$</td>
<td>$0.009$</td>
<td></td>
</tr>
</tbody>
</table>

Without reactor

With reactor
Sensitivity to $\delta_{CP}$

$77\% \ (61\%)$ of $\delta_{CP}$ space covered at $3\sigma \ (5\sigma)$ with better than 19 degrees uncertainty

- Assuming inverted MH, $\sin^2 2\theta_{13} = 0.1$, $\sin^2 \theta_{23} = 0.5$ and $\Delta m^2_{32} = 0.0024$ eV
- (left) Fraction of $\delta_{CP}$ space for which $\sin \delta_{CP} = 0$ can be excluded with $3\sigma/5\sigma$.
- (right) $1\sigma$ uncertainty as a function of the integrated beam power.
Hyper-K schedule

Construction:
- Cavity excavation
- Access tunnels
- Tank construction
- Water filling

Operation:
- T2K will accumulate approved POT

J-PARC Power Upgrade:
- ~240kW
- 750kW and beyond

Events:
- 2015: Design report
- 2018: Construction begins
- 2025: Operation
Proton decay

\[ p \rightarrow e^+ \pi^0 \]

- 10 times better sensitivity than Super-K;
- Hyper-K surpasses SK limits in \( \approx 1 \) year;
- Hyper-K is sensitive in many different modes:
  - \( p \rightarrow e^+ \pi^0 \): \( 1.3 \times 10^{35} \) years at 90% CL;
  - \( p \rightarrow \nu K^+ \): \( 3 \times 10^{34} \) years at 90% CL;
  - \( p, n \rightarrow (e^+, \mu^+) + (\pi, \rho, \omega, \eta) \):
    - \( 10^{34-35} \) years;
  - \( K^0 \) modes;
  - \( \nu \pi^0, \nu, \pi^+ \);
  - ...
Other physics topics at Hyper-K

- **Solar Neutrinos**: 200 $\nu_s$ / day from Sun $\rightarrow$ day/night asymmetry of the solar neutrinos flux can be precisely measured at Hyper-K ($< 1\%$);
  - Currently tank optimisation ongoing to reach 6 MeV threshold (same as Super-K-2).

- **Solar flares** can be discovered at Hyper-K (important information about particle acceleration at work in solar flares);

- **Supernova burst neutrinos**: 200k $\nu_s$ from Supernova at Galactic center (10kpc) $\rightarrow$ time variation and energy can be measured with high statistics;

- **Supernova relic neutrinos**: possible with Gd doping of Hyper-K. $\approx 830$ events in 10 years in 10-30 MeV energy range.
TITUS

Tokai Intermediate Tank for Unoscillated Spectrum

2-kton Gd-doped water Cherekov tank (9.75 m x 9.75 m x 22 m) surrounded by a Muon Range Detector (MRD) covering 3/4 on the length of the sides and the downstream of the detector

- size and shape optimised looking at muon containment and pile-up;

- located at ≈ 2 km from interaction point → TITUS detector sees almost the same spectrum as at Hyper-K:
  - The maximum difference in shape is 5% at the peak energy instead of almost 20% with ND280;

- Photosensors: LAPPDs (provide excellent time/space resolution and reduce NCπ0 background) and HPDs → ANNIE experiment;

- Gd doped → 8 MeV cascade of 2/3 gammas from neutron capture:
  - reduce ν/ν̄ uncertainty to less than a percent;
  - reduce νe/νμ uncertainty to 1-2%;
  - NCπ0 rate will be known better than the current error on the axial mass;

- Can be included in the SuperNova Early Warning system;