Hyper-Kamiokande
Masaki Ishitsuka (Tokyo University of Science)
on behalf of the Hyper-Kamiokande Proto-Collaboration
The Hyper-Kamiokande project is officially approved

2020 February: First year construction budget approved by Japanese Diet
2020 May: Univ. of Tokyo President and KEK Director General signed MOU

KEK will upgrade and operate the J-PARC accelerator to produce a high-intensity neutrino beam

The University of Tokyo will construct and operate the Hyper-Kamiokande detector

Hyper-K is under construction
Operation will begin in 2027
Water Cherenkov detector

- Cherenkov ring
  - Particle identification (>99% efficiency for $\mu/e$ separation)
  - Momentum reconstruction (energy and direction)
- Scalable to larger mass ⇒ rare process (proton decay search and neutrino observation)
- Well established technology → next slide
3rd generation underground water Cherenkov detector in Kamioka

Kamiokande (1983-1996)
- Atmospheric and solar neutrino “anomaly”
- Supernova 1987A

Super-Kamiokande (1996 - ongoing)
- Proton decay: world best-limit
- Neutrino oscillation (atm/solar/LBL)
  - All mixing angles and $\Delta m^2$s

Hyper-Kamiokande (start operation in 2027)
- Extended search for proton decay
- Precision measurement of neutrino oscillation including CPV and MO
- Neutrino astrophysics

Birth of neutrino astrophysics
Discovery of neutrino oscillations
Explore new physics
The Hyper-Kamiokande detector

- High QE Box&Line PMT
- ×2 photon detection
- ×2 timing resolution
- ×2 pressure tolerance
- New detector design (cost reduction)
- R&D for large cavern
- Cavern
- Hyper-K
- Tank
- Water depth: 71 m
- Fiducial volume: 188 kt
- H: 73 m
- Φ: 69 m

Recent update:
- Lower dark rate (similar level to SK)
- Lower radioactive contamination

Precision measurement

High statistics neutrino data

New detector design by synergy of different technologies
Experimental setup of Hyper-Kamiokande

<table>
<thead>
<tr>
<th></th>
<th>Super-K</th>
<th>Hyper-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overburden</td>
<td>1000 m</td>
<td>650 m</td>
</tr>
<tr>
<td>Number of ID PMT</td>
<td>11,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Photo-coverage</td>
<td>40%</td>
<td>40% (×2 sensitivity)</td>
</tr>
<tr>
<td>Total/Fiducial vol.</td>
<td>50 / 22.5 kton</td>
<td>260 / 188 kton</td>
</tr>
</tbody>
</table>

× 8.4 fiducial volume (SK → HK)
× 2.6 beam power (J-PARC upgrade)
→ More than 20 times statistics
Hyper-Kamiokande Proto-Collaboration

18 countries, 82 institutes, ~390 people
Physics in Hyper-Kamiokande

Supernova neutrinos

Solar neutrinos

Atmospheric neutrinos

Proton decay
Long-baseline program with J-PARC neutrino beam

Experimental setup

- 2.5° off-axis $\nu_\mu$ and $\bar{\nu}_\mu$ beam peaked at 0.6 GeV (oscillation maximum at 295km)
  - Major component is QE: $E_\nu$ determined from $(p, \theta)$ of outgoing charged lepton
    - Suppress non-QE and NC contamination by selecting single-ring event
- Measures CP violation in neutrino sector from comparison of $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
  - A few % statistical uncertainties after 10 years operation with >1000 $\nu_e$ and $\bar{\nu}_e$ signals
  - Projected sensitivity based on T2K systematics uncertainties + improvements for HK
Strategy of Hyper-Kamiokande

Combination of long-baseline and atmospheric neutrino observations
⇒ Resolve parameters degeneracy

<table>
<thead>
<tr>
<th>Mass ordering</th>
<th>$\sin^2 \theta_{23}$</th>
<th>Atmospheric neutrino</th>
<th>Atm + Beam</th>
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<tbody>
<tr>
<td>0.40</td>
<td>2.2 $\sigma$</td>
<td>3.8 $\sigma$</td>
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<tr>
<td>0.60</td>
<td>4.9 $\sigma$</td>
<td>6.2 $\sigma$</td>
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</table>

<table>
<thead>
<tr>
<th>$\theta_{23}$ octant</th>
<th>$\sin^2 \theta_{23}$</th>
<th>Atmospheric neutrino</th>
<th>Atm + Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>2.2 $\sigma$</td>
<td>6.2 $\sigma$</td>
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</tr>
<tr>
<td>0.55</td>
<td>1.6 $\sigma$</td>
<td>3.6 $\sigma$</td>
<td></td>
</tr>
</tbody>
</table>

10 years with 1.3MW, normal mass ordering is assumed

Atmospheric neutrino: sensitive to mass ordering by Earth’s matter effects
⇒ Constraints on mass ordering enhance sensitivity to CP violation by long-baseline
Precision measurement of neutrino oscillations

• Exclusion of $\sin \delta_{CP} = 0$
  - $\sim 8 \sigma$ for $\delta_{CP} = -90^\circ$ (favored by T2K)
  - Good opportunity to make discovery of $CP$ violation in neutrino sector at $>5 \sigma$

• Measurement of $\delta_{CP}$
  - $23^\circ$ for $\delta_{CP} = 90^\circ$ / $7^\circ$ for $\delta_{CP} = 0^\circ$

Syst. errors (T2K 2016 + improvements for Hyper-K)
Prospects for CP violation measurement

• **Reduction of systematic uncertainties** has impact to CPV measurement
  ➢ Uncertainties on neutrino interaction models are major components ⇒ **Near detectors**

• **On-axis beam monitor** (MUMON and INGRID)

• **Off-axis magnetized tracker** (ND280) with upgrades
  ➢ Constraints on beam flux, neutrino interactions, wrong-sign components , etc.

• **Intermediate water Cherenkov detector** (IWCD)
  ➢ $\nu_e$ cross-section, $E_\nu$ vs. $E_{rec}$, NC and intrinsic $\nu_e$ BG , neutron multiplicity
ND280 upgrade plan for T2K

• **Large angle acceptance** to constrain neutrino interaction models
• Measurement of **short tracks** to identify non-QE, NC $\gamma$ etc.

SuperFGD (scintillator target tracker)
~2m³, ~2M cubes, ~60k ch

High Angle TPC

Improve reconstruction of hadron (short) tracks

Hyper-K is planning to use ND280 after T2K has finished
International contributions for further upgrades are welcome

There will be talk by Patrick Dunne on July 2nd
“Latest Neutrino Oscillation Results from T2K”
Intermediate water Cherenkov detector (IWCD)

- 1kton scale water Cherenkov detector at ~1km baseline
- Detector can vertically move ⇒ measurement at different off-axis angles

Physics target
- $\nu$-int. measurement by off-axis scanning
- $\nu_e$ cross section (3-5% for $\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\nu_e)/\sigma(\nu_\mu)$)
- NC and intrinsic $\nu_e$ BG measurement (3-4%)
- Neutron multiplicity with Gd loading

Linear sum to make monochromatic energy

Reconstruction
Neutrino astrophysics

- Observation of $\sim 10$ MeV neutrinos with the time, energy and direction
  - Unique role in multi-messenger observation
- Solar neutrinos: up-turn at vacuum-MSW transition region, D/N, hep $\nu$
- Supernova burst: explosion mechanism, BH/NS formation, alert with $1^\circ$ pointing
- Supernova Relic Neutrino (SRN): stellar collapse, nucleosynthesis and history of the universe

Posters
- #65: Radon background model for Hyper-Kamiokande (Guillaume Pronost)
- #391: Supernova Model Discrimination with Hyper-Kamiokande (Jost Migenda)

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Modulation induced by SASI statistical fluctuation in HK

SRN rate

Calculation from FV and $E_{th}$

Efficiency is not accounted

$\sim 70k \nu$’s at 10kpc
Proton decay search

• One possible approach to reach GUT energy scale
• Extend proton decay search by one order of magnitude beyond the current limits

After 10 years of HK
if $\tau = 1.7 \times 10^{34}$ years ...

Free proton

Bound proton

$\nu \rightarrow e^+ + \pi^0$

$10^{35}$ yr

$p \rightarrow \nu + K^+$

$3 \times 10^{34}$ yr
Detector R&D for Hyper-Kamiokande

Multi-PMT module: (ref. KM3NeT)
High resolution Cherenkov ring imaging essential for IWCD
Consider to use for part of HK

20-inch MCP PMT:
Test in dark room

IWCD simulation
Prototype at TRIUMF
Electronics at INFN

mPMT in Memphyno water tank in France

Box&Line PMT in Super-K
Detector R&D for Hyper-Kamiokande

**Outer detector:** PMT + WLS plate (UK)

**PMT cover** in Spain

**ID mockup** at ICRR

**Sync and clock system** test bench at TokyoTech

**Underwater electronics:**
- Case design and feedthrough
- Master clock generator
- TDC-QTC prototype

**3-inch water proof PMT**
Hyper-Kamiokande schedule

FY2020 | FY2021 | FY2022 | FY2023 | FY2024 | FY2025 | FY2026 | FY2027 | FY2028
---|---|---|---|---|---|---|---|---
Geo. survey | Access/ Cavern design | Cavern excavation | Tank const. | PMT installation
PMT production | PMT cases, mirrors, electronics etc. | Water system | Filling water | Operation
Upgrade of J–PARC accelerator and neutrino beamline | Near detector facility, R&D, production | ND construction
Summary

• Hyper-Kamiokande is the next generation underground water Cherenkov detector in Kamioka aiming for groundbreaking physics:
  - Search for proton decay by one order of magnitude beyond the current limits
  - Reveal full picture of neutrino oscillations including CP violation and mass ordering
    - Unprecedented high statistic neutrino data with upgraded J-PARC neutrino beam
  - Unique contribution to astrophysics by the neutrino observations (solar, SN burst, SRN)
• Hyper-Kamiokande is officially approved in Japan
  - Hyper-Kamiokande is under construction and will begin operation in 2027
  - International R&D is actively ongoing to improve the physics potential
    - Near detectors, photo-sensors and covers, electronics, outer detector etc.
  - New collaborators are welcome to contribute to the detectors and the pioneering physics!