The Hyper-Kamiokande Project
A New Adventure in $\nu$ Physics

Alessandro Bravar
on behalf of the HK Proto-Collaboration

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Hyper-K Physics Overview
Broad Science Program with Hyper-K

Neutrino oscillation physics
- comprehensive study with beam and atmospheric neutrinos
  - determination of neutrino mass hierarchy
  - determination of $\theta_{23}$ octant
  - measurement of CP Violation in leptonic sector
  - reveal exotic scenarios

Search for nucleon decay
- possible discovery with $\sim 10 \times$ SK sensitivity
  - all visible modes including $p \rightarrow e^+ \pi^0$ and $p \rightarrow \bar{\nu} K^+$
  - reach $10^{35}$ years sensitivity

Solar neutrino physics
- precision measurement of $\Delta m^2_{21}$
  - measurement of energy spectrum upturn
  - discovery & measurement of hep neutrinos

Neutrino Astrophysics
- high statistics measurement of SN burst neutrinos
  - detection and study of relic SN neutrinos
  - indirect Dark Matter search from Galactic Core, Sun, Earth

Geophysics (“neutrinography” of Earth’s interior)
The Hyper-Kamiokande Detector

Large Water Cherenkov Detector

Larger mass for more statistics

Better sensitivity by more photons with improved sensors

Optimized for cost and quick start

- Total volume: 260kton × 2
- Fiducial volume: 190kton × 2
  (~×10 of Super-K per tank)
- Start with one tank, staging
- 40% coverage with new sensor
  ×2 photon sensitivity
- 40,000 50cm ID PMTs
- 6,700 20cm OD PMTs

60 m

74 m
3 Generations of Kamioka Detectors

Kamiokande (1983-1996)

- 3 kton
- 20% coverage
- with 50 cm PMT

Super-Kamiokande (1996-)

- 50 kton
- 40% coverage
- with 50 cm PMT

Hyper-Kamiokande (~2026-)

- 260 kton $\times$ 2
- 40% coverage with high-QE 50 cm PMT

Observation of SN1987A

Discovery of $\nu$ oscillations

Prepare for the unknown
Hyper-K is listed in the MEXT (funding agency) Large Projects Roadmap

2018 – 2025 Hyper-K construction

2026 onwards
- CPV study, Atmospheric $\nu$, Solar $\nu$, Supernova $\nu$, Proton decay, …

Staged approach: 2nd identical tank starts operation 6 years after the first one
The Hyper-K Collaboration

Formed in Jan. 2015

15 countries

~300 members (and growing)
The Kamioka Site

The candidate site located in Tochibora, under Mt. Nijugo-yama
~8 km south from Super-K, 295 km from J-PARC, 2.5° off-axis
overburden ~650 m (~1755 m w.e.)

Cavern can be built with existing technologies
Upgraded Photo-Sensors

Super-K PMT
used in SK for 20 yrs

HQE SK PMT
under validation

50 cm HQE Box&Line PMT
under validation

Venetian Blind
Box-and-Line Dynode

Enhanced performance

Photo Detection Efficiency \(2 \times\) bigger

Timing resolution \(2 \times\) as good

Increased Pressure tolerance \(\times\) 2

- enhance \(p \rightarrow \bar{\nu} K^+\) signal
- solar \(\nu\) lower threshold
- neutron capture signature
  \((n + p \rightarrow d + \gamma - 2.2\text{MeV} \gamma)\)
Photo-Sensor Developments

Hybrid Photo Detectors (HPDs)

50 cm HQE HPD w/ 20mm φ AD

R&D development and validation

Multi-PMT

directional sensitivity
usage for ID/OD
higher pressure tolerance
no compensation for geomagnetism needed
Cavern and Tank

Cavern geological survey and find analysis undertaken

Water containment: 3 layers of lining
outer water-proof sheet; concrete; High Density Polyethylene (HDPE) sheet (constructed simultaneously to reduce cost and time)
Hyper-K detector consists of inner detector (ID) and outer detector (OD)

Seismic response analysis: earthquakes do not damage the detector (PMTs) even if no water in the tank
Electronics

Candidates for signal digitization:
1. Charge to Time converter with FPGA-based TDC (similar to SK)
2. ~100MHz FADC + digital signal processing
3. GHz digitizers based on capacitor arrays

Front-end electronics requirements:
- wide charge dynamic range
  0.1 to 1250 p.e.
- good time resolution
  $\Delta T = \text{sub-nsec}$,
- self triggering
  (channel by channel)
- low power consumption
  $< 1W/\text{ch}$

Front-end electronics, HV, and network connections under water
From J-PARC to Kamioka

Nominal design:
1st tank in Tochibora with the second tank following after 6 years

260 kton Water Cherenkov Detector

Upgraded J-PARC neutrino beam
New / upgraded near detectors
Beam Events in Hyper-K

$\nu_e$ appearance

10 years data taking

$\nu_\mu$ disappearance

difference from $\delta_{CP} = 0$
0.75 MW in 2018
MR power supply upgrade

1.3 MW by ~2026
repetition cycle from 2.48 s to 1.3 s
# protons $2.4 \times 10^{14}$ / spill to $3.2 \times 10^{14}$ / spill

Given highest priority in KEK Project Implementation Plan (2016)
The Near Detectors @ J-PARC

Upgraded ND280 Near Detector

- Designed to address $\nu$ – Nucleus interactions and modeling
- Enlarge phase space (4\pi coverage)
- Efficiency for short hadron tracks with proton reconstruction
- Improve electron neutrino selection
- **New:** horizontal TPCs, scintillator target

Intermediate Water Cherenkov

- Located at $\sim$1 km from $\nu$ source
- Off-axis angle spanning orientation
- Vary $\nu$ peak energy
- Probe neutrino energy vs. reconstructed energy
- Gd loading to measure neutron production
Hyper-K Sensitivity to $\delta_{CP}$

$\sin \delta_{CP} = 0$ exclusion:

- ~8-σ significance if $\delta_{CP} = \pm 90^\circ$
- ~6-σ significance if $\delta_{CP} = \pm 45^\circ$
- ~80% coverage of $\delta_{CP}$ parameter space

The comparison with DUNE is just for a reference. The real sensitivity depends on the assumption.
$$\delta(\Delta m^2_{32}) \sim 1.4 \times 10^{-5} \text{ eV}^2$$
→ mass hierarchy sensitivity
  in combination with reactor

$$\delta(\sin^2 \theta_{23}) \sim 0.015 \text{ (for } \sin^2 \theta_{23} = 0.5)$$
  ~0.006 \text{ (for } \sin^2 \theta_{23} = 0.45)$$
→ octant determination input to models
Proton decay $p \rightarrow e^+ \pi^0$ is a favoured model of many GUTs.

Similar analysis as in SK but with neutron tagging (remove events with a tagged neutron) thanks to improved PMTs.

“Background free” measurement of proton decay
- 0.06 Bkg events / Mt $\times$ year
- Bkg atm-$\nu$ events are largely reduced by “neutron tag” with H capture
- eff.~70% with new PMT
  $(n + p \rightarrow d + \gamma$ (2.2MeV $\gamma$)

3-$\sigma$ discovery sensitivity reaches $\tau_p/BR = 10^{35}$ years for $p \rightarrow e^+ \pi^0$

Best discovery potential for GUT signal!
Proton $p \rightarrow \bar{\nu} K^+$ Decay Sensitivity

$p \rightarrow \nu K^+$ decays are one of the most prominent features of Supersymmetric GUTs

$K^+$ below Cherenkov threshold
→ observe $K^+$ decay

$K^+ \rightarrow \mu^+ \nu_{\mu}$ (BR 65%)  
$K^+ \rightarrow \pi^+ \pi^0$ (BR 21%)

3-σ discovery sensitivity
$\tau_p/BR = 3 \times 10^{34}$ years for $p \rightarrow \bar{\nu} K^+$
Bkg Suppression in Proton Decay

Neutron tagging with hydrogen capture (2.2 MeV $\gamma$)

- Tag and suppress atmospheric $\nu$ background
- Already in use for p-decay search in SK-4 (~20% eff.)
- Extrapolated to Hyper-K with 40% high-QE PMT
- 70% tagging efficiency possible
- Gadolinium option also under consideration
# Nucleon Decay Searches

Need broad searches including other possible modes

- Robust estimate based on Super-K performance
- $\sigma$ potential exceeds current limits by an order of magnitude (or more)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Sensitivity (90% CL) [years]</th>
<th>Current limit [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow e^+\pi^0$</td>
<td>$1.2\times10^{35}$</td>
<td>$1.4\times10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \bar{\nu}K^+$</td>
<td>$2.8\times10^{34}$</td>
<td>$0.7\times10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+\pi^0$</td>
<td>$9.0\times10^{34}$</td>
<td>$1.1\times10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow e^+\eta^0$</td>
<td>$5.0\times10^{34}$</td>
<td>$0.42\times10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+\eta^0$</td>
<td>$3.0\times10^{34}$</td>
<td>$0.13\times10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow e^+\rho^0$</td>
<td>$1.0\times10^{34}$</td>
<td>$0.07\times10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+\rho^0$</td>
<td>$0.37\times10^{34}$</td>
<td>$0.02\times10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow e^+\omega^0$</td>
<td>$0.84\times10^{34}$</td>
<td>$0.03\times10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+\omega^0$</td>
<td>$0.88\times10^{34}$</td>
<td>$0.08\times10^{34}$</td>
</tr>
<tr>
<td>$n \rightarrow e^+\pi^-$</td>
<td>$3.8\times10^{34}$</td>
<td>$0.20\times10^{34}$</td>
</tr>
<tr>
<td>$n \rightarrow \mu^+\pi^-$</td>
<td>$2.9\times10^{34}$</td>
<td>$0.10\times10^{34}$</td>
</tr>
</tbody>
</table>

- Discovery possible!
Solar Neutrino Physics

2-σ tension between Solar and reactor (KamLAND) neutrinos on $\Delta m^2_{21}$

measurement with $\nu_e$ possible only with Solar neutrinos

sensitivity to address solar and reactor neutrinos discrepancy

Definite observation (5-σ) of Day-Night asymmetry due to Earth matter effects sensitive to $\Delta m^2_{21}$

Solar+KamLAND
KamLAND

from no Day-Night asymmetry from KamLAND best fit params

6.5 MeV Energy threshold

2 tanks staged
Spectrum Upturn of Solar $\nu$

Spectrum upturn in low energy not yet seen

various non-standard scenario possible

$> 5$-$\sigma$ possible with BG/calibration similar to SK

low E threshold w/ high photon efficiency essential

Also solar physics: short time variation, hep neutrinos, …
More Physics with Atmospheric $\nu$

Atmospheric $\nu$: neutrinos with various energy, flight length, and flavor

$\nu_\tau$ cross section measurement

Sterile neutrinos

Lorentz violation studies

Geophysics

chemical composition of Earth’s outer core using matter effect
Supernova Burst Neutrinos

Measurement of neutrino flavor, energy, time profile will provide detailed information on core-collapse supernova $\nu_e$ from neutronization: 12 ~ 80 events

SN explosion mechanism

Galactic SN

Large statistics: 104,000 ~ 158,000 events (10 kpc)
Time spectrum of SN$\nu$: SN model separation, SN burst time
Energy spectrum measurement: $\Delta E/E \sim 20\%$ at 10-20 MeV
Direction, time, fluctuations of $\nu$ flux
Expect tens of events from Andromeda
Supernova Relic Neutrinos

Neutrinos from past SN fill our Universe

Detectable with enough sensitivity

Measurement will probe:
- star formation rate
- black hole generation
- energy spectrum SN ν

Bkg suppression with neutron tagging

Expected events in HK in 10 years
~98 ± 20 (4.8σ).
Indirect Dark Matter Searches

WIMP annihilation in Sun and/or Galaxy center

\[ \chi\chi \rightarrow \nu\nu \]

Unique sensitivity especially for low mass region

Improve $3-10 \times$ over SK limit

From Galactic center
New Idea: 2\textsuperscript{nd} Tank in Korea

Advantages of a second tank in Korea

Measure CP effect at 2\textsuperscript{nd} oscillation maximum (3 × larger)

Enhanced mass hierarchy sensitivity (longer baseline)

Reduced backgrounds due to the deeper site

2.50 Off-axis ~1100 km baseline

\begin{align*}
\text{1\textsuperscript{st} osc. peak} & & P(\nu_\mu \rightarrow \nu_e) \text{ at HK} \\
(295 \text{ km baseline}) & & P(\nu_\mu \rightarrow \nu_e) \text{ in Korea} \\
(1000 \text{ km baseline}) & \\
\end{align*}
Conclusions

A new adventure in \(\nu\) Physics to start

Proto-Collaboration established on January 15\(^{th}\) 2015
Collaboration growing ~300 members from 15 countries

A rich physics program:
- atmospheric, SN, solar, accelerator neutrinos
- proton decay

Optimized detector configuration:
- built on successful technology established with past/ongoing experiments
- higher photo-coverage
- improved PMTs (higher QE)

International R&D efforts underway
- photo-sensors
- electronics and DAQ
- calibrations
- geological surveys

Hyper-K is listed in the MEXT (funding agency) Large Projects Roadmap
Construction to begin in 2018, start physics in 2026
## Hyper-K Physics Potential

<table>
<thead>
<tr>
<th></th>
<th>HK (2TankHD w/ staging)</th>
</tr>
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<tbody>
<tr>
<td><strong>LBL (13.5MWyr)</strong></td>
<td>δ precision</td>
</tr>
<tr>
<td></td>
<td>7°-21°</td>
</tr>
<tr>
<td></td>
<td>CPV coverage (3/5σ)</td>
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<tr>
<td></td>
<td>78%/62%</td>
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<tr>
<td></td>
<td>sin^2θ_{23} error (for 0.5)</td>
</tr>
<tr>
<td></td>
<td>±0.017</td>
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<tr>
<td><strong>ATM+LBL (10 years)</strong></td>
<td>MH determination</td>
</tr>
<tr>
<td></td>
<td>&gt;5.3σ</td>
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<tr>
<td></td>
<td>Octant (sin^2θ_{23}=0.45)</td>
</tr>
<tr>
<td></td>
<td>5.8σ</td>
</tr>
<tr>
<td><strong>Proton Decay (10 years)</strong></td>
<td>e^+π^0 90%CL</td>
</tr>
<tr>
<td></td>
<td>1.2×10^{35}</td>
</tr>
<tr>
<td></td>
<td>νK 90%CL</td>
</tr>
<tr>
<td></td>
<td>2.8×10^{34}</td>
</tr>
<tr>
<td><strong>Solar (10 years)</strong></td>
<td>Day/Night (from 0/from KL)</td>
</tr>
<tr>
<td></td>
<td>6σ/12σ</td>
</tr>
<tr>
<td></td>
<td>Upturn</td>
</tr>
<tr>
<td></td>
<td>4.9σ</td>
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<tr>
<td><strong>Supernova</strong></td>
<td>Burst (10kpc)</td>
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<tr>
<td></td>
<td>104k-158k</td>
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<tr>
<td></td>
<td>Nearby</td>
</tr>
<tr>
<td></td>
<td>2-20 events</td>
</tr>
<tr>
<td></td>
<td>Relic (10 yrs)</td>
</tr>
<tr>
<td></td>
<td>98evt/4.8σ</td>
</tr>
</tbody>
</table>