Hyper-Kamiokande

- Introduction
- Far Detector Design
- Neutrino Astrophysics & Proton Decay
- Beam and Near Detectors
- CP Violation, Mass Hierarchy & Mixing Angles
- Construction Schedule & 2\textsuperscript{nd} Detector in Korea

Steve Playfer
NuPhys2019, London, 18\textsuperscript{th} December 2019
Hyper-K Proto-collaboration Sept. 2019 ~350 Collaborators from 17 countries

Far Detector (Kamioka)
Design is being finalised

Beam & Near Detectors (JPARC)
Conceptual Design Report in preparation

295 km

Steve Playfer, NuPhys2019, London
Hyper-K  Far Detector

8x larger than Super-K (will be largest man-made cavern in the world)
Location 8km south of Super-K

- A 260kton tank of pure water
- Inner Detector 216kt

Fiducial volume ~200kt
Up to 40% photosensor coverage (40k 20” PMTs)

- Outer Detector veto region
  1m to 2m thick (~13k 3” PMTs)
- Japanese budget request 2019 covers cavern excavation, tank, water system and half the photosensors.
  International contributions are needed for more photosensors!

Steve Playfer, NuPhys2019, London
Photosensors – 20” PMTs

These are either Hamamatsu B&L or NNVT MCP-PMT

- Quantum efficiency 30% at 390nm (x1.4 compared to Super-K)
- Collection efficiency 95% at $10^7$ gain (x1.3 compared to Super-K)
- Transit time spread 2.7ns for 1p.e.  Charge resolution 27% for 1p.e.
- Dark count rate 8.5kHz → 5.7kHz (in past 2 years) → 4kHz?
Imagesensors - mPMT Modules

We are considering adding ~5,000 multi-PMT modules

- 19 x 3” PMTs + reflectors
- Acrylic cover + optical gel
- Pressure Vessel
- Frontend Electronics
- 50cm

- 3” PMTs are Hamamatsu R14374 or ETEL D794KFL or HZC XP82B20
- Collection efficiency 45% due to packing fraction of PMTs
- Dark count rate 100-300Hz/PMT

Improved spatial accuracy, timing, dynamic range, lower dark rate?

Cost comparison mPMT $8k, 20” PMT + cover + electronics $5k

Steve Playfer, NuPhys2019, London
Block diagram (20inch PMT readout electronics)

Inside tank in waterproof case

(We can use same system for OD.)

Steve Playfer, NuPhys2019, London
A broad neutrino physics programme…
Energy range 4 MeV to 100 GeV

… and proton decay
Upward-going atmospheric neutrinos

Oscillations are sensitive to mass hierarchy, $\theta_{23}$ octant and $\delta_{CP}$

This is just for electron neutrinos! For antineutrinos the MSW peak is suppressed in NH

Steve Playfer, NuPhys2019, London
Solar Neutrinos

Day/night asymmetry depends on $1/\Delta m_{21}^2$

Expected to be a few %

From Super-K

From reactor

Solar deficit in range 3-5 MeV?

MINUIT: Vertex resolution

Can reach 4 MeV with 20% coverage + mPMTs

30-40% coverage reaches 3 MeV (but limited by radioactive backgrounds)

Steve Playfer, NuPhys2019, London
Supernova Neutrinos

SN at 10kpc expect 50-100k events in 20s. Betelgeuse would give MHz!

Expect ~10 events from SN in M31 (Andromeda)

Inverse beta decay of anti-$\nu_e$ on p gives flavour, energy and direction from $e^+$ (and n)

$\nu + e^-$ scattering also gives energy and direction. Initial spike is sensitive to oscillations.

Steve Playfer, NuPhys2019, London
Supernova Relic Neutrinos

15-40 MeV anti-$\nu_e$ from ancient SN detected by inverse $\beta$–decay

Neutron-tag crucial to reduce backgrounds $n$-tag with capture on H is 30-70% efficient (depends on dark rate and photocoverage)

$n$-tag with capture on Gd is >80% efficient (with a much lower mistag rate)
Proton Decay

We can improve limit on decay to $e^+\pi^0$ from $10^{34}$ to $10^{35}$ years.

We may eventually run into background from atmospheric $\nu$ but neutron tags help reduce this.

Can also improve limit on decay to $K^+\nu$ but the signature for this is harder and there is atmospheric $\nu$ background.

$K^+$ is below water Cherenkov threshold. Detect $K^+$ decay to 236 MeV/c $\mu^+$ in coincidence with 6.3 MeV $\gamma$ from $^{15}N^*$ decay (after $p$ decays in $^{16}O$)

Steve Playfer, NuPhys2019, London
J-PARC Beam

Off-axis 2.5 degrees

$E_\nu = 600$ MeV (peak)

1.3MW beam power

Being upgraded for T2K

Will be available at start of Hyper-K

Further upgrades?

Steve Playfer, NuPhys2019, London
Near Detectors at 280m

INGRID monitors beam position

ND280 is being upgraded for T2K in 2021

Will be available at start of Hyper-K

Further upgrades?

ND280 magnetic spectrometer for $\nu_e$ and wrong sign beam components
Intermediate Water Cherenkov

Located at 1-2km

Shaft is 50-100m deep

Tank diameter 10m, height 8m moves up and down shaft using buoyancy (pit water)

Spans off-axis angles 1 to 4°

Detector has 480 mPMTs

Measures water Cherenkov signals as function of $\nu$ energy and flavour

Determines $\nu$ cross-sections

A new detector for Hyper-K
Planned to be ready in 2026

Steve Playfer, NuPhys2019, London
Systematics aimed for by Hyper-K

### HK design report

<table>
<thead>
<tr>
<th>Flux &amp; ND-constrained cross section</th>
<th>ND-independent cross section</th>
<th>Far detector</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ν mode</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Appearance</td>
<td>3.0%</td>
<td>0.5%</td>
<td>0.7%</td>
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<tr>
<td>Disappearance</td>
<td>3.3%</td>
<td>0.9%</td>
<td>1.0%</td>
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<td>3.3%</td>
<td>0.9%</td>
<td>1.1%</td>
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CP reach depends on Syst. errors!

Stat. error ~3%

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**Figure 8.** Expected significance to exclude sin$^{2}\theta_{CP} = 0$. Three times larger statistics than nominal configuration (1 tank with 187 kton and 1.3 MW beam for 10 years) is assumed with 10 years operation of 1 Mton detector with 750 kW beam. NUMBERS TO BE CONFIRMED.

**Figure 9.** Ratio of energy spectrum predicted with CP$^{\dagger}$ and CP$^{90}$ (red), and the same ratio with 0.5% energy scale bias introduced by hand to that with the nominal energy scale with no bias (blue).

- Energy bias due to contamination of non-QE: As the neutrino energy is reconstructed from the momentum of outgoing charged lepton in single-ring events assuming QE scattering, contamination of non-QE causes bias in energy scale, as illustrated in Fig 10. Such biases are made due to nuclear effects as explained in the previous section. In addition, it was pointed out by recent studies that multi-nucleon interaction, called two particles - two holes or 2p-2h in contrast to genuine QE as 1p-1h, cause bias in neutrino energy reconstruction.

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**Table XXXVIII.** Uncertainties for the expected number of events at Hyper-K from the systematic uncertainties assumed in this study.

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**Figure 140** shows examples of the 90% CL allowed regions on the sin$^{2}\theta_{CP}$-plane resulting from the true values of CP$^{\dagger}$ = (90°, 0°, 90°, 180°). The left (right) plot shows the case for the normal (inverted) mass hierarchy. Also shown are the allowed regions when we include a constraint from the reactor experiments, sin$^{2}\theta_{CP} = 0.100 \pm 0.005$. With reactor constraints, although the CP reach depends on Syst. errors!

Stat. error ~3%
Hyper-K long baseline (10 years)

Assumes Normal Hierarchy, beam $\nu : \bar{\nu} = 1 : 3$

Neutrino mode: appearance

$\sim 1600 \, \nu_e$ events (far detector)

Antineutrino mode: appearance

$\sim 1200 \, \bar{\nu}_e$ events

$\sim 10000 \, \nu_\mu$ events

Steve Playfer, NuPhys2019, London
Long baseline beam + atmospheric $\nu$

$\sin^2 \theta_{23} = 0.45$

$\sin^2 \theta_{23} = 0.55$

Octant of $\theta_{23}$ can be resolved for $\sin^2 \theta_{23} < 0.45$ or $\sin^2 \theta_{23} > 0.55$

CP violation can be measured at $3\sigma$ ($5\sigma$) over 75% (60%) of the full range of $\delta_{CP}$

Error on $\delta_{CP} = 0$ ($\pi/2$) is $7^o$ ($20^o$)

Steve Playfer, NuPhys2019, London
Second Detector in Korea

Baseline 1100km
At 2nd maximum (750 MeV)
At 1st maximum (2 GeV)

A number of sites are being considered with off-axis beam of 1 to 2 degrees.

Aim is to build this after Kamioka far detector is running.

First far detector (Kamioka)

Second far detector (Korea)

CP violation at 2nd max is x3
Compensates for 1/R²
Same $\delta_{CP}$ statistical accuracy
Systematics smaller
More sensitivity to matter effects and non-SM physics

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Steve Playfer, NuPhys2019, London
## Construction Timeline

### 2018 - 2020
- Japanese seed-funding and U.Tokyo commitment to 2020 start

### 2020 onwards
- Funding applications in other participating countries

### Technical Report

Steve Playfer, NuPhys2019, London
December 13th 2019

Nature – December 16th 2019
Japan will build the world’s largest neutrino detector
Cabinet greenlights US$600-million Hyper-Kamiokande experiment, which scientists hope will bring revolutionary discoveries.
BACKUP SLIDES
Source water fills tank in 240 days at 45 tons/hour.

Purification, cooling and recirculation of water at 155 tons/hour.

May double this after start of experiment and add Gd.
Comparison of SK and HK PMTS

Detection efficiency $\times 1.9$

Based on 136 HK PMTs installed in Super-K in 2018
Three signal digitizers are being considered:

1) QTC chip developed for Super-K in 2008

2) FADC waveform sampling 100-250MHz

3) Switched capacitor arrays

Hit rate is driven by Supernova burst

Dynamic range is x10 less for mPMTs

Front-end electronics is inside tank

Power limit driven by water cooling

<table>
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<tr>
<th>Item</th>
<th>Requirements</th>
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<tr>
<td>Trigger</td>
<td>self triggering for each channel</td>
</tr>
<tr>
<td>PMT impedance</td>
<td>50Ω</td>
</tr>
<tr>
<td>Signal reflection</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Discriminator threshold</td>
<td>&lt;0.25 p.e. (well below 1 p.e.)</td>
</tr>
<tr>
<td>Processing speed/hit (channel dead time)</td>
<td>&lt;1 µs</td>
</tr>
<tr>
<td>Maximum hit rate</td>
<td>&gt;1 MHz for each channel</td>
</tr>
<tr>
<td>Charge dynamic range</td>
<td>0.1 to 1250 p.e. (0.2 to 2500 pC)</td>
</tr>
<tr>
<td>Charge resolution</td>
<td>RMS~ 0.05 p.e. (below 25 p.e.)</td>
</tr>
<tr>
<td>Timing LSB</td>
<td>&lt;0.5ns</td>
</tr>
<tr>
<td>Timing resolution</td>
<td>RMS &lt;0.3ns at 1 p.e.</td>
</tr>
<tr>
<td></td>
<td>RMS &lt;0.2ns above 5 p.e.</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt;1W per channel</td>
</tr>
</tbody>
</table>

Designing watertight front-end boxes (24 channels) and watertight fibre-optic/LV and signal/HV connectors

Need up to 2200 of these boxes

Another area where international contributions are expected

*Steve Playfer, NuPhys2019, London*
Data Acquisition System

Hyper-K Reference Design

Front end network

Back end network

Designed to handle nearby Supernova (Betelgeuse):

75M ν events in 1s, 180M events in 10s, 327GB of data, 1MHz hits/PMT
Calibration systems

These are based on 20 year of experience at Super-K, but need to improve accuracy at Hyper-K.

- Low energy calibration uses Linac and radioactive sources: D-T generator, Cf(Ni), Am(Be)
  Aiming at 0.5% calibration of energy scale for solar $\nu$

- High energy calibration uses cosmic ray data: Stopping muons, Michel electrons, $\pi^0$ mass
  Statistics will increase at Hyper-K

- Light injection system monitors water transparency and PMT response
Motivation for Near Detectors

- To measure the product of the unoscillated neutrino flux ($N_{\nu}$) times cross-section ($\sigma_{\nu}$) as a function of $E_{\nu}$, off-axis angle, horn current (F/B) and $\nu$ flavour ($\nu_e/\bar{\nu}_e/\nu_\mu/\bar{\nu}_\mu$).

- To predict the expected event rates in the far detector as a function of the oscillation parameters. Uncertainties in these predictions enter as systematic errors on Hyper-K CP violation measurements.

- To measure the properties of $\nu$ interactions, their detector signatures and final state particles.

The differences between the near and far detectors should be minimized.
Off Axis Measurements

- Probe cross-sections and final states as a function of $E_\nu$
- Mean energy varies from 0.4GeV ($4^\circ$) to 1.0GeV ($1^\circ$)
- Fraction of $\nu_e$ varies from 0.5% ($1^\circ$) to 1.5% ($4^\circ$), with a high energy tail from Kaon decays
- Can use linear combinations of different angles to define “quasi-monochromatic” beams
- Aim for direct measurement of $\sigma(\bar{\nu}_e)/\sigma(\nu_e)$ to few % accuracy
mPMTs improve vertex resolution compared to 8” PMTs

Tuning of event reconstruction ongoing

Also expect better angular resolution and $e/\mu/\pi^0$ separation