Near Detectors for Hyper Kamiokande

- Motivation and goals of Near Detectors
- Physics impact on HyperK
- Intermediate Water Cherenkov Detector (IWCD)
- Off-axis spanning measurements
- Neutron-tagging with Gd

Steve Playfer (on behalf of HyperK and E61)
ICHEP, Seoul, 6th July 2018
An 8x larger version of Super K in a new cavern in Kamioka mine

250 kTon detector (water)

\( L = 295 \text{ km} \)

JPARC Beam 1.3MW

\( E_\nu = 600 \text{ MeV} \)

Construction from 2019

Start of operations 2026

Main goals (within 10 years)

- CP violation in \( \nu \) oscillations with Long Baseline Beam + Atmospheric neutrinos (Talks by Ishitsuka, Bravar)
- Proton decay (Talk by Yokoyama)
- Astrophysical \( \nu \) (Talk by Shimizu)

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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 HyperK as a function of the oscillation parameters. Uncertainties in these predictions enter as systematic errors on HyperK measurements.

- To measure the properties of $\nu$ interactions, their detector signatures and final state particles
  - Essential information for LBL accelerator $\nu$
  - Important input to p decay (atmospheric $\nu$ backgrounds)
  - Improves reconstruction of atmospheric $\nu$

- The differences between the near and far detectors should be minimized.

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Unoscillated Beam Flux

- Need unoscillated $\nu_\mu$ rate ($\nu_\mu$-CC) from 1-ring $\mu$ candidates
- Need intrinsic $\nu_e$ component ($\nu_e$-CC ~1%) from 1-ring e candidates
- Can calculate beam composition from hadronic interactions to 5% accuracy (see backup)
- Intermediate Water Cherenkov Detector (IWCD) measure CC 1e events to ~3% (stat.)

![HyperK study with IWCD](image)

**FIG. 5.** The neutrino spectra at Hyper-K for the neutrino enhanced (left) and antineutrino enhanced (right) components (4) at the IWCD and HK and the ratio of unoscillated $\nu_e$ events ($\nu_e$-CC) to CC 1e events to ~3% (stat.)
Neutrino Interactions

- Quasielastic Charged Current (CCQE) production of e or μ
- Separate out samples with additional π⁺ (and π⁰, p)
- Model additional contributions to the CC 0π sample from multi-nucleon (2p2h), resonant processes, Neutral Current (NC), ν background, and final state interactions (FSI)
- Targets water(O), scintillator(C)

They differ by a few %

- For appearance need σ(νₑ)
- Plan is to measure σ(νₑ)/σ(ν_μ)
- Currently T2K measures σ(ν_μ) and uses theory to relate CCQE rates for μ and e

(T2K talks by Wilkinson/Hadley/Zito)

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Systematics aimed for by HyperK

<table>
<thead>
<tr>
<th>HK design report</th>
<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></td>
<td>Appearance</td>
<td>3.0%</td>
<td>0.5%</td>
<td>0.7%</td>
</tr>
<tr>
<td></td>
<td>Disappearance</td>
<td>3.3%</td>
<td>0.9%</td>
<td>1.0%</td>
</tr>
<tr>
<td></td>
<td>Appearance</td>
<td>3.2%</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td></td>
<td>Disappearance</td>
<td>3.3%</td>
<td>0.9%</td>
<td>1.1%</td>
</tr>
</tbody>
</table>

More details in backup

CP reach depends on Syst. errors!

Stat. error ~3%
Overview of Near Detectors at JPARC

- INGRID is an on-axis detector
  Measures beam position to 0.2mrad and monitors flux

- ND280 is an off-axis (2.5°) magnetic detector
  Measures CC production of right and wrong-sign µ and e
  Being upgraded for T2K2 (Talk by M.Zito)

- E61 is a proposed Intermediate Water Cherenkov Detector (IWCD)
  Uses almost identical detector technologies to HyperK
  The subject of the rest of this talk

... and for completeness there are two other near detectors

- WAGASCI/BabyMIND measures ν cross-sections in water (Talk by A.Blondel)

- NINJA measures ν cross-sections with nuclear emulsion

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Intermediate Water Cherenkov

~1kTon Water Cherenkov detector

Diameter 8m (Inner Detector), 10m (Outer Detector) contains charged muons up to ~1GeV with high efficiency

Height 8m to 12m (depends on baseline) + several m of water overburden for passive shielding against $\gamma$ and n backgrounds

Moves vertically in 50-100m shaft to scan off-axis beam

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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 $\sigma(\nu_e)/\sigma(\nu_e)$ to few % accuracy
- Take advantage of $4\pi$ coverage of IWCD with same target and similar detection efficiency

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HyperK Predicted $\nu_\mu$ from IWCD

$\sin^2 \theta_{23} = 0.48$
$\Delta m_{32}^2 = 2.41 \times 10^{-3}$

Fold in $E_{\text{rec}}$ as a function of $E_\nu$

Correct for IWCD acceptance

Fit to reconstructed Energy
Gives non-CCQE component

Linear Combination, 0.9 GeV Mean

Use weighted Spectrum from scan

$<E_\nu> = 0.9$ GeV
Off-axis 1.7°
Multi-PMT Photosensors

Need fine-grained photodetectors (scale down from 20” PMTs in HyperK)

Build modules with 19 x 3” PMTs facing inwards (and add some PMTs facing outwards)

500 to 800 Modules needed to cover ID (10 to 15k PMTs)

Readout electronics integrated into structure

More detailed design in backup

(See Talk by V. Berardi)

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Reconstruction Performance

Improvement in vertex resolution compared to 8” PMTs

Tuning of event reconstruction ongoing

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

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Neutron Tagging in IWCD

- Load water with 0.2% Gd$_2$(SO$_4$)$_3$
  Enhances n capture rate

- Capture time $\sim 10\,\mu s$, distance $\sim 50\,cm$
- Tagging efficiency $\sim 80\%$ (8MeV $\gamma$ energy)

- Helps separate $\bar{\nu}$ and $\nu$
- Measures n production in $\nu$ scattering

Simulated neutron capture time and
Reconstructed distance from primary vertex

- Method demonstrated in EGADS
- Planned for SuperK from 2019
  (See talks by Simpson/Marti)

- Gd loading is also proposed for HyperK itself

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Beam Test and Schedule

Aim is to test mPMTs and calibration procedures

- Half-size tank, 5m height, 3-4m diameter, ~170 mPMTs
- Charged particle beams (e,μ,π,p) in the sub-GeV range
- Preferred site Fermilab MCenter or MTest

Schedule for Test Beam and Full IWCD construction

<table>
<thead>
<tr>
<th>Year</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
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<th>2024</th>
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<td>Full Detector Design</td>
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Backup Slides
**Current T2K systematic errors**

TABLE I. Effect of 1σ variation of the systematic uncertainties on the predicted event rates of the SK samples.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>1-Ring μ</th>
<th>1-Ring e</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FHC RHC</td>
<td>FHC RHC FHC 1 d.e. FHC/RHC</td>
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<tr>
<td>SK Detector</td>
<td>2.40</td>
<td>2.01</td>
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<tr>
<td>SK FSI + SI + PN</td>
<td>2.20</td>
<td>1.98</td>
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<tr>
<td>Flux and cross-section (w/ ND280 constraint)</td>
<td>2.88</td>
<td>2.68</td>
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<tr>
<td>Nucleon removal energy</td>
<td>2.43</td>
<td>1.73</td>
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<tr>
<td>σ(νe)/σ(νe)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>NC 1-γ</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>NC Other</td>
<td>0.25</td>
<td>0.25</td>
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<tr>
<td>Oscillation parameters</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Total</td>
<td>4.91</td>
<td>4.28</td>
</tr>
</tbody>
</table>

These errors should be reduced for HyperK with more far detector events.

Reduction T2K to HyperK
Total error 5% to 3%

These errors should be reduced for HyperK with addition of IWCD.
Beam Flux uncertainties

Integral flux ~5% dominated by hadronic interactions
Proton beam is flat 3% contribution
Horn gives ~10% at high energies

**SK: Neutrino Mode, \(\nu_\mu\)**

- Hadron Interactions
- Proton Beam Profile & Off-axis Angle
- Horn Current & Field
- Horn & Target Alignment

**SK: Neutrino Mode, \(\bar{\nu}_\mu\)**

- Hadron Interactions
- Proton Beam Profile & Off-axis Angle
- Horn Current & Field
- Horn & Target Alignment

**SK: Neutrino Mode, \(\nu_e\)**

- Hadron Interactions
- Proton Beam Profile & Off-axis Angle
- Horn Current & Field
- Horn & Target Alignment

**SK: Neutrino Mode, \(\bar{\nu}_e\)**

- Hadron Interactions
- Proton Beam Profile & Off-axis Angle
- Horn Current & Field
- Horn & Target Alignment
Uncertainties in predicted $\nu_e$ and $\nu_\mu$ events at HyperK

<table>
<thead>
<tr>
<th></th>
<th>Flux &amp; ND-constrained</th>
<th>ND-independent</th>
<th>Far detector</th>
<th>Total</th>
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<tbody>
<tr>
<td></td>
<td>cross section</td>
<td>cross section</td>
<td></td>
<td></td>
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<tr>
<td>T2K in 2016</td>
<td>$\nu$ mode</td>
<td>3.0%</td>
<td>3.9%</td>
<td>2.5%</td>
</tr>
<tr>
<td></td>
<td>$\bar{\nu}$ mode</td>
<td>3.3%</td>
<td>4.2%</td>
<td>3.1%</td>
</tr>
<tr>
<td>HK Design Report</td>
<td>$\nu$ mode</td>
<td>3.0%</td>
<td>0.5%</td>
<td>0.7%</td>
</tr>
<tr>
<td></td>
<td>$\bar{\nu}$ mode</td>
<td>3.2%</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

### HyperK goals

- INGRID error on beam direction is more important for HyperK
- IWCD water Cherenkov measurements transfer some uncertainties from ND-independent to ND-constrained
- Far detector understanding is improved by IWCD information on $E_{rec}$ and by large statistics sample of atmospheric $\nu$
- Statistical errors on appearance are $\sim$3% (see next slide)

**Steve Playfer, ICHEP 2018, Seoul**
HyperK statistics after 10 years

Neutrino mode: appearance

![Histogram of reconstructed neutrino energy distribution for several values of CP.sin^2.13]=0.1 and normal hierarchy is assumed.](image1)

![Difference of reconstructed neutrino energy spectrum from CP=0 for the cases CP=90, 90, and 180. The error bars correspond to the statistical uncertainty.](image2)

By using not only the total number of events but also the reconstructed energy distribution, the sensitivity to CP can be improved and one can discriminate all the values of CP, including the difference between CP=0 and 180 for which CP symmetry is conserved.

Figure 136 shows the reconstructed neutrino energy distributions of the \( \nu_\mu \) sample, for the cases with sin^2 \( \theta_{23} = 0.5 \) and without oscillation. Thanks to the narrow energy spectrum tuned to the oscillation maximum with o-axis beam, the effect of oscillation is clearly visible.

Antineutrino mode: appearance

![Histogram of reconstructed antineutrino energy distribution for several values of CP.sin^2.13]=0.1 and normal hierarchy is assumed.](image3)

![Difference of reconstructed antineutrino energy spectrum from CP=0 for the cases CP=90, 90, and 180. The error bars correspond to the statistical uncertainty.](image4)

As described earlier, a binned likelihood analysis based on the reconstructed neutrino energy distribution is performed to extract the oscillation parameters. Both \( \nu_e \) appearance and \( \nu_\mu \) disappearance mode are analyzed.

- **Figure 135.** Top: Reconstructed neutrino energy distribution for several values of CP.sin^2.13]=0.1 and normal hierarchy is assumed. Bottom: Difference of the reconstructed neutrino energy distribution from the case with CP=0. The error bars represent the statistical uncertainties of each bin.

- **Figure 136.** Reconstructed neutrino energy distributions for the cases CP=90, 90, and 180. The error bars correspond to the statistical uncertainty.
INGRID on axis detector

Measures H/V beam position

Gives $0.9\%(1.7\%)$ systematic on $\nu$ ($\bar{\nu}$) beam for T2K

Error will increase for HyperK

• Beam flux $x2$ higher.
• Pileup is an issue.
• Detector aging?
• HyperK is not on the same axis as ND280 & SK

Estimate $1.5\%(3.6\%)$ systematic on $\nu$ ($\bar{\nu}$) beam for HyperK, but hope to improve this
ND280 Upgrade for T2K2

The reference upgraded detector configuration consists of a new tracker that will replace the central part of the P0D detector. The upstream ECAL part of the P0D (lead scintillator sandwich, $4.9 \times 0$) will be kept. The new tracker will be made of a high granularity Scintillator Detector (SD), of about 2 tons, sandwiched between two horizontal High-Angle TPCs (HATPC), one above and one below, to measure the tracks produced at high angle with respect to the neutrino beam center direction. Neutrino interactions will occur in the SD, which will precisely measure the vertex position and track the particles. High precision measurements of the kinematics of the leptons will be performed with the TPCs. The whole new tracker will be surrounded by a Time-of-Flight (ToF) detector. The downstream part of ND280 will be untouched and will continue to provide measurements of neutrino interactions both in water and plastic. We plan to keep the existing ECAL detectors that surround the inner detectors in the whole solid angle. It corresponds to about $10^{-11} \times 0$. However, in the upstream part of ND280, the ECAL detector (ECAL-P0D) has a coarser segmentation and correspond to $4.3 \times 0$. We are evaluating whether the upgrade of this part of the ECAL detector is also required.

A schematic picture of the new configuration is shown in Fig 19.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current ND280 (%)</th>
<th>Upgrade ND280 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK flux normalisation $(0.6 &lt; E_\nu &lt; 0.7 \text{ GeV})$</td>
<td>3.1</td>
<td>2.4</td>
</tr>
<tr>
<td>$MA_{QE} \ (\text{GeV/c}^2)$</td>
<td>2.6</td>
<td>1.8</td>
</tr>
<tr>
<td>$\nu_\mu$ 2p2h normalisation</td>
<td>9.5</td>
<td>5.9</td>
</tr>
<tr>
<td>2p2h shape on Carbon</td>
<td>15.6</td>
<td>9.4</td>
</tr>
<tr>
<td>$MA_{RES} \ (\text{GeV/c}^2)$</td>
<td>1.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Final State Interaction ($\pi$ absorption)</td>
<td>6.5</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Overall errors on $\nu_\mu$ flux $\times \sigma$ reduced from 2.3% to 1.9% by upgrade.
MULTI-PMT MODULE DESIGN

One mPMT module design being considered:

- UV transparent acrylic
- Optical gel coupling between PMT and acrylic
- 3D printed PMT support structure
- Reflectors to improve light collection
- HV generation at PMT base
- Readout electronics board
- Scintillator panel
- Stainless steel or aluminum cylinder