E61 experiment

An intermediate water Cherenkov detector for the Hyper-Kamiokande experiment: Overview and Status

Evangelia Drakopoulou for the J-PARC E61 collaboration.

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The Hyper-Kamiokande experiment

- Hyper-Kamiokande (Hyper-K): a 0.26 Mton water Cherenkov detector
- Main focus: measurement of the CP violation in the neutrino sector.
- Staged approach: 2\textsuperscript{nd} tank after 6 years or in Korea
- Detector at 2.5\textdegree{} off the J-PARC beam axis → narrow neutrino beam profile peaked at the $P(\nu_\mu \rightarrow \nu_e)$ oscillation maximum of $0.6 \text{ GeV}$ at 295 km.

- Broad physics program: beam physics, solar, atmospheric and supernova neutrinos, proton decay, Earth tomography

More Hyper-K contributions at ICRC2017:
- T. Yano – Astrophysical $\nu$ (poster)
- S. Zsoldos – Hyper-K (talk: July 15\textsuperscript{th})
- D. N. Yeum – Supernova $\nu$ (poster)
The Hyper-Kamiokande & the E61 experiment

- T2K/Super-K: smaller and running predecessor of Hyper-K
- Hyper-K will measure the oscillated neutrino spectrum.
- The observed neutrino event rate depends on many parameters:

  - Oscillation probability
  - Neutrino Flux
  - Interaction Cross-section
  - Detector Efficiency
  - Detector Fiducial Mass

- Hyper-K: limited by systematic rather than statistical uncertainties
- Main systematic uncertainty: relation between observables and $E_\nu$ → neutrino-nucleus interaction models → large uncertainties

The E61 experiment:
- measure the neutrino flux before oscillation is essential
- direct measurement of the lepton kinematics

- measure cross sections on H$_2$O directly
- off-axis spanning technique
- Gd doped water - neutron tagging
May 2017 E61 collaboration formed → merging NuPRISM and TITUS
E61 will be placed at approximately 1 km from J-PARC neutrino beam.
Staged approach:
**Phase-0**: water Cherenkov detector on surface (ID: 6m tall, 8m diam.)
**Phase-1**: the intermediate water Cherenkov detector underground

- movable instrumented detector – placed in a 50 m deep pit
- ID: 10m tall, 8m diameter - OD: 14m tall, 10m diameter
The E61 experiment - Schedule

<table>
<thead>
<tr>
<th>Year</th>
<th>Phase-0</th>
<th>Phase-1</th>
<th>Hyper-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>design</td>
<td>design</td>
<td>design</td>
</tr>
<tr>
<td>2018</td>
<td>construction</td>
<td>construction</td>
<td>construction</td>
</tr>
<tr>
<td>2020</td>
<td>operation</td>
<td>operation</td>
<td>operation</td>
</tr>
</tbody>
</table>

**Phase-0:** 1 kTon water Cherenkov detector on surface
- $\sim 3\%$ precision measurement of $\sigma(v_e)/\sigma(v_\mu)$
- Measure neutron multiplicities in neutrino-nucleus interactions
- Demonstrate the detector performance and calibration precision

**Phase-1:** intermediate water Cherenkov detector underground
- Improved $\sigma(v_e)/\sigma(v_\mu)$ measurement and of $\sigma(\bar{v}_e)/\sigma(\bar{v}_\mu)$
- Systematic uncertainties can be reduced from 4% to 1% with E61
- Investigate relation between neutrino energy and lepton kinematics
- Measure neutron multiplicities in neutrino-nucleus interactions
Off-axis spanning

- A detector that spans 1-4 degrees off the neutrino beam axis will measure the final states for varying neutrino spectra.

- E61 can observe the muon kinematic distributions in each off-axis bin.
Spectra at each off-axis bin

Linear combinations: 600 MeV mono-energetic beam using slices in off-axis angles

Super-K oscillated flux
Linear combination of E61 off-axis fluxes

Linear combinations and hypotheses for oscillation parameters reproduce the oscillated flux.
**Neutron tagging**

Benefits from neutron tagging:
- Discrimination between $\nu_\mu$ and $\bar{\nu}_\mu$
- Measure neutron multiplicity → reduce uncertainties between neutrino interaction theoretical models
- Improved purity of CCQE sample: better signal/background separation, improved neutrino energy reconstruction

- 0.2% Gadolinium Sulphate (0.1% Gd)
- Captures ~90% neutrons
- ~8MeV of gammas
- ~25µs capture time (compared to ~200µs and 2.2MeV gammas from capture on H)
Multi-PMT concept for photon sensor:

- Leveraging from KM3NeT mPMT design.
- Finer granularity detection
- Modular approach to PMT instrumentation.
- Array of small (~3”) PMTs – 19 for ID, 7 for OD
- Improved directional information & vertex resolution.

Example of an event signature of a Cherenkov ring on the multi-PMTs.
The E61 experiment

• Theoretical models have large uncertainties on the neutron multiplicity → lacking measurements

• Using the neutron tagging at E61 we can measure the neutron multiplicity for CC0pi events at the beam energy

• This can inform the neutrino interaction models

• In supernova ν and proton decay analyses, the Hyper-K analysis tags the neutron.

The E61 neutron multiplicity measurement will help in reducing the errors on the expected number of neutrons.
The Kamiokande detector, the ancestor of Super-Kamiokande, firstly observed $\nu$ from Supernova 1987A.

Hyper-K: $\nu$ detection from supernova burst and SRN

E61 detector: too small size to allow for supernova $\nu$ detection.

Information to Super-K/Hyper-K searches for supernova $\nu$: measuring the number of neutrons can reduce backgrounds

Super-K has set the lower limit of proton lifetime using $e^+\pi^0$.

E61 can provide information to Super-K /Hyper-K searches

Neutron tagging:

1. signal/background separation
2. reduce the main background in $e^+\pi^0$: by atmospheric $\nu$ requiring signal without neutrons can reject background events
• Hyper-K \(\rightarrow\) complementary measurements for both accelerator and atmospheric neutrinos.

• These studies will begin from the Gd doped Super-K & E61.

• **Neutron tagging:**
  \(\rightarrow\) discrimination between neutrinos and anti-neutrinos
  \(\rightarrow\) improve atmospheric neutrino measurements in Hyper-K
E61 collaboration newly formed from nuPRISM and TITUS:

- An off-axis angle spanning water Cherenkov detector with Gd for neutron tagging.
- E61 detector will help reduce theoretical model dependence and systematic uncertainties arising from neutrino-nucleus interactions in Hyper-K → precise CP violation search.
- Beam and atmospheric neutrinos studies: exploiting the benefits of neutron tagging in atmospheric measurements and proton decay searches.
- 100 physicists - 30 institutions - 8 countries
- E61 was granted Phase-1 approval in July 2016
- Technical Design Report under development for final approval in 2018
- E61 Phase-0 construction 2019 – first data 2021
Thank you!

Interior of Super-K
E61 experiment

Backup
The E61 experiment

Spans 1-4 degrees from the neutrino beam axis.
Hyper-K has a broad physics program including:

- **Neutrino oscillation physics** – CP violation measurement
- Beam and atmospheric neutrinos
- Search for nucleon decay
- Neutrino astrophysics:
  - Precision measurements of solar neutrinos
  - High statistics measurements of neutrinos from supernova bursts
  - Detection and study of relic supernova neutrinos
- Earth tomography using neutrinos
The E61 experiment

• Hyper-K will combine the complementary measurements from both accelerator and atmospheric neutrinos.

**enhance the precision of $\delta_{CP}$ measurement**

**good sensitivity of more than 3σ after 5 years, more than 5σ after 10 years to the mass hierarchy**

**precision measurements of $\theta_{23}$ octant and $\Delta m_{23}$**

• These studies will begin from the Gd doped Super-K and E61 experiments.
• Neutron tagging:
  → discrimination between neutrinos and anti-neutrinos
  → improve atmospheric neutrino measurements in Hyper-K.
The E61 experiment

- Super-K has set the lowest limit of proton lifetime.
- E61 does not aim to provide a limit for information for Super-K/Hyper-K showing the benefits of neutron tagging.
- Being ~ 10 times larger than Super-K, the Hyper-K detector will collect larger numbers of protons and reach Super-K limit within two years.

Tagging neutrons in E61 can allow to:
- signal/background separation
- reduce the main background in $e^+\pi^0$: by atmospheric neutrinos
- requiring signal without neutrons to reject background events
- Measuring the neutron content in the cross section events to important input to the background determination for proton decays in Hyper-K.

increase existing sensitivity to proton decay by an order of magnitude
Systematic Uncertainties

Systematic uncertainty on number of $\nu e$ events at T2K:
18\% (2011) $\rightarrow$ 9.9\% (2012) $\rightarrow$ 8.8\% (2013) $\rightarrow$ 6.8\% (2014) $\rightarrow$ 5.5\% (2016)

Target systematic uncertainty in T2K-II: ~4\%

With further improvements foreseen in
- Cross section with near and intermediate detector
- Detector uncertainties with better calibration

Size of systematic uncertainties assumed in HK study:

<table>
<thead>
<tr>
<th></th>
<th>$\nu$ mode</th>
<th>anti-$\nu$ mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\nu e$</td>
<td>$\nu \mu$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3.2</td>
<td>3.6</td>
</tr>
</tbody>
</table>

With correlation between energy/flavor bins taken into account based on the T2K error matrix
Systematic Uncertainties

Extrapolation from T2K experience

- Beam flux + near detector constraint
  - Conservatively assumed to be the same
- Cross section uncertainties not constrained by ND
- Nuclear difference removed assuming water measurements
- Far detector
  - Reduced by increased statistics of atmospheric $\nu$ control sample and fundamental detector response understanding with improved calibration

Uncertainty on the expected number of events at Hyper-K (%)

<table>
<thead>
<tr>
<th></th>
<th>$\nu$ mode</th>
<th>anti-$\nu$ mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\nu_e$</td>
<td>$\nu_\mu$</td>
</tr>
<tr>
<td>Flux&amp;ND</td>
<td>3.0</td>
<td>3.3</td>
</tr>
<tr>
<td>XSEC model</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Far Det. +FSI</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>3.2</td>
<td>3.6</td>
</tr>
</tbody>
</table>

- Further reduction by new near detectors under study
- Benefit from experience with T2K(-II)
Systematic Uncertainties

Hyper-Kamiokande systematic errors

Estimations and simulations will be based on T2K and SK studies with real data

<table>
<thead>
<tr>
<th>v-mode $\nu_e$ candidates</th>
<th>T2K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source of uncertainty</td>
<td>$\delta N_{SK}/N_{SK}$</td>
</tr>
<tr>
<td>SKDet+FSI+SI</td>
<td>3.48%</td>
</tr>
<tr>
<td>SKDet only</td>
<td>2.28%</td>
</tr>
<tr>
<td>FSI+SI only</td>
<td>2.63%</td>
</tr>
<tr>
<td>Flux</td>
<td>3.67%</td>
</tr>
<tr>
<td>2p-2h (corr)</td>
<td>3.90%</td>
</tr>
<tr>
<td>2p-2h bar (corr)</td>
<td>0.05%</td>
</tr>
<tr>
<td>NC other (uncorr)</td>
<td>0.15%</td>
</tr>
<tr>
<td>NC 1gamma (uncorr)</td>
<td>1.47%</td>
</tr>
<tr>
<td>XSec nue/numu (uncorr)</td>
<td>2.61%</td>
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<tr>
<td>XSec Tot (corr)</td>
<td>4.26%</td>
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<tr>
<td>XSec Tot</td>
<td>5.21%</td>
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<tr>
<td>Flux+XSec (ND280 constrained)</td>
<td>2.90%</td>
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<tr>
<td>Flux+XSec (All)</td>
<td>4.17%</td>
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<tr>
<td>Flux+XSec+SKDet+FSI+SI</td>
<td>5.45%</td>
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<tr>
<td>Flux+XSec+SKDet+FSI+SI (pre-fit)</td>
<td>12.1%</td>
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<tr>
<td>Oscillations</td>
<td>4.20%</td>
</tr>
<tr>
<td>All</td>
<td>6.91%</td>
</tr>
<tr>
<td>All (pre-fit)</td>
<td>12.6%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\bar{v}$-mode $\bar{\nu}_e$ candidates</th>
<th>T2K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source of uncertainty</td>
<td>$\delta N_{SK}/N_{SK}$</td>
</tr>
<tr>
<td>SKDet+FSI+SI</td>
<td>3.95%</td>
</tr>
<tr>
<td>SKDet only</td>
<td>3.11%</td>
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<tr>
<td>FSI+SI only</td>
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<td>Flux</td>
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<tr>
<td>2p-2h (corr)</td>
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<tr>
<td>2p-2h bar (corr)</td>
<td>2.36%</td>
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<tr>
<td>NC other (uncorr)</td>
<td>0.33%</td>
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<tr>
<td>NC 1gamma (uncorr)</td>
<td>2.95%</td>
</tr>
<tr>
<td>XSec nue/numu (uncorr)</td>
<td>1.46%</td>
</tr>
<tr>
<td>XSec Tot (corr)</td>
<td>4.46%</td>
</tr>
<tr>
<td>XSec Tot</td>
<td>5.55%</td>
</tr>
<tr>
<td>Flux+XSec (ND280 constrained)</td>
<td>3.20%</td>
</tr>
<tr>
<td>Flux+XSec</td>
<td>4.60%</td>
</tr>
<tr>
<td>Flux+XSec+SKDet+FSI+SI</td>
<td>6.28%</td>
</tr>
<tr>
<td>Flux+XSec+SKDet+FSI+SI (pre-fit)</td>
<td>13.3%</td>
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<tr>
<td>Oscillations</td>
<td>4.00%</td>
</tr>
<tr>
<td>All</td>
<td>7.38%</td>
</tr>
<tr>
<td>All (pre-fit)</td>
<td>14.1%</td>
</tr>
</tbody>
</table>

Goal
Reduction from ~ 6-7% in T2K to ~3-4% in T2HK for the expected number of events in HK. Beam Flux, XSections, HKDet + New near detectors constraint.
Supernova ν

- The Kamiokande detector, the ancestor of Super-Kamiokande, firstly observed ν from Supernova 1987A.
- Hyper-K: ν detection from supernova burst and SRN
- E61 detector: too small size to allow for supernova ν detection.
- Aim: provide information to Super-K/Hyper-K searches for supernova ν

Neutron tagging can:
- Separate neutrinos from various radiogenic and spallation backgrounds via neutron tagging
- detect diffuse supernova ν background.
- Identification of inverse beta decay events
- background reduction and flavor tagging of $\bar{\nu}_e$