Hyper-Kamiokande
physics potential

on behalf of the HK proto-collaboration

Lluís Martí-Magro, ICRR
H2020 OP workshop (Valencia). November 28th, 2018
How to make a Nobel laureate happy?
Seed funding towards the construction of the next-generation water Cherenkov detector Hyper-Kamiokande has been allocated by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) within its budget request for the 2019 fiscal year. Seed fundings in the past projects usually lead to full funding in the following year, as it was the case for the Super-Kamiokande project.

The University of Tokyo pledges to ensure construction of the Hyper-Kamiokande detector commences as scheduled in April 2020. The University of Tokyo has made this decision in recognition of both the project’s importance and value both nationally and internationally.

The neutrino research that lead to Nobel prizes for Special University Professor Emeritus Koshiba and Distinguished University Professor Kajita has entered a new era. The international community has demonstrated the need for Hyper-Kamiokande. The considerable expertise and achievements of the University of Tokyo and Japan, and unique and invaluable contributions from national and international collaborators will ensure the project will make significant contributions to the intellectual progress of the world.

Makoto Gonokami
President, The University of Tokyo
HYPER-KAMIOKANDE EXPERIMENT TO BEGIN CONSTRUCTION IN APRIL 2020

Last week at the 7th Hyper-Kamiokande proto-collaboration meeting, a statement was issued by the University of Tokyo recognizing the significant scientific discoveries which the planned Hyper-Kamiokande experiment would enable.

It states that, based on these exciting prospects, the University of Tokyo will ensure that construction of the experiment will begin in 2020. Hyper-Kamiokande now moves from planning to a real experiment.

The Hyper-Kamiokande proto-collaboration welcomes this exciting endorsement of the project and the boost it will give to increasing even further the international contributions and participation in the experiment. Introducing the statement, Professor Takaaki Kajita, Director of the Institute for Cosmic Ray Research at the University of Tokyo and 2015 Nobel Laureate in Physics, pointed out that the Japanese funding agency MEXT has included seed funding for Hyper-Kamiokande in its JFY 2019 budget request. He illustrated with many examples that it is standard in Japan for large projects to begin with a year of seed funding, and said that in any case the University of Tokyo commitment meant that Hyper-Kamiokande construction will begin in April 2020.

The Hyper-Kamiokande Proto-Collaboration will now work to finalize designs, and is very open to more international partners to join in this far-reaching new experiment.

~300 collaborators, 75 institutes
15 countries

Construction start: 2020
International partners welcomed
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Posted on SEPTEMBER 19, 2018 5:01 PM by ADMIN

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Construction start: 2020

International partners welcomed

@Queen Mary (London)
@UAMadrid

(1st ProtoCollab) http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=67#all.detailed
(2nd ProtoCollab) http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=79#all.detailed
(3rd ProtoCollab) http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=93#all.detailed
(4th ProtoCollab) http://indico.ipmu.jp/indico/event/100/timetable/#all.detailed
(5th ProtoCollab) http://indico.ipmu.jp/indico/event/133/timetable/#all.detailed
(6th ProtoCollab) https://indico.ipmu.jp/indico/event/152/timetable/#all.detailed
Result: Happy Kajita-sensei….and collaborators!
From Kamiokande, through Super-Kamiokande towards Hyper-Kamiokande*

<table>
<thead>
<tr>
<th></th>
<th>Super-K</th>
<th>Hyper-K (1st tank)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>Mozumi</td>
<td>Tochibora</td>
</tr>
<tr>
<td>ID</td>
<td>11.129</td>
<td>40.000</td>
</tr>
<tr>
<td>OD</td>
<td>1.885</td>
<td>6.700</td>
</tr>
<tr>
<td>ID Photo-coverage</td>
<td>40%</td>
<td>40% (x2 1PE eff.)</td>
</tr>
<tr>
<td>Mass (fiducial) [kton]</td>
<td>50 (22.5)</td>
<td>260 (187)</td>
</tr>
<tr>
<td>Overburden (water equivalent)</td>
<td>1000 m (2700 m)</td>
<td>650 m (1750 m)</td>
</tr>
</tbody>
</table>

*From Koshiba-sensei, through Kajita-sensei towards the next Nobel?
Hyper-Kamiokande ID photo-sensors

- Newly developed Hamamatsu HQE B&L PMT with high QE

- \(x2\) better single photon efficiency as compared to the SuperK PMTs

50-cm HQE B&L R12860

![Graph showing quantum efficiency comparison](image)
Hyper-Kamiokande ID photo-sensors

- Newly developed Hamamatsu HQE B&L PMT with high QE
- x2 better single photon efficiency as compared to the SuperK PMTs
- Improved charge and timing resolutions

<table>
<thead>
<tr>
<th></th>
<th>SK</th>
<th>HK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise [ns]</td>
<td>10.6</td>
<td>6.7</td>
</tr>
<tr>
<td>FWHM [ns]</td>
<td>18.5</td>
<td>13</td>
</tr>
</tbody>
</table>

50-cm HQE B&L R12860
Beam very similar to that in SuperK:
- Hyper-K is about 8 km away from SuperK
- $L = 295$ km
- Beam off-axis angle: $2.5^\circ \rightarrow$ narrow energy peak at $E = 600$ MeV
Long Baseline Beam Neutrino: T2HK

Hyper-K Flux for Neutrino Mode

Hyper-K Flux for Antineutrino Mode
Increased beam power:
- Current: 485 kW (cycle 2.5 s)
- Expected 2020: 750 kW (cycle 1.28 s)
- Expected HK: 1.34 MW (cycle 1.16 s)

Possible ND280 upgrade and intermediate detectors (room for international contributions)
Main Physics Goals

Rich physics program:

- Oscillation
  - Mass hierarchy
  - Search for CP violation in the neutrino sector $\delta_{CP}$
  - Precision oscillation parameters measurements: $\theta_{23}$

- Astrophysics
  - Supernova detection
  - Supernova Relic Neutrinos
  - WIMP dark matter searches

- Solar neutrino
  - day/night asymmetry, matter effects

- Proton decay

ESO: https://www.eso.org/public/images/eso0932a/
CP Violation

- Large differences in some $\delta_{CP}$ scenarios: $A = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \approx 28\%$

- Even in cases with similar probabilities, the energy spectrum helps us to extract information on $\delta_{CP}$

- If mass hierarchy not determined already by other experiments HyperK itself has sensitivity with atmospheric neutrinos
Expected events

Assuming: 1 HyperK tank; normal mas hierarchy; $\sin^2 2\theta_{13} = 0.1$; $\sin^2 \theta_{23} = 0.5$; $\delta_{CP} = 0$; 10 years with 1.3 MWx10x10$^7$ sec; beam running mode time ratio: $\nu:\bar{\nu} = 1:3$

<table>
<thead>
<tr>
<th>$\delta_{CP} = 0$</th>
<th>Appearance signal</th>
<th>Wrong sign</th>
<th>$\nu_e$ beam background</th>
<th>NC background</th>
<th>Background total</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ mode</td>
<td>1643</td>
<td>15</td>
<td>259</td>
<td>134</td>
<td>400</td>
<td>2058</td>
</tr>
<tr>
<td>$\bar{\nu}$ mode</td>
<td>1183</td>
<td>206</td>
<td>317</td>
<td>196</td>
<td>517</td>
<td>1906</td>
</tr>
</tbody>
</table>
Expected events

Assuming: 1 HyperK tank; normal mas hierarchy; $\sin^2 \theta_{13} = 0.1$; $\sin^2 \theta_{23} = 0.5$; 10 years with $1.3 \text{ MW} \times 10^7 \text{ sec}$; beam running mode time ratio: $\nu: \bar{\nu} = 1:3$

- Statistical errors only
- Total number of events as well as $E^{\text{rec}}$ to enhance sensitivity to $\delta_{\text{CP}}$
Sensitivity to CP and prospects

Assuming: 10 years with $1.3 \text{ MW} \times 10^7 \text{ sec}$; beam running mode time ratio: $\nu: \bar{\nu} = 1:3$

Exclusion of $\sin \delta_{\text{CP}} = 0$ at $8\sigma$
for $\delta_{\text{CP}} = -\pi/2$

5$\sigma$ ($3\sigma$) observation of CP violation in 57% (75%) of the $\delta_{\text{CP}}$ parameter space

HyperK stat. uncertainties: 3.5-4%
T2K systematic uncertainties: 5-6%
Sensitivity to CP and prospects

Assuming: 10 years with 1.3 MWx10x10^7 sec; beam running mode time ratio: v:ν = 1:3

Precision of $\delta_{CP}$ measurement:
- $\sigma \sim 23^\circ$ for $\delta_{CP} = \pm \pi/2$
- $\sigma \sim 7^\circ$ for $\delta_{CP} = 0$ or $\pi$

CP sensitivity dependence on $\theta_{23}$:
$\sin \delta_{CP} = 0$ exclu. @ 3$\sigma$ and 5$\sigma$
Atmospheric neutrinos have a broad energy spectrum and arrive at our detectors at different zenith angles. Oscillations are mainly driven by $\theta_{23}$ and $\Delta m^2_{23}$ but since $\theta_{13} \neq 0$ matter effects become important. Sensitive to mass hierarchy, $\theta_{23}$ octant and $\delta_{\text{CP}}$. 

![Diagram of atmospheric neutrino interactions](image)
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Atmospheric neutrinos

Hierarchy and octant sensitivities:
Combination of beam and atmospheric analyses for 1 HyperK tank

After 10 years:
- Mass hierarchy determination at $3.8 \sigma @ \sin^2 \theta_{23} > 0.4$
- Octant determination at $3\sigma @ |\theta_{23} - 45^\circ| \geq 2.3$
Supernova neutrinos

Main reaction in HyperK: $\nu_e + p \rightarrow n + e^+$ ($E_{\text{thr}} = 3 \text{ MeV}$)

Many topics involved: oscillation physics, core collapse SN

Features of the neutrino burst can be easily seen due to the large statistics

Largest rate $\sim 50k \text{ Hz} @ 10 \text{ kpc} \rightarrow \text{SNe are a challenge for the DAQ}$

Vast amount number of events:

- $50k – 80k$ at $10 \text{ kpc}$ ($\sim$ galactic center)
- $2k – 3k$ at LMC
- $\sim 10$ at Andromeda!
Supernova Relic neutrinos

Neutrinos from all the core collapse SN neutrinos in the history of the universe


Expected to be seen in SuperK-Gd first

Collect enough statistics to measure their spectrum
- Star formation, metallicity, etc
- Black hole formation
2\textsuperscript{nd} Detector in Korea

KNO
Korean Neutrino Observatory
1~3 deg. off axis

Hyper-K
2.5 deg. off axis

- Very similar tanks
- More benefits than just a 2\textsuperscript{nd} tank
2nd Detector in Korea

Beam off-axis energy profile

At HK, Japan (L=295 km)

At KNO, Korea (L=1000 km)
2\textsuperscript{nd} Detector in Korea

Benefits of T2KK:

There is the obvious benefit of \textbf{more statistics} but:

- Neutrino mass hierarchy determination
- Leptonic CP violation phase measurement \hspace{1cm} \{ HK 1\textsuperscript{st} vs KNO 2\textsuperscript{nd} maxima \\

- Non-standard neutrino interactions \hspace{1cm} Higher energy \hspace{1cm} Longer baseline \\
\hspace{1cm} Higher matter density

\textbf{Deeper site:} much better for Solar/SRN/SN/geoneutrinos \hspace{1cm} (HK 650 m vs KNO 1 km)
More information

- **Hyper-Kamiokande Design Report:**
  K.Abe et al. (Hyper-Kamiokande Collaboration)  
arXiv:1805.04163

- **Physics Potentials with the second Hyper-Kamiokande Detector in Korea:**
  K.Abe et al. (Hyper-Kamiokande Collaboration) PTEP 2018(2018) 6, 063C01

- **A Long Baseline Neutrino Oscillation Experiment Using J-PARC Neutrino Beam and Hyper-Kamiokande:**
  K.Abe et al (Hyper-Kamiokande Working Group) arXiv:1412.4673

Hyper-K web page: http://www.hyperk.org/
Summary

- Hyper-K has a very broad range of physics topics:
  - neutrino oscillation
  - astrophysics
  - proton decay
  - solar neutrino, etc

- Funding for the first Hyper-K tank is now secured, operation will begin in 2026
Summary

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-Many topics to contribute, many opportunities. Pick yours!
BACKUP
Hyper-Kamiokande