Next-Generation Water Cherenkov Detectors (1)
Hyper-Kamiokande

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SUNY
# 3 Generations of Kamioka Nucleon Decay Experiments

<table>
<thead>
<tr>
<th></th>
<th>Kamiokande</th>
<th>Super-Kamiokande</th>
<th>Hyper-Kamiokande</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>3,000 t</td>
<td>50,000 t</td>
<td>1,000,000 t</td>
</tr>
<tr>
<td></td>
<td>(+1,500 t)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photosensitive</td>
<td>20 %</td>
<td>40 % (SK-1)</td>
<td>?</td>
</tr>
<tr>
<td>Coverage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observation Started</td>
<td>1983</td>
<td>1996</td>
<td>?</td>
</tr>
<tr>
<td>Cost (Oku-Yen)*</td>
<td>5</td>
<td>100</td>
<td>400 – 500?**</td>
</tr>
</tbody>
</table>

* 1 Oku-Yen ≈ 1M$
** Target cost; No realistic estimate yet
Hyper-Kamiokande: A Multi Purpose Detector

- Proton decay
  - $\nu K^+$
  - $e^+ \pi^0$
  - and other modes

- Supernova neutrino ($\sim 10^5$ neutrinos for a SN at the center of the galaxy.)

- JHF-Kamioka long baseline neutrino oscillation experiment:
  - 2nd phase, CP violation
  - If the $\theta_{13}$ measurement in the 1st phase gives only an upper limit, the 2nd phase will enhance the reach.

Why water Cherenkov?

- The primary reason for Super-Kamiokande to have been successful is that it is only one order of magnitude extension of the well-proven Kamiokande.

- One order of magnitude extension of well-proven Super-Kamiokande will not cause any serious difficulty both in construction and in operation. (We now know how to avoid an accident caused by the implosion of a PMT under water pressure.)

- Water is the cheapest detector material.
Overview of the JHF-to-Kamioka Experiment

- $\nu_\mu$ beam of ~1GeV
- Super-K: 50 kton Water Cherenkov
- ~Mt “Hyper Kamiokande”
- 1st Phase: $\nu_\mu \rightarrow \nu_x$ disappearance, $\nu_\mu \rightarrow \nu_e$ appearance, NC measurement
- 2nd Phase: CPV, proton decay
- JAERI (Tokai-mura)
- 0.75 MW 50 GeV PS
- 4MW 50 GeV PS
\( \sin^2 2\theta_{13} \) from \( \nu_e \) Appearance (JHF 1st Phase)

\[
\begin{array}{cccccc|cc}
\sin^2 2\theta_{13} & \nu_\mu & \nu_e & \bar{\nu}_\mu & \bar{\nu}_e & \text{total} & \text{Signal} & \text{Signal + BG} \\
0.1 & 12.0 & 10.7 & 1.7 & 0.5 & 24.9 & 114.6 & 139.5 \\
0.01 & 12.0 & 10.7 & 1.7 & 0.5 & 24.9 & 11.5 & 36.4 \\
\end{array}
\]
Sensitivity to $\sin^2 2\theta_{13}$ as a function of exposure

\[ \Delta m^2 = 0.003 \text{ eV}^2 \]

$0.5 \sin^2 2\theta_{13}$ sensitivity

- 90\% C.L. 3\% 
- $\delta_{BC} = 10\%$
- $\delta_{BC} = 5\%$
- $\delta_{BC} = 2\%$

Exposure/(22.5kt x 10^{21} \text{ pot})

Phase 1

5XJHF $\rightarrow$ 20XSK 5year

Phase 2

SK unit

JHF $\cdot$ yr
JHF-Kamioka Neutrino Project: Phase-II

★ 0.75 → 4 MW beam power
★ Hyper-Kamiokande (1 Mt FV)

→ 10⁶ events

CP Violation

\[ \nu: 2 \text{ yr} \quad \bar{\nu}: 6.8 \text{ yr} \]

\[ \sin^2 2\theta_{13} = 0.05 (\theta_{13} = 0.11) \]

\[ \Delta m^2_{21} = 5 \times 10^{-5} \text{eV}^2 \]
\[ \theta_{12} = \pi/8 \]
\[ \Delta m^2_{32} = \Delta m^2_{31} = 3 \times 10^{-3} \text{eV}^2 \]
\[ \theta_{23} = \pi/4 \]

\[ \sin^2 2\theta_{13} = 0.1 (\theta_{13} = 0.16) \]

\[ \Delta m^2_{21} > 0 \]
\[ \Delta m^2_{31} < 0 \]
Sensitivity (3σ) to CPV (JHFν 2nd Phase)

Chooz excluded

@|\Delta m_{31}| \sim 3 \times 10^{-3} \text{eV}^2

3σ discovery region

4MW, 1Mt Fid. Vol.
2yr for νμ
6.8yr for νμ

δ > \sim 14 \text{deg}

δ > \sim 27 \text{deg}

Δm_{21}=5 \times 10^{-5} \text{eV}^2
θ_{12}=\pi/8
Δm_{32}=Δm_{31}=3 \times 10^{-3} \text{eV}^2
θ_{23}=\pi/4
Conceptual Design

48m × 50m × 500m, Total mass = 1 Mton
Fiducial volume: $39\,\text{m}\phi \times 45\,\text{m} \times 10\,\text{sections} = 0.54\,\text{Mton}$

Total Inner detector volume: $43\,\text{m}\phi \times 49\,\text{m} \times 10\,\text{sections} = 0.72\,\text{Mton}$

Total detector volume: 1 Mton

Total number of PMTs: 200,000  (if 2/m$^2$)
Wished Construction Plan

JHF-I

Discovery of $\theta_{13}$?

HK construction

HK experiment

Any other way to start Hyper-K earlier?
2 detectors × 48m × 50m × 250m, Total mass = 1 Mton
Wished Construction Plan (2 Detector Hyper-K)

- JHF-I: Discovery of $\theta_{13}$ ?
- $\frac{1}{2}$ HK construction
- Half HK experiment
- Full HK experiment
R&D Items

- Site selection
- Cavity design and assessment
  - Rock stress analysis
  - Cost analysis, optimization
- Detector tank design and study of construction method
- Simulation studies for
  - Proton decay
    - $K^+\nu$
    - $e^+p^0$
  - Long baseline neutrino oscillation experiment
- Development of new photo-detectors
  - PMT?
    - Larger size?
    - High QE?
    - Flat & thin?
    - ....
  - Hybrid Photo-detector?
  - Other technique?

How to improve S/N
Optimize photocathode coverage

Initially some R&D, but no more after the SK accident
Not very successful
Not very active
Present focus
Not active
Plan to Develop 40-inch PMT Was Given up due to the SK Accident

<table>
<thead>
<tr>
<th>品名</th>
<th>有効面</th>
<th>Dynode構造</th>
<th>段数</th>
<th>TTS(FWHM) (nsec)</th>
<th>Rise (nsec)</th>
<th>Fall (nsec)</th>
<th>P/V比</th>
</tr>
</thead>
<tbody>
<tr>
<td>R3600(20&quot;)</td>
<td>ϕ 500mm</td>
<td>ベネチアン</td>
<td>11</td>
<td>6</td>
<td>10</td>
<td>33</td>
<td>1.7</td>
</tr>
<tr>
<td>100cm(40inch)径PMT</td>
<td>ϕ 980mm</td>
<td>Line</td>
<td>10</td>
<td>予想値 6.97</td>
<td>予想値 15.8</td>
<td>予想値 36</td>
<td>予想値2.5以上</td>
</tr>
</tbody>
</table>

浜松ホトニクス（株）
2001/1/25
Candidate Site

Super-K (Depth: 2700mwe)

Hyper-K (Depth: 1400 – 1900mwe, not decided yet)
(Tochibora-mine of the Kamioka mining company)

North-south

Candidate place

About 500 – 600 m.
Mozumi Mine

- Geology is not preferable for excavation of a very large cavity.
- Large-scale blastings should be avoided near the Super-K and KamLAND detectors.
Tochibora Mine
Decay Pipe Common for SK/HK

Possible site for Hyper-K

must cover p/π beam axis -(3~4) deg corresponding to $\Delta m^2=(2.2~3.2) \times 10^{-3}$ eV${}^2$
Finite Element Analysis of the Hyper-K Cavity Using the Onsite Rock Condition

Experts say:
Regions with the safety factor < 1.3 need supports (rock bolt or wire)
The depth of the region with safety factor < 1.3 is similar to that in Super-K.

very preliminary

pressure (horizontal) = 0.45
pressure (vertical) = 1.0

It seems possible to excavate the Hyper-K cavity.

Need more detailed studies.
Design of PMT Support Structure
Construction Plan for the Water Tank and PMT Support Frame

- Movable scaffolding
- Panel
- Reinforced concrete
- Upper deck
- Movable scaffolding for building PMT support frame
- PMT support frame
Development of Large Spherical Hybrid Photo Detectors (HPD)

- high efficiency
- simple structure → low cost
- high production rate
- pressure resistant (no chain-reaction of explosion)

- 5-inch HPD prototype tested.
- 13-inch HPD prototype to be developed.
- Design of a 20-inch spherical HPD.

Diagram:
- Glass
- Photocathode
- Photoelectrons
- Light
- Support
- Diode-1
- Diode-2
- Reflector
5-inch HPD Prototype Tested

electron bombarded gain $1000 \times$ avalanche gain $50 = 50,000$

photocathode $-8\text{kV}$

Avalanche diode $3\text{mm}\phi$, bias $150\text{V}$
# Characteristics of 5-inch HPD Prototype (1)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>5 inch</td>
</tr>
<tr>
<td>Effective area</td>
<td>80 mm $\phi$</td>
</tr>
<tr>
<td>QE@400nm</td>
<td>24(%)</td>
</tr>
<tr>
<td>Rise time</td>
<td>3.2 ns @-8kV</td>
</tr>
<tr>
<td>Fall time</td>
<td>5.2 ns @-8kV</td>
</tr>
<tr>
<td>Dark rate</td>
<td>24000Hz, 8500Hz, 380Hz</td>
</tr>
<tr>
<td>Avalanche gain</td>
<td>50</td>
</tr>
<tr>
<td>Bias</td>
<td>50</td>
</tr>
<tr>
<td>HV value</td>
<td>-8kV, -16kV</td>
</tr>
<tr>
<td>Bombarded gain</td>
<td>1000, 3000</td>
</tr>
<tr>
<td>Total gain</td>
<td>$5 \times 10^4$, $1.5 \times 10^5$</td>
</tr>
<tr>
<td>P/V</td>
<td>----, 20.5</td>
</tr>
<tr>
<td></td>
<td>~2@Super-K</td>
</tr>
</tbody>
</table>

*Due to non-spherical glass bulb and small (3mm) APD*
Hyper-K R&D: Summary

■ Site: Tochibora mine is seriously considered as a candidate site.

■ Cavity excavation: FEA in progress. Geological survey to be done; boring, in situ measurement of initial stress, rock sample taken from the candidate site for mechanical tests, etc.

■ Water tank and PMT support: Conceptual design started.

■ Spherical HPD: 5-inch prototype tested, larger HPD to be developed.

■ Further physics simulation: to be done.