Water Cherenkov R&D in Japan

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Hyper Kamiokande

1Mton full vol.
0.54Mton fid vol. (0.27Mton x 2 detectors)
Needs ~200,000 PMTs for 40% coverage (20inch PMT)
~100,000 PMTs for 20% coverage
Candidate detector site

Mozumi Mine

Super-Kamiokande

Tochibora Mine

~10km

0M: 845.0m
peak: 1156.0m
Photo sensor

• Current plan for Hyper-Kamiokande
  • 200,000 PMT (20inch)
  • $3,000 x 200,000 = 600M$ (1$=100yen)
• Cost reduction of photo sensors is one of the key issue for Huge Water Cherenkov Detector

• Cost reduction of photo sensor
  • HPD
  • High QE PMT or HPD
  • Number of photo sensor?
Recently, we performed systematic study of nucleon decays \((N \rightarrow l^+ (\pi, \rho, \eta, \omega), \nu K^+)\) for SK-I (40%-photo coverage) and SK-II (19%).

**SK-I**
- ID 20inch PMT: 11146
- Photo coverage: 40%
- p res.: 3.0% for 1GeV/c electron
- Livetime: 1489 days

**SK-II**
- ID 20inch PMT: 5182
- Photo coverage: 19%
- p res.: 4.1% for 1GeV/c electron
- Livetime: 799 days
Comparison of reconstruction performance for SK-I and SK-II

Detector performance for SK-I (photo coverage: 40%) and SK-II (photo coverage: 19%) (free proton decay(p→e⁺π⁰))

<table>
<thead>
<tr>
<th></th>
<th>SK-I</th>
<th>SK-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>mis-PID probability</td>
<td>3.3%</td>
<td>3.4%</td>
</tr>
<tr>
<td>detection efficiency</td>
<td>44.9%</td>
<td>43.7%</td>
</tr>
</tbody>
</table>

SK-I and SK-II have almost same performance for p→e⁺π⁰
### Charged lepton + meson modes

<table>
<thead>
<tr>
<th></th>
<th>SK-I</th>
<th>SK-II</th>
<th>eff. (xBr.) (%)</th>
<th>atm. ν BG</th>
<th>candidate</th>
</tr>
</thead>
<tbody>
<tr>
<td>p→e⁺π⁰</td>
<td>44.6</td>
<td>43.5</td>
<td>0.20</td>
<td>0.11</td>
<td>0 0</td>
</tr>
<tr>
<td>p→μ⁺π⁰</td>
<td>35.5</td>
<td>34.7</td>
<td>0.23</td>
<td>0.11</td>
<td>0 0</td>
</tr>
<tr>
<td>p→e⁺η (2γ)</td>
<td>18.8</td>
<td>18.2</td>
<td>0.19</td>
<td>0.09</td>
<td>0 0</td>
</tr>
<tr>
<td>p→μ⁺η (2γ)</td>
<td>12.4</td>
<td>11.7</td>
<td>0.03</td>
<td>0.01</td>
<td>0 0</td>
</tr>
<tr>
<td>p→e⁺η (3π⁰)</td>
<td>8.1</td>
<td>7.6</td>
<td>0.08</td>
<td>0.08</td>
<td>0 0</td>
</tr>
<tr>
<td>p→μ⁺η (3π⁰)</td>
<td>6.1</td>
<td>5.4</td>
<td>0.30</td>
<td>0.15</td>
<td>0 2</td>
</tr>
<tr>
<td>p→e⁺ρ⁰</td>
<td>4.9</td>
<td>4.2</td>
<td>0.23</td>
<td>0.12</td>
<td>0 0</td>
</tr>
<tr>
<td>p→μ⁺ρ⁰</td>
<td>1.8</td>
<td>1.5</td>
<td>0.30</td>
<td>0.12</td>
<td>1 0</td>
</tr>
<tr>
<td>p→e⁺ω (π⁰γ)</td>
<td>2.4</td>
<td>2.2</td>
<td>0.10</td>
<td>0.04</td>
<td>0 0</td>
</tr>
<tr>
<td>p→μ⁺ω (π⁰γ)</td>
<td>2.8</td>
<td>2.8</td>
<td>0.24</td>
<td>0.07</td>
<td>0 0</td>
</tr>
<tr>
<td>p→e⁺ω (3π)</td>
<td>2.5</td>
<td>2.3</td>
<td>0.26</td>
<td>0.13</td>
<td>1 0</td>
</tr>
<tr>
<td>p→μ⁺ω (3π)</td>
<td>2.7</td>
<td>2.4</td>
<td>0.10</td>
<td>0.07</td>
<td>0 0</td>
</tr>
<tr>
<td>n→e⁺π⁻</td>
<td>19.4</td>
<td>19.3</td>
<td>0.16</td>
<td>0.11</td>
<td>0 0</td>
</tr>
<tr>
<td>n→μ⁺π⁻</td>
<td>16.7</td>
<td>15.6</td>
<td>0.30</td>
<td>0.13</td>
<td>1 0</td>
</tr>
<tr>
<td>n→e⁺ρ⁻</td>
<td>1.8</td>
<td>1.6</td>
<td>0.25</td>
<td>0.13</td>
<td>1 0</td>
</tr>
<tr>
<td>n→μ⁺ρ⁻</td>
<td>1.1</td>
<td>0.94</td>
<td>0.19</td>
<td>0.10</td>
<td>0 0</td>
</tr>
</tbody>
</table>

### Total BG

<table>
<thead>
<tr>
<th></th>
<th>SK-I+II</th>
<th>IMB-3</th>
<th>KAM-I+II</th>
</tr>
</thead>
<tbody>
<tr>
<td>exposure(kt*yr)</td>
<td>141</td>
<td>7.6</td>
<td>3.8</td>
</tr>
<tr>
<td>Total BG</td>
<td>4.7</td>
<td>47.9</td>
<td>11.5</td>
</tr>
<tr>
<td>candidates</td>
<td>6</td>
<td>32</td>
<td>9</td>
</tr>
</tbody>
</table>

Total B.G. was decrease by factor 5~10 with 20 times larger exposure in Super-Kamiokande compared with IMB-3 or Kamiokande-I+II.

For all modes, efficiency and expected BG for SK-II are almost similar with SK-I, BG expectation is less than 0.5 events.

91.7kt yr / 49.2kt yr
### p→νK⁺ mode

**summary of each analysis**

<table>
<thead>
<tr>
<th>K-→</th>
<th>Eff (%)</th>
<th>BKG</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>μ⁺ν</td>
<td>Pμ</td>
<td>SK-1 37.0±0.4</td>
<td>188.9±5.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SK-2 35.7±0.4</td>
<td>95.5±2.0</td>
</tr>
<tr>
<td></td>
<td>Prompt γ</td>
<td>SK-1 7.2±1.6</td>
<td>0.16±0.05</td>
</tr>
<tr>
<td></td>
<td>tag</td>
<td>SK-2 5.8±1.3</td>
<td>0.08±0.03</td>
</tr>
<tr>
<td>π⁺π₀</td>
<td>SK1</td>
<td>6.2±0.5</td>
<td>0.43±0.13</td>
</tr>
<tr>
<td></td>
<td>SK2</td>
<td>4.8±0.4</td>
<td>0.31±0.10</td>
</tr>
</tbody>
</table>

Efficiency for SK-II are about 80% of SK-I.

Expected backgrounds for K⁺→μ⁺νμ+prompt γ, K⁺→π⁺π₀ are small.
Summary for photo coverage

• SK-I (40% photo coverage) and SK-II (19%) has almost same performance for $p \rightarrow e^+ \pi^0$, $\mu^+ \pi^0$.

• For $p \rightarrow$ charged lepton + meson and $\overline{\nu}K^+$, very small B.G. coming from atmospheric $\nu$ are achieved.

• Almost same efficiencies (80%~100%) are achieved in SK-II compared to SK-I.

20% photo coverage is enough for these nucleon decay modes.
High QE PMT (or HPD)

Hi QE PMT (Hamamatsu)

R3600 (Current 20inch PMT)

<table>
<thead>
<tr>
<th>Photocathode</th>
<th>QE at peak wavelength</th>
<th>Type Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra Bialkali (UBA)</td>
<td>Min. 38%</td>
<td>Typ. 43%</td>
</tr>
<tr>
<td>Super Bialkali (SBA)</td>
<td>Min. 32%</td>
<td>Typ. 35%</td>
</tr>
</tbody>
</table>

Large PMT (or HPD) with High QE ⇒ more cost reduction

- same number (100,000) of smaller PMT
- less number of 20inch PMT (need confirmation on reconstruction)
Site study

- Crack Tensor Analysis by Shimizu Corporation
- Further survey plan
Results of Crack Tensor Analysis (Displacement)


Direction: E-W
- Displacement Value at Side Wall is 92 mm.

Direction: N-S
- Displacement Value at Side Wall is 55 mm.

Distribution of Displacements on Cavern Wall
- In the Case of E-W, Displacement Value at Side Wall is 92 mm. On the Other Hand, in the Case of N-S, Displacement Value at Side Wall is 55 mm.
## Crack Tensor analysis

<table>
<thead>
<tr>
<th>initial stress</th>
<th>direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) isotropic (depth=500m, $K_0=1.0$)</td>
<td>$\theta=0,30,60,90,120,150^\circ$</td>
</tr>
<tr>
<td>(2) $K_0=0.5,1.5,2.0$</td>
<td>$\theta=0^\circ$</td>
</tr>
</tbody>
</table>

### Initial stress

Relation between horizontal to vertical stress ratio and Depth

![Graph showing relation between horizontal to vertical stress ratio and depth](image)

- Horizontal to vertical stress ratio, $K_0$
  - $K_0=0.5\sim2.0$ for depth=500m

### Direction

$K_0$ : ratio of horizontal to vertical stress

![Diagram showing direction](image)

- $\theta=90^\circ$
- $\theta=180^\circ$
- $\theta=0^\circ$

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1. Japan Nuclear Cycle Development Institute, 1999
Displacement value for $K_0=1.0$

- $\theta=0^\circ$ (N-S)  
- $\theta=30^\circ$  
- $\theta=60^\circ$  
- $\theta=90^\circ$ (E-W)  
- $\theta=120^\circ$  
- $\theta=150^\circ$  

Displacement value at side wall is maximum for $\theta=90^\circ$ (E-W) and minimum for $\theta=0^\circ$ (N-S)
Maximum deformation for $K_0=1.0$

- $\theta=0^\circ$ (N-S) × 100%
- $\theta=30^\circ$ × 100%
- $\theta=60^\circ$ × 100%
- $\theta=90^\circ$ (E-W)
- $\theta=120^\circ$
- $\theta=150^\circ$

• maximum deformation > 0.3% (Yellow-red) $\equiv$ unstable
• Unstable region is minimum at $\theta=0^\circ$ and maximum at $\theta=60^\circ$, $90^\circ$ and $120^\circ$. 
Displacement value for $K_0=0.5, 1.5, 2.0$ (depth=500m)

$\theta=0^\circ$ (N-S)

$K_0=0.5$

Maximum displacement value are 57mm at bottom for $K_0=0.5$, 118mm at end cap part for $K_0=1.5$ and 159mm at end cap part for $K_0=2.0$.

Displacements value at side are 15mm, 95mm and 136mm for $K_0=0.5$, $K_0=1.5$ and $K_0=2.0$, respectively.
Maximum deformation for $K_0=0.5$, 1.5, 2.0

- No unstable region for $K_0=0.5$
- Unstable regions: 7.5m for $K_0=1.5$ and 15m for $K_0=2.0$
  (length of cable bolt for reinforcement of rock: 15m)

We need
- to measure initial stress of the detector candidate site.
- to check additional joints and faults.
Further survey of detector site (plan)

- We are discussing about the further survey of detector site, survey of existing tunnel, seismic traveltime tomography, initial stress measurement, boring and borehole loading test, etc. (Depending on the cost, priority, etc)
Conclusion

• From the systematic nucleon decay search,
  – efficiencies for SK-II are same or about 80% of SK-I, even with 19% photo coverage on SK-II (SK-I: 40%).
  – expected background for SK-II are almost same level of SK-I.
  – For future Mton class nucleon decay experiment, 20% photo coverage is acceptable for these nucleon decay search.
  – Using higher QE PMT, further cost reduction may be achieved.

• From crack tensor analysis, initial stress has a large effect on the stability of cavern.

• We plan to do the further survey of the candidate site include the initial stress measurement.

• We are also discussing about photo sensor, electronics, tank, structure, water system, etc to realize the Mton class water Cherenkov detector.