Outline

• The Hyper-Kamiokande Experiment
  – Design overview
  – Technology upgrades

• Particle Physics:
  – Leptonic CP violation
  – Proton decay

• Astroparticle Physics:
  – Supernova burst
  – Supernova relic neutrinos

• Summary & conclusions
The Kamioka Trilogy

1) Kamiokande: 680 tonne fiducial mass

2) Super-Kamiokande: 22.5 ktonne fiducial mass [~33 x K]

3) Hyper-Kamiokande: 560 ktonne fiducial mass [~25 x SK]
Broad physics programme:
- Neutrino oscillation:
  - Accelerator neutrinos [see next slide]
  - Atmospheric neutrinos (still statistics limited!)
  - Solar neutrinos
- Proton decay
- Neutrino astrophysics
  - Supernova burst (~250,000 events expected @ 10 kpc)
  - Supernova relic neutrinos
- Various other physics (indirect WIMP search, n-\bar{n} osc., etc.)
Hyper-K Beam Programme

Hyper-Kamiokande

( Total volume ~ 1M ton )

J-PARC Main Ring Neutrino beamline

( KEK – JAEA )

• Expected # of events for $\sin^2 2\theta_{13} = 0.1$, $\delta = 0$ and NH

  ($7.5 \times 10^7$ MW·sec)

<table>
<thead>
<tr>
<th></th>
<th>Signal ($\nu_\mu \rightarrow \nu_e$ CC)</th>
<th>Wrong sign appearance</th>
<th>$\nu_\mu/\overline{\nu}_\mu$ CC</th>
<th>beam $\nu_e/\overline{\nu}_e$ contamination</th>
<th>NC</th>
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</thead>
<tbody>
<tr>
<td>$\nu$</td>
<td>3,016</td>
<td>28</td>
<td>11</td>
<td>523</td>
<td>172</td>
</tr>
<tr>
<td>$\overline{\nu}$</td>
<td>2,110</td>
<td>396</td>
<td>9</td>
<td>618</td>
<td>265</td>
</tr>
</tbody>
</table>

Much larger statistics merit better systematics:

New near detector(s)!

(see talk by N. Prouse in PPAP Parallel: Neutrino Detectors I)
Next-Gen Water Cherenkov

Photosensors

Flowchart

Super-K PMT

20"

QE~22%

well-known

High-QE SK PMT

High-QE R3600

x 1.4

Normal QE R3600

8” HPD

20” high-QE B&L PMT

20” high-QE HPD

Gadolinium loading

- **CCQE for v:** $\nu + n \rightarrow l^- + p$ (p is “invisible”)  
- **CCQE for $\bar{\nu}$:** $\bar{\nu} + p \rightarrow l^+ + n$
- Coincident signal from Gd allows:
  - $\nu$ vs. $\bar{\nu}$ discrimination
  - Sensitivity to $\nu$ interaction mode

30 Mar 2015

M. Malek, Imperial College
CP Violation: The Past is Prologue

- T2K observes 28 $\nu_e$ events (4.92 ± 0.55 events expected for $\sin^2(2\theta_{13}) = 0$)
- Comparison to null hypothesis gives 7.3$\sigma$ significance for $\theta_{13} \neq 0$

Tension with $\theta_{13}$ measurement at reactors already gives some sensitivity to $\delta$
  - Some regions excluded at 90% CL
  - $\delta = -\pi/2$ preferred for both hierarchies

Ultimate CP sensitivity:
Sensitivity: Exclusion of $\sin(\delta) = 0$ (for $7.5 \times 10^7$ MW sec)

Exclusion of $\sin(\delta) = 0$:
- 76% (58%) of $\delta$ space covered at $3\sigma$ ($5\sigma$) in a nominal 10 year exposure

Also:
- Neutrino mass ordering may be resolved by combining accelerator and atmospheric neutrinos at Hyper-Kamiokande (multi-baseline)
Proton Decay

In a water Cherenkov detector, a typical signal looks like:

- Three rings (all electron-like)
- Total energy close to $M_p$
- Unbalanced momentum close to 0.

\[ p \rightarrow e^+ + \pi^0 \]

Modern GUTs predict lifetimes of $10^{35-36}$ years.

→ Current limits from SK at $\sim 10^{34}$ year level

At this scale, previously negligible backgrounds from atmospheric neutrinos start to limit sensitivity.
Proton Decay @ Hyper-K

$p \rightarrow e^+ + \pi^0$ sensitivity

Hyper-Kamiokande (with 10% B.G.)

Hyper-Kamiokande (baseline design)

Super-Kamiokande

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Supernova Neutrino Burst

Stars with $M > 8 \, M_\odot$ end as a core-collapse supernova when nuclear fuel exhausted:

All 6 $\nu$ species produced; most likely to detect in WC is $\bar{\nu}_e$ via inverse beta decay (89%):

We expect $\sim 250,000$ events at HK from a SN near the galactic centre (10 kpc distance)!

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30 Mar 2015
M. Malek, Imperial College
In 1987, neutrinos were detected from a SN burst in Large Magellanic Cloud (Sanduleak -69° 292 → SN1987a)

25 neutrino events at 3 detectors (Kamiokande, IMB, Baksan)

Our universe is big, with many supernovae explosions; besides neutrinos from individual SN bursts, it should also be possible to detect a diffuse isotropic neutrino signal from all the core-collapse supernova ever.

Measuring the spectrum of these “Supernova Relic Neutrinos” (SRN) would allow us to measure the SN rate (and star formation rate) of the universe as a function of redshift!

Searches for SRN are currently BG-limited; using Gd in Hyper-K could isolate the signal
Summary & Conclusions

- **Hyper-Kamiokande: Kamioka's Next Generation**
  - Improved statistical power of 25x Super-Kamiokande
  - New technologies incorporated (better photosensors, possibly Gd-loaded water)

- **Particle physics goals:**
  - Neutrino oscillation
    - Accelerator programme (“T2HK”) will have world-leading sensitivity to leptonic CP violation
    - 76% (58%) of $\delta$-space covered at 3 (5) sigma level
    - Joint analysis with atmospheric neutrinos gives strong sensitivity to resolving mass ordering
  - Proton decay

- **Astroparticle physics goals:**
  - Supernova neutrinos (burst and relic)
  - Also: Indirect searches for dark matter, and solar neutrinos

- **For more information, see these upcoming talks:**
  - N. Prouse: TITUS [PPAP Parallel: Neutrino Detectors I] (Tuesday)
  - S. Short: DAQ [PPAP Parallel: Neutrino Detectors II] (Wednesday)