potential of Hyper-Kamiokande at some non accelerator physics and nucleon decay search programs

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On behalf of

The Hyper-Kamiokande proto-Collaboration

• Hyper-Kamiokande: the next-generation
• Expectations for some DM searches
• Expectations for Nucleon Decay searches

ICHEP-2016
2016/08/06, Chicago, Illinois
neutrino physics in Japan: A most successful experimental program

Kamiokande \rightarrow \text{Super-Kamiokande [K2K, T2K]} \rightarrow

- maximizes available resources \rightarrow \text{minimizes time, useless efforts ...}
- maximizes experience & know-how \rightarrow \text{minimizes risks, delays, failures}

\rightarrow \text{Hyper-Kamiokande [T2HK]}

- uses Water-Cherenkov:
  - unique technique to achieve \text{huge amount of instrument matter}

\begin{itemize}
  \item precise rec. of particle’s energy, position, direction, type ...
\end{itemize}
The key of HK: very large mass and excellent photosensitivity

- current baseline: high-QE Box&Line PMT Hamamatsu R12860
  - R&D since 2011

- also new bulb shape with higher pressure tolerance (> 100 m)
- now ready for mass production
- ≈ 80k 50 cm PMTs at inner detector

exterior view of Hamamatsu’s new building, No. 10, at the Toyooka Factory

Exterior view of the new Building No. 10 at the Toyooka Factory
the Hyper-Kamiokande [ T2HK ] experimental physics program

v oscillation physics
- determination of \( \nu \) Mass Hierarchy (atmospheric & beam)
- determination of \( \theta_{23} \) octant (atm. & beam)
- measurement of CP Violation in leptonic sector (atm. & beam)
- reveal exotic scenarios

Solar \( \nu \) physics
- precision measurement of \( \Delta m^2_{21} \)
- measurement of energy spectrum up-turn
- discovery & measurement of hep neutrino

\( \nu \) Astrophysics
- energy spectrum of Diffuse Supernova Neutrino Background
- galactic Supernova, high statistics, energy, time evolution ...
- indirect Dark Matter search from GC, Sun, Earth

Grand Unification physics
- \( p \rightarrow e^+\pi^0, p \rightarrow \nu K^+ \) & all visible modes
- reach \( 10^{35} \) sensitivity

#1036-talk M. Gonin “HK’s neutrino oscillation physics sensitivity”

#635-poster L. Labarga “Astrophysics Potential of HK”
main characteristics
high-QE Box&Line PMT
Hamamatsu R12860

Quantum Efficiency

improved from SK’s by ~ 50%

single p.e. w/ pedestal
peak/valley ≈ 4
σ ≈ 35 %

transit time for single p.e.
4.1 ns FWHM
fast left side rise
σ = 1.1 ns

2 x better efficiency,
timing resolution,
charge resolutions →
- enhance solar νs,
- signature n(p,d) γ
- p → ν K+
DM WIMP induced $\nu$, searches at the Sun

- $\chi \chi \rightarrow \tau^+ \tau^-, b\bar{b}, W^+W^- \rightarrow \nu X$
  search for $\nu$ “excess” from the sun
  
  use SK PRL 114, 141301 (2015) to illustrate

- assume on WIMPs capture and annihilations

$\rightarrow$ 90% CL limits on WIMP nucleon scattering cross-section:

spin dependent

spin independent

in black is SK for the same modes as HK

remarkable at $< 10$ GeV
DM WIMP-induced $\nu$, searches at the Galaxy

DM induced $\nu$ event excess from $\chi\chi \to b\bar{b} \to \nu X$

**SENSITIVITY 99% CL (DM annihilation, NFW profile)**

- 99% CL Hyper-K sensitivity band
- 99% CL Super-K sensitivity band

Livetimes used:
- SK: 11.6 yrs
- FC/PC: 12.4 yrs
- HK: 10 yrs
- UPMU: 10 yrs

**velocity averaged WIMP self-annihilation cross-section**

90% CL UPPER LIMIT

- Super-K current limit $b\bar{b}$
- Hyper-K sensitivity 10yrs $b\bar{b}$
- Super-K current limit $W^+W^-$
- Hyper-K sensitivity 10yrs $W^+W^-$
- Super-K current limit $\mu^+\mu^-$
- Hyper-K sensitivity 10yrs $\mu^+\mu^-$
- Hyper-K sensitivity 10yrs $\nu\bar{\nu}$
- IceCube-79 limit $b\bar{b}$


**expectation for thermal relic scenario**
an Hyper-Kamiokande primary goal: nucleon decay

status & next generation expectations (10 y exposure), most important modes:

design emphasizes $p \rightarrow e^+\pi^0$, $p \rightarrow \nu K^+$ while keeping sensitivity to many other
\[ p \rightarrow \bar{\nu} K^+ \]

- feature of super-symmetric GUTs
- rather interesting but difficult to reconstruct
- at decay \( p(K^+) = 340 \text{ MeV} \), \( K^+ \) ch-light threshold: 749 MeV
  \[ \rightarrow \text{reconstruct } K^+ \text{ from its decay products} \]
  \[ K^+ \rightarrow \nu \mu^+ (64\%), \ K^+ \rightarrow \pi^+\pi^0 (21\%) \]
- 2-body decays \( \rightarrow \) monochromatic particles: \( p(\mu^+) = 236 \text{ MeV} \), \( p(\pi^+) = p(\pi^0) = 205 \text{ MeV} \)
- \( \tau(K^+) \approx 12\text{ns} \rightarrow \) possible to observe prompt 6 MeV \( \gamma \) from \(^{16}\text{O} \) de-excitation

prompt 6 MeV \( \gamma \)

\[ \begin{align*}
\mu^+ \text{ from } K^+ \rightarrow \nu \mu^+ & \\
\pi^+\pi^0 \text{ search} & \\
\end{align*} \]

\( \text{proton decay MC} \)

\( \text{Michel } e^- \text{ from } \mu \text{ decay} \)

\( \text{atmospheric } \nu \text{ background} \)

\( \gamma \text{ background} \)

\( \text{used } \tau_p = 6.6 \times 10^{33} (\text{SK limit}), 10 \text{ years exposure} \)
$p \rightarrow \bar{\nu} K^+$ benefits from increased photon yield and timing resolution

- search for the prompt 6 MeV $\gamma$ from $^{16}$O de-excitation:

  number of hits within 12 ns wide time window prior to the $\mu^+$

  prompt- $\gamma$ tagging efficiency as a function of the $K^+$ decay time

  $K^+$ that decay earlier can be used in the analysis

LD / HD : 20% / 40% photo-coverage
$p \rightarrow \bar{\nu} K^+$

**discovery potential (3 $\sigma$)**

- **HK 560 kton LD**
- **HK 186 kton HD**
- **LAr 40 kton**
- **HK 372 kton HD (staged)**

**90% C.L. limits achievable if no event is observed**

**[Staging: 2nd tank comes into operation after 6 years]**

LAr discovery potential computed using numbers from DUNE CDR 2015:
- signal efficiency: 97%, background: 1 event Mton/year, no systematic errors
\[ p \rightarrow e^+\pi^0 \]

- favored by non-supersymmetric GUTs
- nearly model independent reaction

- back-to-back \( e^+, \pi^0 \) (459 MeV)
- \( e^+, \pi^0 \rightarrow \gamma \gamma \) are detected
- final state fully reconstructed in Water Cherenkov detectors

\[ \tau_p = 1.7 \times 10^{34} \text{(SK limit), 10 years exposure} \]
$p \rightarrow e^+\pi^0$

90% C.L. limits achievable if no event is observed

discovery potential (3 $\sigma$)

LAr discovery potential computed using numbers from DUNE CDR 2015:
signal efficiency: 97%, background: 1 event Mton/year, no systematic errors

[Staging: 2$^{nd}$ tank comes into operation after 6 years]
\(p \rightarrow e^+ \pi^0\) some of the benefits from increased photon yield

- neutron tagging (veto):
  - \(p\) decay: no neutrons // atmospheric \(\nu\) background: yes neutrons
  - neutrons at (pure) water: 2.2 MeV \(\gamma\) from \(n (p, d) \gamma\)

**discovery potential (3 \(\sigma\))**

\[\text{number of hits} \quad \text{Partial Lifetime (years)}\]

- Super-K, R3600 PMT
- Super-K, B&L PMT
- Hyper-K, B&L PMT

\(\rightarrow\) SK criterion:
- \(\approx 18\%\) tagging efficiency
- \(\rightarrow\) much better expected for Hyper-Kamiokande

\(\rightarrow\) a factor of \(\approx 2\)!
**other modes**

90% C.L. limits achievable if no event is observed

*exposure: 5.6 Mton·year, detector: HK 560 kton LD*

<table>
<thead>
<tr>
<th>B - L</th>
<th>conserving</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>Sensitivity (90% CL) [years]</th>
<th>Current limit [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow e^+ \pi^0$</td>
<td>$1.2 \times 10^{35}$</td>
<td>$1.4 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \bar{\nu}K^+$</td>
<td>$2.8 \times 10^{34}$</td>
<td>$0.7 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+ \pi^0$</td>
<td>$9.0 \times 10^{34}$</td>
<td>$1.1 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow e^+ \eta^0$</td>
<td>$5.0 \times 10^{34}$</td>
<td>$0.42 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+ \eta^0$</td>
<td>$3.0 \times 10^{34}$</td>
<td>$0.13 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow e^+ \rho^0$</td>
<td>$1.0 \times 10^{34}$</td>
<td>$0.07 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+ \rho^0$</td>
<td>$0.37 \times 10^{34}$</td>
<td>$0.02 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow e^+ \omega^0$</td>
<td>$0.84 \times 10^{34}$</td>
<td>$0.03 \times 10^{34}$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+ \omega^0$</td>
<td>$0.88 \times 10^{34}$</td>
<td>$0.08 \times 10^{34}$</td>
</tr>
<tr>
<td>$n \rightarrow e^+ \pi^-$</td>
<td>$3.8 \times 10^{34}$</td>
<td>$0.20 \times 10^{34}$</td>
</tr>
<tr>
<td>$n \rightarrow \mu^+ \pi^-$</td>
<td>$2.9 \times 10^{34}$</td>
<td>$0.10 \times 10^{34}$</td>
</tr>
</tbody>
</table>

| $\Delta (B - L) = 2$, $|\Delta B| = 2$ |

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<tr>
<th>Mode</th>
<th>Sensitivity (90% CL) [years]</th>
<th>Current limit [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow e^+ \nu\nu$</td>
<td>$10.2 \times 10^{32}$</td>
<td>$1.7 \times 10^{32}$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+ \nu\nu$</td>
<td>$10.7 \times 10^{32}$</td>
<td>$2.2 \times 10^{32}$</td>
</tr>
<tr>
<td>$p \rightarrow e^+ X$</td>
<td>$31.1 \times 10^{32}$</td>
<td>$7.9 \times 10^{32}$</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+ X$</td>
<td>$33.8 \times 10^{32}$</td>
<td>$4.1 \times 10^{32}$</td>
</tr>
<tr>
<td>$n \rightarrow \nu\gamma$</td>
<td>$23.4 \times 10^{32}$</td>
<td>$5.5 \times 10^{32}$</td>
</tr>
<tr>
<td>$np \rightarrow e^+ \nu$</td>
<td>$6.2 \times 10^{32}$</td>
<td>$2.6 \times 10^{32}$</td>
</tr>
<tr>
<td>$np \rightarrow \mu^+ \nu$</td>
<td>$4.2 \times 10^{32}$</td>
<td>$2.0 \times 10^{32}$</td>
</tr>
<tr>
<td>$np \rightarrow \tau^+ \nu$</td>
<td>$6.0 \times 10^{32}$</td>
<td>$3.0 \times 10^{32}$</td>
</tr>
</tbody>
</table>

→ basically 1 order of magnitude for most of the modes
Hyper-Kamiokande: the very-high mass, high precision, high beam power, highly reliable next generation M-ton neutrino and nucleon decay experiment

The photo-sensor is now ready for mass production. It features a 2x better efficiency, time and charge resolutions.

Unique sensitivity to medium mass DM WIMPS at the Galaxy and Sun

Nucleon decay: partial lifetimes limits (90% C.L., 10 y exposure) of $1.1 \times 10^{35}$ years for $p \rightarrow e^+\pi^0$, $4 \times 10^{34}$ years for $p \rightarrow \nu K^+$ and basically one order of magnitude improvement for many other nodes

Thus,

*if you want to explore GUTs experimentally in the next decades you’d better work (within your field) for Hyper-Kamiokande*
Thank you!
Additional
Inaugural Symposium of the HK proto-collaboration@Kashiwa, Jan-2015

12 countries, ~250 members and growing

• Proto-collaboration formed.
• International steering group
• International conveners
• International chair for international board of representative (IBR)
• International Advisory Committee (HKAC)

KEK-IPNS and UTokyo-ICRR signed a MoU for cooperation on the Hyper-Kamiokande project.
• 2018 - 2025 HK construction.
• 2026 onwards CPV study, Atmospherics ν, Solar ν, Supernova ν, Proton decay searches, …
• The 2nd identical tank starts operation 6yrs after the first one.
FIG. 62. Output linearity of the HOE B&L PMT in charge, where a dotted line shows an ideal linear response. It is derived by measurements of a coincident emission by two light sources compared with an expectation by sum of individual detections.

FIG. 63. Gain stability of a delayed pulse after a primary pulse, compared with no primary pulse. The charge set is about 150 PEs at $10^7$ gain for both primary and delayed pulses in various delayed time.

FIG. 64. A measured gain stability as a function of the pulse rate in three light intensities of 25, 50 and 100 photoelectrons, relative to outputs at 100 Hz. Each charge is calculated using the baseline just before the pulse.
Figure 1. The neutrino yields for electron and tau neutrinos as functions of $z = E_\nu / m_\chi$ for six different WIMP annihilation channels at production in the center of the Sun and the Earth. Note that the muon neutrino yields are the same as the electron neutrino yields and are therefore not shown separately.
\[ p \rightarrow e^+ \pi^0 \quad \text{MC} \]

\[ \rightarrow \text{neutron veto} \]

Atmospheric \( \nu \) MC

background probability reduced from 44% to 9%
FIG. 143. Reconstructed muon momentum distributions for muons found in the prompt $\gamma$ search for $p \rightarrow \bar{\nu}K^+$. The hatched histograms show the atmospheric neutrino background and the solid crosses denote the sum of the background and proton decay signal. Here the proton lifetime is assumed to be, $6.6 \times 10^{33}$ years, just beyond current Super-K limits. The plots on the left and right show the expectation for the 1TankHD and 3TankLD designs, respectively, after a 10 year run. In the latter a second tank is assumed to come online six years after the start of the experiment.
FIG. 144. Reconstructed kaon mass based on the reconstructed final in the $p \rightarrow \bar{\nu}K^+$ modes $\pi^+\pi^0$ search. The hatched histograms show the atmospheric neutrino background and the solid crosses denote the sum of the background and proton decay signal. Here the proton lifetime is assumed to be, $6.6 \times 10^{33}$ years, just beyond current Super-K limits and all cuts except for the cut on visible energy opposite the $\pi^0$ candidate have been applied. The plots on the left and right show the expectation for the 1TankHD and 3TankLD designs, respectively, after a 10 year run. In the latter a second tank is assumed to come online six years after the start of the experiment.
FIG. 138. Reconstructed invariant mass distribution of events passing all steps of the $p \rightarrow e^+\pi^0$ event selection except the invariant mass cut. The hatched histograms show the atmospheric neutrino background and the solid crosses denote the sum of the background and proton decay signal. Here the proton lifetime is assumed to be, $1.7 \times 10^{34}$ years, just beyond current Super-K limits. The plots on the left and right show the expectation for the 1TankHD and 3TankLD designs, respectively, after a 10 year run. For the former an additional tank is assumed to come online six years after the start of the experiment. In each configuration the free (bound) proton enhanced bin appears in the upper (lower) panel of each figure.
TABLE XXXVIII. Signal efficiency and background rates as well as estimated systematic uncertainties for the analysis $p \rightarrow e^+\pi^0$ at Hyper-K.

<table>
<thead>
<tr>
<th>Design</th>
<th>$\epsilon_{\text{sig}}$ [$%$]</th>
<th>$\sigma_\epsilon$ [$%$]</th>
<th>Bkg [/Mton·yr]</th>
<th>$\sigma_{\text{Bkg}}$ [$%$]</th>
<th>$\epsilon_{\text{sig}}$ [$%$]</th>
<th>$\sigma_\epsilon$ [$%$]</th>
<th>Bkg [/Mton·yr]</th>
<th>$\sigma_{\text{Bkg}}$ [$%$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1TankHD</td>
<td>18.7</td>
<td>6.5</td>
<td>0.06</td>
<td>32.8</td>
<td>19.4</td>
<td>14.9</td>
<td>0.62</td>
<td>31.9</td>
</tr>
<tr>
<td>3TankLD</td>
<td>18.8</td>
<td>5.3</td>
<td>0.27</td>
<td>29.0</td>
<td>20.4</td>
<td>15.2</td>
<td>2.17</td>
<td>31.3</td>
</tr>
</tbody>
</table>

TABLE XXXIX. Signal efficiency and background rates as well as estimated systematic uncertainties for the analysis $p \rightarrow \bar{\nu}K^+$ at Hyper-K. Background rates are listed as events per Mton·yr.

<table>
<thead>
<tr>
<th>Design</th>
<th>$\epsilon_{\text{sig}}$ [$%$]</th>
<th>$\sigma_\epsilon$ [$%$]</th>
<th>Bkg</th>
<th>$\sigma_{\text{Bkg}}$ [$%$]</th>
<th>$\epsilon_{\text{sig}}$ [$%$]</th>
<th>$\sigma_\epsilon$ [$%$]</th>
<th>Bkg</th>
<th>$\sigma_{\text{Bkg}}$ [$%$]</th>
<th>$\epsilon_{\text{sig}}$ [%]</th>
<th>Bkg</th>
<th>$\sigma_{\text{fit}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1TankHD</td>
<td>12.7</td>
<td>19.0</td>
<td>0.9</td>
<td>27.0</td>
<td>10.8</td>
<td>10.0</td>
<td>0.7</td>
<td>31.0</td>
<td>31.0</td>
<td>1916.0</td>
<td>8.0</td>
</tr>
<tr>
<td>3TankLD</td>
<td>7.4</td>
<td>19.0</td>
<td>2.7</td>
<td>25.0</td>
<td>6.7</td>
<td>10.0</td>
<td>3.4</td>
<td>29.0</td>
<td>31.0</td>
<td>1916.0</td>
<td>8.0</td>
</tr>
</tbody>
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