Search for proton decay using Super-Kamiokande and future prospects with Hyper-Kamiokande

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Grand Unification

Running coupling constants seem to cross at single point (unification scale)

Unification of interactions and
Unification of quark and lepton

Possibility of transition from quark to lepton

Proton decay
Predicted decay modes of proton

Two major decay modes

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

\[ p \rightarrow \bar{\nu}K^+ \]

Theoretical predictions
Every day, ~20 solar and *atmospheric neutrinos* are observed.
Super-Kamiokande detector

History of the SK detector

SK-I
April 1996 ~ June 2001
11146 ID PMTs (40% coverage)

SK-II
October 2002 ~ October 2005
5182 ID PMTs (19% coverage)

SK-III
June 2006 ~ September 2008
11129 ID PMTs (40% coverage)

SK-IV
September 2008 ~ running
Electronics Upgrade

Acrylic (front) + FRP (back)
Super-Kamiokande detector

Event reconstruction

- Amount of the Cherenkov photons
  \[ \propto \text{Momentum of the particle} \]
  → Use observed # of photons to reconstruct energy.

- Interaction position
  \( \sim \) starting point of the charged particle
  → Use photon arrival timing.
  Ring pattern is also used for the precise reconstruction.

- # of the charged particles & \( \gamma \)
  → # of the Cherenkov rings

Also, electrons generated by the decay of \( \mu, \pi \) etc. gives useful information.
Particle types (e-like or μ-like) can be identified by the shape of the Cherenkov ring. Electron (or gamma) generates electro-magnetic shower and ring is more diffused compared to the muon.

But weak in detecting low momentum heavy particles.

Real data $p_\mu \sim 1.3\text{GeV/c}$

Real data $p_e \sim 1\text{GeV/c}$
Proton decay search in SK

Ring imaging water Cherenkov detectors have very high efficiency in identifying both $e^+$ and $\pi^0$.

$\nu_e = \nu_\pi = 459$ MeV/c

Clear 3 $e^-$-like rings are expected to be observed.
Proton decay search in SK ~ background source ~ atmospheric neutrino

Primary cosmic ray ( p, He .. )

Atmospheric neutrino energy spectrum

Atmospheric neutrino energy spectrum
Peaked at several hundreds of MeV.

~ mass of nucleon ~
Proton decay search in SK ~ signal and background ~

Proton decay signal

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

Background (example)

\[ \bar{\nu}_e + p \rightarrow e^+ + \pi^0 + n \]

Background atmospheric neutrino events could be rejected if neutrons are tagged.

In the water, neutron is captured by hydrogen (\(\sim 200 \, \mu s\)) and emit 2.2 MeV \(\gamma\) ray.

\[ n + p \rightarrow d + \gamma \]
Proton decay search in SK

~ background rejection using neutron tag method ~

New DAQ system installed for Super-K IV allows us to store all the PMT hit information for > 500 µs after the atmospheric ν or proton decay candidates.

Possible to search for 2.2 MeV γ, which gives about 10 PMT hits.

Search for hit cluster ( N≥7 in 10ns ) after prompt event and select candidates using neural network.

Detection efficiency ~ 20.5% ( mis-tag ~ 1.8% )

About half of the background events could be rejected by requiring no neutron candidates.
Proton decay search in SK

Event selection criteria

- No activity in the outer detector
- Vertex in the fiducial volume
- No decay electron
- 2 or 3 e-like ring
  \( (e^+ + 1 \text{ or } 2 \gamma) \)
  \( \sim \) one of the \( \gamma \)s may have low energy or overlap with the other rings
- Reconstructed \( \pi^0 \) mass
  \( 85 \sim 185 \text{ MeV/c}^2 \)
  (for 3 ring events)
- Reconstructed proton mass
  \( 800 \sim 1050 \text{ MeV/c}^2 \)
- Reconstructed total (proton) momentum
  \( p_{\text{tot}} < 250 \text{ MeV/c} \)
- No tagged neutron (only for SK4)
Proton decay search in SK

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

### SK-IV

<table>
<thead>
<tr>
<th></th>
<th>Low ( P_{\text{tot}} )</th>
<th>High ( P_{\text{tot}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal efficiency</td>
<td>18.7 ( ± 1.9 ) %</td>
<td>19.4 ( ± 3.4 ) %</td>
</tr>
<tr>
<td>Background ( /Mt*yr)</td>
<td>( 0.18^{+0.25}_{-0.13} )</td>
<td>1.1 ± 0.3</td>
</tr>
</tbody>
</table>
Proton decay search in SK

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

One of the major sources of inefficiency

$\pi$ interaction in Oxygen (before escaping from $^{16}$O)

- charge exchange ($\pi^0 \rightarrow \pi^\pm$)
- inelastic scattering $\sim$ change momentum and direction of $\pi^0$

$\pi^+$ interaction cross-section on carbon

$\pi^0$ interaction probability in $^{16}$O

momentum of $\pi^0$

(from stationary proton’s decay)
Proton decay search in SK

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

One of the major sources

of inefficiency

\( \pi \) interaction in Oxygen (before escaping from \(^{16}\)O)

\{ 
  - charge exchange (\(\pi^0 \rightarrow \pi^\pm\))
  - inelastic scattering \(\sim\) change momentum and direction of \(\pi^0\)
\}

Further reduction of background

Divide the sample into two.

Low momentum sample (\( p < 100 \text{MeV/c} \))
  to search for the decay of Hydrogen
  Smaller \# of backgrounds

High momentum sample (\( 100 < p < 250 \text{ MeV/c} \))
  to search for the decay of proton in Oxygen
  Larger \# of backgrounds
Proton decay search in SK

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

Toward the precise estimation of the background

Data from the accelerator experiments are very useful.

For the SK analysis,

data from the 1kt water Cherenkov detector

in the K2K experiment

were used to check our estimations.

K2K : \( \nu_\mu \) beam, \( E_\nu \sim \) a few hundreds of MeV \( \sim \) a few GeV.

Good agreement

K2K (\( p \rightarrow e^+ + \pi^0 \) BG by \( E_\nu < 3 \text{GeV} \))

1.63 \(+0.42/-0.33\) (stat.)

\(+0.45/-0.51\) (sys.)

events / Mt\( \cdot \)yr

Data from \( \pi \) beam experiments are also useful.
Proton decay search in SK

Source of the background events

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

\[ 30\% \text{ from CC single } \pi \]
\[ (\nu_e N \rightarrow e N' \pi) \]

\[ 20\% \text{ from CC multi } \pi \]
\[ (\nu_e N \rightarrow e N' m\pi) \]

\[ 30\% \text{ from CC QE} \]
\[ \pi^0 \text{ from secondary interactions of nucleon} \]
\[ (\nu_e N \rightarrow e N' + \text{secondary } \pi^0) \]

\[ 20\% \text{ from NC} \]
\[ (\nu N \rightarrow \nu N' X) \]

\[ \pi \text{ interaction in Oxygen or in the detector changes the charge, momentum and direction of } \pi. \]
Proton decay search in SK

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

Partial lifetime limit = $1.6 \times 10^{34}$ year

So far, no candidate events have been observed.

Upper block : Low momentum region
Lower block : High momentum region
Proton decay search in SK

Event selection criteria

• No activity in the outer detector
• Vertex in the fiducial volume
• No decay electron
• 2 or 3 rings and only 1 $\mu$-like
  ($\mu^+ + 1$ or $2\gamma$)
  ~ one of the $\gamma$s may have low energy
  or overlap with the other rings
• Reconstructed $\pi^0$ mass
  $85 \sim 185$ MeV/c$^2$
  ( for 3 ring events )
• Reconstructed proton mass
  $800 \sim 1050$ MeV/c$^2$
• Reconstructed total (proton) momentum
  $p_{\text{tot}} < 250$ MeV/c
• No tagged neutron (only for SK4)
Proton decay search in SK

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

### Total Mass (MeV/c^2)

#### SK-IV

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<td>Signal efficiency</td>
<td>20.1 (±1.9) %</td>
<td>18.2 (±3.3) %</td>
</tr>
<tr>
<td>Background (Mt*yr)</td>
<td>$0.09^{+0.21}_{-0.08}$</td>
<td>1.7 ± 0.6</td>
</tr>
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</table>
Proton decay search in SK

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

Partial lifetime limit = $7.7 \times 10^{33}$ year

2 candidate events have been observed in high momentum region.
Proton decay search in SK

\( p \rightarrow \bar{\nu} + K^+ \)

Ring imaging water Cherenkov detectors can not detect \( K^+ \) from proton decay directly due to its small momentum. \( (p_K = 339 \text{ MeV/c}) \)

Interaction probability of low momentum \( K^+ \) is small and most of \( K^+ \) are expected to decay at rest.

→ Use decay products of \( K^+ \) for the identification of the candidate events

\( K^+ \rightarrow \pi^+ + \pi^0 \)

- Two e-like rings with 1 decay-e
- Small activity (from \( \pi^+ \)) in the opposite direction of \( \pi^0 \)

\[ Br = 20.7\% \]

\( p_{\pi} = 205 \text{ MeV/c} \)

\( K^+ \rightarrow \mu^+ + \nu^- \)

- Single \( \mu \)-like ring with 1 decay electron

\[ Br = 63.5\% \]

\[ p_\mu = 236 \text{ MeV/c} \]
When a proton in oxygen decays, 6.3MeV de-excitation $\gamma$ is also emitted with probability of $\sim 40\%$.

- Search for 1 ring $\mu$-like events with $p_\mu \sim 236$ MeV/c with 1 decay electron
- Additionally, search for the pre-activity from prompt de-excitation 6.3 MeV $\gamma$
Proton decay search in SK

\[ p \rightarrow \overline{\nu} + K^+ \]

\[ K^+ \rightarrow \mu^+ + \nu^- \] with prompt \( \gamma \) tag.

\[ \nu \rightarrow ^{16}\text{O} \rightarrow ^{15}\text{N} \]

\[ \gamma (6.3\text{MeV}) \]

Event selection criteria:

- No activity in the outer detector
- Vertex in the fiducial volume
- 1 decay electron
- 1 \( \mu \)-like ring
- No tagged neutron (only for SK4)

\[ T_{\mu} - T_{\gamma} < 75\text{ns} \]
Proton decay search in SK

\[ p \rightarrow \bar{\nu} + K^+ \]

momentum of muons

Number of hits

Red histogram: Atmospheric $\nu$ MC (scaled to live-time of data)
Blue histogram: Signal MC (arbitrary scale)
Dot with cross: Data
Proton decay search in SK

\[ p \rightarrow \bar{\nu} + K^+ \]

\[ K^+ \rightarrow \mu^+ + \bar{\nu} \]

with prompt \( \gamma \) tagging

<table>
<thead>
<tr>
<th></th>
<th>Exposure (kt.yr)</th>
<th>Efficiency (%)</th>
<th>Background</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK1</td>
<td>91.7</td>
<td>7.9 ± 0.1</td>
<td>0.08</td>
<td>0</td>
</tr>
<tr>
<td>SK2</td>
<td>49.2</td>
<td>6.3 ± 0.1</td>
<td>0.14</td>
<td>0</td>
</tr>
<tr>
<td>SK3</td>
<td>31.9</td>
<td>7.7 ± 0.1</td>
<td>0.03</td>
<td>0</td>
</tr>
<tr>
<td>SK4</td>
<td>133.5</td>
<td>8.5 ± 0.1</td>
<td>0.14</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>306.3</td>
<td></td>
<td>0.39</td>
<td>0</td>
</tr>
</tbody>
</table>

Red: Atm. \( \nu \) MC
Blue: Signal MC
Dot with cross: Data
Proton decay search in SK

Event selection criteria \( K \rightarrow \pi^+ + \pi^0 \)

- No activity in the outer detector
- Vertex in the fiducial volume
- 1 decay electron
- 1 or 2 e-like rings (from \( \pi^0 \))
- Reconstructed \( \pi^0 \) mass 
  \[ 85 \sim 185 \text{ MeV}/c^2 \]
- Reconstructed \( \pi^0 \) momentum 
  \[ 175 \sim 250 \text{ MeV}/c \]
- Visible energy sum in \( 140^\circ \sim 180^\circ \) from \( \pi^0 \) direction (\( E_{bk} \))
  \[ 10 < E_{bk} < 50 \text{ MeV} \]
- Visible energy sum in \( 90^\circ \sim 140^\circ \) from \( \pi^0 \) direction (\( E_{res} \))
  \[ E_{res} < 12 \text{ MeV} \) (2 rings), 20 MeV (1 ring)
- Charge distribution likelihood cut
- No tagged neutron (only for SK4)

\[ \text{Br} = 20.7\% \]
Proton decay search in SK

\[ p \rightarrow \bar{\nu} + K^+ \]

\[ K \rightarrow \pi^+ + \pi^0 \]

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<td>0</td>
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<td>0</td>
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<tr>
<td>SK4</td>
<td>133.5</td>
<td>9.0 ± 0.1</td>
<td>0.12</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>306.3</td>
<td></td>
<td>0.56</td>
<td>0</td>
</tr>
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Proton decay search in SK

\[ p \rightarrow \bar{\nu} + K^+ \]

\[ K^+ \rightarrow \mu^+ + \bar{\nu} \]

with prompt \( \gamma \) tag.

\[ K^+ \rightarrow \pi^0 + \pi^+ \]

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<td>0.39</td>
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</table>

Partial lifetime limit (combined) = \( 6.6 \times 10^{33} \) year @ 306.3 kt·yr
Extensive studies have been performed. However, no signature of nucleon decay was observed.

*) Blue lines are analysis with less than 300kt yr data and we can improve with revised analyses.

Nucleon decay search in SK
So far, we have not found any indication of nucleon decay. Latest lifetime limits from SK

\[ p \rightarrow e^+ \pi^0 \quad \tau/B > 1.6 \times 10^{34} \text{ yr} \]

\[ p \rightarrow \bar{\nu} K^+ \quad \tau/B > 6.6 \times 10^{33} \text{ yr} \]
Hyper Kamiokande project

What is not sufficient in SK? => ~ Statistics = target mass ~

500 kton (Fiducial volume ~ 380 kton) scale detector

Expand the size of the cylindrical (SK-like) detector
Effective photo sensitive area ~ 40%
High photon sensitivity

Maximum utilization of resources and experiences in SK
~ Use established technology for the long term operation to achieve physics goal in timely manner.

SK : Fiducial 22.5 kton

HK : Fiducial 380 kton ~ 17 x SK
Hyper-Kamiokande detector

Is it possible to construct such gigantic detectors?

**Candidate site: Tochibora mine in Kamioka**

Based on the geological survey and analyses, the cavern and the supporting structures were designed. *Possible to construct HK Caverns with existing technology.*
Hyper-Kamiokande detector ~ Further improvements ~

Photo sensors ~ **R&D to improve the detector performance**
Better timing resolution ~ better vertex resolution
Higher quantum efficiency

<table>
<thead>
<tr>
<th>Baseline (reference)</th>
<th>Candidates (R&amp;D phase)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20” Super-K PMT</td>
<td>20” Box&amp;line PMT</td>
</tr>
<tr>
<td>R3600</td>
<td>R12860</td>
</tr>
<tr>
<td>HPK</td>
<td>HPK</td>
</tr>
</tbody>
</table>

Venetian blind dynode

- Various drift path
- Might miss dynode

Box&line dynode

- Unique drift path
- Large acceptance

Avalanche diode (AD)

- Short drift path
- High first step gain (x1600)

<table>
<thead>
<tr>
<th>Quantum eff.</th>
<th>22%</th>
<th>30%</th>
<th>30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collection eff.</td>
<td>80%</td>
<td>93%</td>
<td>95%</td>
</tr>
<tr>
<td>Timing res. (FWHM)</td>
<td>5.5 nsec</td>
<td>2.7 nsec</td>
<td>1 nsec</td>
</tr>
</tbody>
</table>
Hyper-Kamiokande project ~ Notional Timeline ~

**Assuming funding from 2018**

The 1st detector construction in 2018~2025

- Cavern excavation: ~5 years
- Tank (liner, photosensors) construction: ~3 years
- Water filling: 0.5 years
Hyper-Kamiokande detector ~ Further improvements ~

**Photo sensors ~ R&D to improve the detector performance**
- Better timing resolution ~ better vertex resolution
- Higher quantum efficiency

New photo sensor
- Higher quantum efficiency 22% → > 30%
- Higher collection efficiency 80% → ~ 90%

Photon detection efficiency
- is expected to be improved by > 50%

![20” Box&line PMT R12860](image)

With the same photo sensitive coverage,
- # of photons expected to be larger.
- Efficiency to detect 2.2 MeV $\gamma$ from neutron capture
- is expected to be improved by ~ 3 times.
Proton decay search @ Hyper-K

\[ p \rightarrow e^+\pi^0 \]  # of background is further reduced with `improved’ neutron tag efficiency.

<table>
<thead>
<tr>
<th>( p \rightarrow e^+\pi^0 )</th>
<th>( 0 &lt; p_{\text{tot}} &lt; 100 \text{ MeV/c} )</th>
<th>( 100 &lt; p_{\text{tot}} &lt; 250 \text{ MeV/c} )</th>
</tr>
</thead>
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<tr>
<td>( )</td>
<td>Signal efficiency</td>
<td># of background ( /Mton-yr)</td>
</tr>
<tr>
<td>SK IV</td>
<td>19%</td>
<td>0.2</td>
</tr>
<tr>
<td>Hyper-K</td>
<td>19%</td>
<td>0.06</td>
</tr>
</tbody>
</table>

\[ p \rightarrow \bar{\nu} K^+ : \quad \text{Efficiencies are improved owing to higher photon detection efficiency.} \]

<table>
<thead>
<tr>
<th>( p \rightarrow \bar{\nu} K^+ )</th>
<th>( K^+ \rightarrow \mu^+\nu_\mu ) with prompt ( \gamma )</th>
<th>( K^+ \rightarrow \pi^+\pi^0 )</th>
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<tr>
<td>SK IV</td>
<td>8.5%</td>
<td>1.1</td>
</tr>
<tr>
<td>Hyper-K</td>
<td>13%</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Proton decay search @ Hyper-K

\[ p \rightarrow e^+\pi^0 \quad \text{For } \tau_{p/Br} = 1.7 \times 10^{34} \text{ years} \]

\[ p \rightarrow \bar{\nu}K^+ \quad \text{For } \tau_{p/Br} = 6.6 \times 10^{33} \text{ years} \]

HK 10 years MC

- 0 < \text{Ptot} < 100\text{MeV/c}
- 100 < \text{Ptot} < 250\text{MeV/c}

Signal + BG
Atm. \nu BG

Proton mass peak

- \text{K}^+ \rightarrow \mu^+ + \nu
- \text{K}^+ \rightarrow \pi^+ + \pi^0
For $p \to e^+\pi^0$ $3\sigma$ discovery will reach $\sim 10^{35}$ years
Summary

So far, we have not found no indication of nucleon decay.

Latest lifetime limits from SK

\[ p \rightarrow e^+ \pi^0 \quad \tau/B > 1.6 \times 10^{34} \text{ yr} \]

\[ p \rightarrow \bar{\nu} K^+ \quad \tau/B > 6.6 \times 10^{33} \text{ yr} \]
Summary

With Hyper-Kamiokande detector,

$p \rightarrow e^+\pi^0$ 3σ discovery will reach $\sim 10^{35}$ years
fin.
Search for dinucleon decay and $n - \bar{n}$ oscillation in Super-Kamiokande

Sakharov conditions

Three minimum properties of Nature for any baryogenesis to occur.

1. *At least one B-number violating process.*
2. C- and CP-violation
3. Interactions outside of thermal equilibrium.

No experimental signature of $|\Delta B| = 1$ baryon number violation (proton decay) until now.

Other possibilities of $|\Delta B| = 2$

- **Dinucleon decay**
- **$n - \bar{n}$ oscillation** etc...

References

Search for $n - n\bar{b}$ oscillation in Super-Kamiokande, K. Abe et al., Phys. Rev. D 91, 072006 (2015)
Search for dinucleon decay in Super-Kamiokande

Search for $\text{NN} \rightarrow \pi\pi$ in Oxygen

One example of Feynman diagram for dinucleon decay

$$q_1, q_2 : u \text{ or } d$$
$$X_1, X_2 : \text{Scalar particle}$$

Search for 3 channels using SK data

$$\text{pp} \rightarrow \pi^+\pi^+$$
$$\text{pn} \rightarrow \pi^+\pi^0$$
$$\text{nn} \rightarrow \pi^0\pi^0$$

Ref. J. M. Arnold, B. Fornal, and M. B. Wise
Search for dinucleon decay in Super-Kamiokande

Basic Idea: Search for two back-to-back pions in an event and calculate the reconstruct invariant mass.

Signal: Reconstructed Invariant mass $\sim (2xM_{\rho} - 2xM_{\pi})$

In SK, $\pi^+$ is identified as non-showering ring (μ-like ring) $\pi^0$ could be reconstructed from 2 showering rings (e-like rings)

Background

Atmospheric $\nu$ events ($\nu N \rightarrow \nu N' \pi \pi$ etc.)

Difficulties

$\mu$ is also identified as non-showering ring
dinucleon decay occurs in Oxygen and go through water → pions interact with the other nucleons.
= May change charge, direction and momentum.
In the worst case, pions are absorbed.

*Simple cut-based analysis results in poor efficiency and poor background rejection power.*
Search for dinucleon decay in Super-Kamiokande (I)

**pp → π⁺π⁺**

Pre-selection (to reduce large background of atmospheric ν)

- **A0)** Fully contained in fiducial events
- **A1)** More than 1 Cherenkov ring
- **A2)** Two most energetic rings are non-showering (μ-like)
- **A3)** Opening angle of the two most energetic rings > 120 deg.
- **A4)** Total visible energy (electron equiv. energy) < 1600 MeV

**Total exposure**: 282.1 kt·yr (SK I to SK IV)

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<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eff. (%)</td>
<td>11.2 ± 0.2</td>
<td>10.5 ± 0.2</td>
<td>12.0 ± 0.2</td>
<td>12.1 ± 0.2</td>
</tr>
<tr>
<td>Bkg.</td>
<td>33 ± 0.9</td>
<td>17 ± 0.5</td>
<td>13 ± 0.4</td>
<td>45 ± 1.2</td>
</tr>
<tr>
<td>data</td>
<td>27</td>
<td>14</td>
<td>8</td>
<td>43</td>
</tr>
</tbody>
</table>

( Total number of FC atmospheric ν ~ 37700 & 70% are 1 ring events.)
Search for dinucleon decay in Super-Kamiokande (I)

\[ pp \rightarrow \pi^+\pi^+ \]

Use Boosted Decision Trees (BDT) to improve analysis

Use 9 parameters to enhance the signal selection efficiency and background rejection power.

a1) Angle between two most energetic rings
a2) Ratio of charge carried by most energetic ring
a3) Total visible energy (electron equiv. energy)
a4) Maximum distance to the decay electron
a5) Maximum angle between \( \mu \)-like ring and decay electron vertex
a6) Magnitude of vector sum of corrected charge (\( \sim \) total momentum)
a7) Number of rings
a8) Number of decay electrons
a9) Number of non-showering rings
Search for dinucleon decay in Super-Kamiokande (1)

\[ pp \rightarrow \pi^+\pi^+ \]

**Importance of each input**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle between $\mu$-like rings</td>
<td>0.16</td>
</tr>
<tr>
<td>Ratio of charge carried by most energetic ring</td>
<td>0.15</td>
</tr>
<tr>
<td>Visible energy</td>
<td>0.15</td>
</tr>
<tr>
<td>Max. distance to Michel vertex</td>
<td>0.13</td>
</tr>
<tr>
<td>Max. angle between $\mu$-like ring and Michel vertex</td>
<td>0.13</td>
</tr>
<tr>
<td>Magnitude of vector sum of corrected charge</td>
<td>0.12</td>
</tr>
<tr>
<td>Number of rings</td>
<td>0.071</td>
</tr>
<tr>
<td>Number of Michel electrons</td>
<td>0.055</td>
</tr>
<tr>
<td>Number of $\mu$-like rings</td>
<td>0.045</td>
</tr>
</tbody>
</table>
Search for dinucleon decay in Super-Kamiokande (I)

**pp → π⁺π⁺**

<table>
<thead>
<tr>
<th></th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eff. (%)</td>
<td>6.1 ± 0.2</td>
<td>5.3 ± 0.2</td>
<td>6.4 ± 0.2</td>
<td>5.8 ± 0.2</td>
</tr>
<tr>
<td>Bkg. (MT-yr)</td>
<td>17.8 ± 1.8</td>
<td>14.3 ± 1.6</td>
<td>17.4 ± 1.7</td>
<td>14.2 ± 1.6</td>
</tr>
<tr>
<td>Bkg. (SK live.)</td>
<td>1.6</td>
<td>0.70</td>
<td>0.56</td>
<td>1.6</td>
</tr>
<tr>
<td>Candidates</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

4.5 background expected, 2 observed. (bkg. consistent ...)

Event displays (remained as candidates)

---

Dashed ring (e-like)

Hard scatter?
Search for dinucleon decay in Super-Kamiokande (I)

$pp \rightarrow \pi^+\pi^+$

Remaining background events

\sim 45\% : Charged current single $\pi$ production ( $\nu N \rightarrow l^- N' \pi^+$ etc. )

\sim 30\% : Charged current deep inelastic scattering (DIS)

\( ( \nu N \rightarrow l^- N' \pi^+ \pi^+ \text{ etc. } ) \)

Systematic uncertainties

<table>
<thead>
<tr>
<th>Signal (%)</th>
<th>$pp \rightarrow \pi^+\pi^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>SK-I 35.2</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>6.0</td>
</tr>
<tr>
<td>BDT</td>
<td>3.6</td>
</tr>
<tr>
<td>Total</td>
<td>35.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Background (%)</th>
<th>$pp \rightarrow \pi^+\pi^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>SK-I 29.1</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>6.1</td>
</tr>
<tr>
<td>BDT</td>
<td>6.8</td>
</tr>
<tr>
<td>Total</td>
<td>30.5</td>
</tr>
</tbody>
</table>

Major uncertainty (Simulation) $\pi$ interactions in/with nucleus

Obtained lifetime limit: $\tau_{pp \rightarrow \pi^+\pi^+} > 7.22 \times 10^{31}$ yrs
Search for dinucleon decay in Super-Kamiokande ( II )

\[ pn \rightarrow \pi^+\pi^0 \]

Pre-selection ( to reduce large background of atmospheric \( \nu \) )

B0) Fully contained in fiducial events
B1) More than 1 Cherenkov ring
B2) At least 1 non-showering ( \( \mu \)-like ) and 1 showering ( \( e \)-like ) rings.
B3) # of decay electron is no more than 1.
B4) Total visible energy
   – reconstructed energy of \( \pi^0 \) < 800 MeV
B5) Opening angle between \( \pi^+ \) and \( \pi^0 > 120 \) deg.

Total exposure : 282.1 kt·yr ( SK I to SK IV )

<table>
<thead>
<tr>
<th></th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eff. (%)</td>
<td>21.0 ± 0.3</td>
<td>21.9 ± 0.3</td>
<td>21.6 ± 0.3</td>
<td>21.1 ± 0.3</td>
</tr>
<tr>
<td>Bkg.</td>
<td>132 ± 1.8</td>
<td>69 ± 1.0</td>
<td>48 ± 0.6</td>
<td>147 ± 2.0</td>
</tr>
<tr>
<td>data</td>
<td>136</td>
<td>66</td>
<td>45</td>
<td>171</td>
</tr>
</tbody>
</table>

( Total number of FC atmospheric \( \nu \) \( \sim 37700 \) & 70 % are 1 ring events. )
Search for dinucleon decay in Super-Kamiokande ( II )

\[ \text{pn} \rightarrow \pi^+\pi^0 \]

Use Boosted Decision Trees ( BDT ) to improve analysis

Use 9 parameters to enhance the signal selection efficiency and background rejection power.

b1) Reconstructed momentum of \( \pi^0 \)
b2) Angle between \( \pi^+ \) and \( \pi^0 \)
b3) Reconstructed momentum of \( \pi^+ \)
b4) Invariant mass of \( \pi^0 \)
   ( For this, we use special \( \pi^0 \) reconstruction tool )
b5) Ratio of charge carried by most energetic ring
b6) Total visible energy ( electron equiv. energy )
b7) Number of decay electrons
Search for dinucleon decay in Super-Kamiokande (II)

\[ pn \rightarrow \pi^+\pi^0 \]

**Importance of each input**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^0 ) candidate momentum</td>
<td>0.19</td>
</tr>
<tr>
<td>Angle between ( \pi^0 ) and ( \pi^+ ) candidates</td>
<td>0.17</td>
</tr>
<tr>
<td>( \pi^+ ) candidate momentum</td>
<td>0.16</td>
</tr>
<tr>
<td>( \pi^0 ) candidate invariant mass</td>
<td>0.15</td>
</tr>
<tr>
<td>Ratio of charge carried by most energetic ring</td>
<td>0.14</td>
</tr>
<tr>
<td>Visible energy</td>
<td>0.14</td>
</tr>
<tr>
<td>Number of Michel electrons</td>
<td>0.058</td>
</tr>
</tbody>
</table>
Search for dinucleon decay in Super-Kamiokande (II)

\[ \text{pn} \rightarrow \pi^+\pi^0 \]

<table>
<thead>
<tr>
<th></th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut</td>
<td>0.19</td>
<td>0.24</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td>Eff. (%)</td>
<td>10.2 ± 0.2</td>
<td>10.0 ± 0.2</td>
<td>9.4 ± 0.2</td>
<td>10.4 ± 0.2</td>
</tr>
<tr>
<td>Bkg. (MT-yr)</td>
<td>2.7 ± 0.7</td>
<td>2.3 ± 0.7</td>
<td>2.2 ± 0.7</td>
<td>2.9 ± 0.8</td>
</tr>
<tr>
<td>Bkg. (SK live.)</td>
<td>0.25</td>
<td>0.11</td>
<td>0.07</td>
<td>0.32</td>
</tr>
<tr>
<td>Candidates</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

0.75 background expected, 1 observed. (bkg. consistent...)

Event display (remained as candidates)

2 ring event
Opening angle = 140 deg.
\[ p_e = 987 \text{ MeV/c} \]
\[ p_\mu = 460 \text{ MeV/c} \]
Reconstructed \( \pi^0 \) mass = 10 MeV/c^2
No decay electron
Search for dinucleon decay in Super-Kamiokande (II)

\[ \text{pn} \rightarrow \pi^+\pi^0 \]

Remaining background events

30 ~ 45% : Charged current single \( \pi \) production

\[ (\nu N \rightarrow l^- N' \pi^+ \text{ etc.}) \]

30 ~ 45% : Charged current deep inelastic scattering (DIS)

\[ (\nu N \rightarrow l^- N' \pi^+ \pi^+ \text{ etc.}) \]

Systematic uncertainties

<table>
<thead>
<tr>
<th>Signal (%)</th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>33.3</td>
<td>32.2</td>
<td>28.4</td>
<td>35.0</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>3.3</td>
<td>1.7</td>
<td>5.6</td>
<td>5.6</td>
</tr>
<tr>
<td>BDT</td>
<td>&lt;1</td>
<td>1.6</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Total</td>
<td>33.4</td>
<td>32.3</td>
<td>28.9</td>
<td>35.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Background (%)</th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>22.1</td>
<td>19.9</td>
<td>24.0</td>
<td>27.8</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>1.8</td>
<td>1.8</td>
<td>3.3</td>
<td>3.8</td>
</tr>
<tr>
<td>BDT</td>
<td>6.3</td>
<td>7.4</td>
<td>10.3</td>
<td>11.3</td>
</tr>
<tr>
<td>Total</td>
<td>23.1</td>
<td>21.3</td>
<td>26.3</td>
<td>28.6</td>
</tr>
</tbody>
</table>

Major uncertainty (Simulation) \( \pi \) interactions in/with nucleus

\textit{Obtained lifetime limit: } \( \tau_{\text{pn} \rightarrow \pi^+\pi^0} > 1.70 \times 10^{32} \text{ yrs} \)
Search for dinucleon decay in Super-Kamiokande (III)

\[ nn \rightarrow \pi^0\pi^0 \]

- C0) Fully contained in fiducial events
- C1) Number of Cherenkov rings = 2, 3 or 4
- C2) All rings are identified as showering (\( e^- \) like).
- C3) No decay electrons
- C4) Total momentum \( \leq 600 \) MeV/c
- C5) Reconstructed Invariant mass from 1600 MeV/c\(^2\) to 2000 MeV/c\(^2\)
Search for dinucleon decay in Super-Kamiokande (III)

\[ nn \rightarrow \pi^0\pi^0 \]

<table>
<thead>
<tr>
<th></th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eff. (%)</td>
<td>22.1 ± 0.3</td>
<td>18.8 ± 0.3</td>
<td>20.9 ± 0.3</td>
<td>21.4 ± 0.3</td>
</tr>
<tr>
<td>Bkg.</td>
<td>0.05 ± 0.02</td>
<td>0.04 ± 0.01</td>
<td>0.03 ± 0.01</td>
<td>0.02 ± 0.01</td>
</tr>
<tr>
<td>Data</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

0.14 background expected, 0 observed.

**Obtained lifetime limit:** \( \tau_{nn \rightarrow \pi^0\pi^0} > 4.04 \times 10^{32} \) yrs
Search for dinucleon decay in Super-Kamiokande (III)

\[ \text{nn} \rightarrow \pi^0\pi^0 \]

Remaining background events

<table>
<thead>
<tr>
<th>mode</th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCDIS</td>
<td>63±32%</td>
<td>30±18%</td>
<td>67±25%</td>
<td>50±50%</td>
</tr>
<tr>
<td>CCDIS</td>
<td>15±16%</td>
<td>50±22%</td>
<td>24±14%</td>
<td>0±50%</td>
</tr>
<tr>
<td>CC1π</td>
<td>21±15%</td>
<td>20±14%</td>
<td>9±9%</td>
<td>51±51%</td>
</tr>
</tbody>
</table>

CC 1π : Charged current single π production (\(\nu N \rightarrow l^- N' \pi^+\) etc.)
CC/NC DIS : Charged/Neutral current deep inelastic scattering
(\(\nu N \rightarrow l N' \pi^+ \pi^+\) etc.)

Systematic uncertainties
Search for dinucleon decay in Super-Kamiokande

Search for 3 channels using SK data (282.1 kt·yr)

\[ pp \rightarrow \pi^+\pi^+, \ pn \rightarrow \pi^+\pi^0, \ nn \rightarrow \pi^0\pi^0 \]

All modes are consistent with background (atmospheric neutrino interactions)
No signature was observed.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frejus limit ((^{56}\text{Fe}))</th>
<th>This analysis ((^{16}\text{O}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( pp \rightarrow \pi^+\pi^+ )</td>
<td>(7.0 \times 10^{29}) yrs</td>
<td>(7.22 \times 10^{31}) yrs</td>
</tr>
<tr>
<td>( pn \rightarrow \pi^+\pi^0 )</td>
<td>(2.0 \times 10^{30}) yrs</td>
<td>(1.70 \times 10^{32}) yrs</td>
</tr>
<tr>
<td>( nn \rightarrow \pi^0\pi^0 )</td>
<td>(3.4 \times 10^{30}) yrs</td>
<td>(4.04 \times 10^{32}) yrs</td>
</tr>
</tbody>
</table>
Search for $n - \bar{n}$ oscillation in Super-Kamiokande
One example of Feynman diagram for dinucleon decay

Ref. J. M. Arnold, B. Fornal, and M. B. Wise

$X_1, X_2$ : Scalar particle

Basically same as the diagram for dinucleon decay.
Search for $n - \bar{n}$ oscillation in Super-Kamiokande

Once an anti-neutron is produced, it annihilates with one the surrounding nucleon and produce pions.

Estimated branching ratio after annihilation.

<table>
<thead>
<tr>
<th>$\bar{n} + p$</th>
<th>$\bar{n} + n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+ \pi^0$</td>
<td>$\pi^+ \pi^-$</td>
</tr>
<tr>
<td>$\pi^+ 2\pi^0$</td>
<td>$2\pi^0$</td>
</tr>
<tr>
<td>$\pi^+ 3\pi^0$</td>
<td>$\pi^+\pi^-\pi^0$</td>
</tr>
<tr>
<td>$2\pi^+\pi^-\pi^0$</td>
<td>$\pi^+\pi^-2\pi^0$</td>
</tr>
<tr>
<td>$2\pi^+\pi^-2\pi^0$</td>
<td>$\pi^+\pi^-3\pi^0$</td>
</tr>
<tr>
<td>$2\pi^+\pi^-2\omega$</td>
<td>$2\pi^+2\pi^-$</td>
</tr>
<tr>
<td>$3\pi^+2\pi^-\pi^0$</td>
<td>$2\pi^+2\pi^-\pi^0$</td>
</tr>
<tr>
<td></td>
<td>$\pi^+\pi^-\omega$</td>
</tr>
<tr>
<td></td>
<td>$2\pi^+2\pi^-2\pi^0$</td>
</tr>
</tbody>
</table>

(Estimated based on the $\bar{p}\,p$ & $\bar{p}\,d$ bubble chamber experiments)
Search for $n - \bar{n}$ oscillation in Super-Kamiokande

Used data set

$\text{SK 1 ( 1489 days ) 92 kt\cdot yr} = 2.45 \times 10^{34} \text{ neutron\cdot year}$

Event selection criteria

a) Number of Cherenkov rings $> 1$

b) Visible energy ( electron equivalent energy )

$700 \sim 1300 \text{ MeV}$

c) Reconstructed total momentum $< 450 \text{ MeV/c}$

d) Reconstructed invariant mass

$750 \sim 1800 \text{ MeV/c}^2$

One of the reasons of rather wide allowed region for visible energy and invariant mass

Among of the produced $\pi$ in Oxygen,

only 49% of pions are escaped without interaction.

And 24% of pions are absorbed,

24% of pions are scattered and

3% of pions produces additional pions,

based on simulation.
Search for $n - \bar{n}$ oscillation in Super-Kamiokande

Used data set

SK 1 (1489 days) 92 kt·yr = 2.45 x 10^{34} \text{ neutron·year}

Number of Cherenkov rings $> 1$

Visible energy

$700 \sim 1300$ MeV
Search for $n - \bar{n}$ oscillation in Super-Kamiokande

Used data set

SK 1 (1489 days) 92 kt·yr = 2.45 x $10^{34}$ neutron·year

Reconstructed total momentum

$< 450$ MeV/c

Reconstructed invariant mass

$750 \sim 1800$ MeV/c$^2$
Search for $n - \bar{n}$ oscillation in Super-Kamiokande

Used data set

SK 1 (1489 days) 92 kt·yr = $2.45 \times 10^{34}$ neutron·year

**Signal efficiency**

12.1%

**Expected # of background events**

24.1

**Systematic errors**

- **Signal**: 22.9% (Dominant $\pi$ interactions in nucleus)
- **Exposure**: 3.0%
- **Background**: 23.7% (Dominant $\nu$ interaction (DIS), ring finding efficiency)
Search for $n - \bar{n}$ oscillation in Super-Kamiokande

Used data set

SK 1 (1489 days) 92 kt·yr = $2.45 \times 10^{34}$ neutron·year

Signal M.C. simulation (A)

Atmospheric $\nu$ M.C. simulation (B)

Real data (C)

Signal efficiency 12.1 %

Expected # of background events 24.1

Observed # of events 24

( background consistent.... )

$\bar{T}_{n-\bar{n}} > 1.9 \times 10^{32}$ years
Search for n – \(\bar{n}\) oscillation in Super-Kamiokande

Relation between oscillation time of a free neutron (\(\tau^2_{n-\bar{n}}\)) and lifetime of a bound neutron (\(T_{n-\bar{n}}\))

\[
T_{n-\bar{n}} = R \cdot \tau^2_{n-\bar{n}} \iff \tau_{n-\bar{n}} = \sqrt{T_{n-\bar{n}}/R}
\]

\(R\) : Nuclear suppression factor (\(O(10^{23})\) sec\(^{-1}\))

Recent calculation : \(R = 0.571 \times 10^{23}\) sec\(^{-1}\)

\[
T_{n-\bar{n}} > 1.9 \times 10^{32}\ \text{years}
\]

\(\Rightarrow \tau_{n-\bar{n}} > 2.7 \times 10^{8}\ \text{sec.}\)
Hyper-Kamiokande detector

Design of the detector structure
Incl. PMT supports

Baseline design of the detector is finished based on the past experiences in SK.