Search for Nucleon Decay in Super-Kamiokande

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1. Introduction

Nucleon decay experiment is the direct probe for GUTs.

Major decay modes

\[ p \rightarrow e^+ \pi^0 \text{ : Minimum SU(5)} \]
\[ p \rightarrow \nu K^+ \text{ : SUSY SU(5)} \]

<table>
<thead>
<tr>
<th>Model</th>
<th>Mode</th>
<th>Prediction (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal SU(5)</td>
<td>$p \rightarrow e^+ \pi^0$</td>
<td>$10^{28.5} \sim 10^{31.5}$ [1]</td>
</tr>
<tr>
<td>Minimal SO(10)</td>
<td>$p \rightarrow e^+ \pi^0$</td>
<td>$10^{30} \sim 10^{40}$ [2]</td>
</tr>
<tr>
<td>Minimal SUSY SU(5)</td>
<td>$p \rightarrow \nu K^+$</td>
<td>$\leq 10^{30}$ [3]</td>
</tr>
<tr>
<td>SUGRA SU(5)</td>
<td>$p \rightarrow \nu K^+$</td>
<td>$10^{32} \sim 10^{34}$ [4]</td>
</tr>
<tr>
<td>SUSY SO(10)</td>
<td>$p \rightarrow \nu K^+$</td>
<td>$10^{32} \sim 10^{34}$ [5]</td>
</tr>
</tbody>
</table>

2. Super-Kamiokande Detector

Location: Kamioka mine, Japan. ~1000 m under ground.
Size: 39 m (diameter) x 42 m (height), 50kton water.
Optically separated into inner detector (ID) and outer detector (OD, ~2.5 m layer from tank wall.)
Photo device: 20 inch PMT (ID), 8 inch PMT (OD, veto cosmic rays).
Mom. resolution: 3.0 % for e 1 GeV/c (4.1%: SK-2).
Particle ID: Separate into EM shower type (e-like) and muon type (µ-like) by Cherenkov ring angle and ring pattern.

<table>
<thead>
<tr>
<th>Period</th>
<th>Exp (kt yrs)</th>
<th>NOTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK1 Apr.96’~Jul.01’</td>
<td>91.7</td>
<td>40% photo coverage</td>
</tr>
<tr>
<td>SK2 Dec.02’~Oct.05’</td>
<td>49.2</td>
<td>19%</td>
</tr>
<tr>
<td>SK3 Jul.06’~Sep.08’</td>
<td>31.9</td>
<td>40%</td>
</tr>
<tr>
<td>SK4 Sep.08’~</td>
<td>87.3(~Feb.13’)</td>
<td>40%, new readout</td>
</tr>
</tbody>
</table>

Improved Michel electron tagging
3. $p \rightarrow e^+ \pi^0$ mode

Event features:
- $e^+$ and $\pi^0$ are back-to-back (459 MeV/c)
- $\pi^0 \rightarrow 2 \gamma$: all particles can be detectable.
- Reconstruct proton mass and momentum.

Selection:
- Fully contained, VTX in fiducial volume.
- 2 or 3 ring
- all e-like, w/o decay-e
- $85 < M_{\pi^0} < 185$ MeV (for 3-ring event).
- $800 < M_p < 1050$ MeV & $P_{tot} < 250$ MeV/c

Signal MC
Results of $p \rightarrow e^+ \pi^0$

<table>
<thead>
<tr>
<th></th>
<th>Exp. (kt\cdot yr)</th>
<th>Eff(%)</th>
<th>BKG</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK1</td>
<td>91.7</td>
<td>39.2 ± 0.7</td>
<td>0.27</td>
<td>0</td>
</tr>
<tr>
<td>SK2</td>
<td>49.2</td>
<td>38.5 ± 0.7</td>
<td>0.15</td>
<td>0</td>
</tr>
<tr>
<td>SK3</td>
<td>31.9</td>
<td>40.1 ± 0.7</td>
<td>0.07</td>
<td>0</td>
</tr>
<tr>
<td>SK4</td>
<td>87.3</td>
<td>39.5 ± 0.7</td>
<td>0.22</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>260.1</td>
<td></td>
<td>0.71</td>
<td>0</td>
</tr>
</tbody>
</table>

Lifetime limit (90% C.L., $p \rightarrow e^+ \pi^0$: $> 1.4 \times 10^{34}$ years

No candidates observed.
4. \( p \rightarrow \bar{\nu} + K^+ \) mode \( \text{(will be published soon)} \)

Method (A) \( K^+ \rightarrow \mu^+ + \nu_\mu \)

\( ^{16}\text{O}\rightarrow^{15}\text{N} \)

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

\[ \bar{\nu} \]

\[ \nu \]

\[ K^+ \]

\[ \mu^+ \]

\[ \nu_\mu \]

\[ e^+ \]

\[ \nu_\mu \]

\[ \mu^+ \]

\[ \nu_\mu \]

\[ \bar{\nu} \]

\[ \nu \]

\[ K^+ \]

\[ \nu \]

\[ \gamma \]

\[ \mu \]

\[ \nu_\mu \]

Visible

Invisible

**Selection:**

- 1 \( \mu \)-like ring with decay-e.
- 215 < \( P_\mu \) < 260 MeV/c
- Search Max hit cluster by sliding time window (12ns width);
  - 8 < \( N_\gamma \) < 60 hits for SK-1,3,4
  - 4 < \( N_\gamma \) < 30 hits for SK-2
- \( T_\mu - T_\gamma \) < 75 nsec

**Event features:**

- \( K^+ \) is invisible, stops and 2 body decay (\( P_\mu = 236 \text{ MeV/c} \)).
  - Excess in \( P_\mu \).
- Proton in \( ^{16}\text{O} \) decays and excited nucleus emits 6 MeV \( \gamma \) (Prob. 41%, not clear ring).
  - Tag \( \gamma \) to eliminate BKG.

**Selection:**

- 1 \( \mu \)-like ring with decay-e.
- 215 < \( P_\mu \) < 260 MeV/c
- Search Max hit cluster by sliding time window (12ns width);
  - 8 < \( N_\gamma \) < 60 hits for SK-1,3,4
  - 4 < \( N_\gamma \) < 30 hits for SK-2
- \( T_\mu - T_\gamma \) < 75 nsec
Results of Method (A)

<table>
<thead>
<tr>
<th>Exp. (kton\cdot yr)</th>
<th>Eff(%)</th>
<th>BKG</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>
</tr>
<tr>
<td>SK2</td>
<td>49.2</td>
<td>6.3 ± 0.1</td>
<td>0.14</td>
</tr>
<tr>
<td>SK3</td>
<td>31.9</td>
<td>7.7 ± 0.1</td>
<td>0.03</td>
</tr>
<tr>
<td>SK4</td>
<td>87.3</td>
<td>9.1 ± 0.1</td>
<td>0.13</td>
</tr>
<tr>
<td>Total</td>
<td>260.1</td>
<td></td>
<td>0.38</td>
</tr>
</tbody>
</table>

No candidates and no excess in $P_\mu$. 

$\gamma$ distributions

[Graph showing $N_\gamma$ distributions with coverage values indicated]
Method (B)  K⁺ → π⁺ + π⁰

Event features;
• Br. 21 %.
• π⁰ and π⁺ are back-to-back and have 205 MeV/c.
• Pπ⁺ is just above Č thres. (not clear ring).

=> Search for monochromatic π⁰ with backward activities.

Selection:
- 1 or 2 e-like rings with decay-e.
- 85 < Mπ⁰ < 185 MeV.
- 175 < Pπ⁰ < 250 MeV/c.
- $E_{\text{bk}}$: visible energy sum in 140-180 deg. of π⁰ dir.
- $E_{\text{res}}$: in 90-140 deg.
- $L_{\text{shape}}$: Likelihood based on charge profile
  - $10 < E_{\text{bk}} < 50$ MeV
  - $E_{\text{res}} < 12$ MeV (20 MeV for 1ring)
  - $L_{\text{shape}} > 2.0$ (3.0 for 1ring)
Results of Method (B)

<table>
<thead>
<tr>
<th></th>
<th>Exp. (kton·yr)</th>
<th>Eff(%)</th>
<th>BKG</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK1</td>
<td>91.7</td>
<td>7.8±0.1</td>
<td>0.18</td>
<td>0</td>
</tr>
<tr>
<td>SK2</td>
<td>49.2</td>
<td>6.7±0.1</td>
<td>0.17</td>
<td>0</td>
</tr>
<tr>
<td>SK3</td>
<td>31.9</td>
<td>7.9±0.1</td>
<td>0.09</td>
<td>0</td>
</tr>
<tr>
<td>SK4</td>
<td>87.3</td>
<td>10.0±0.1</td>
<td>0.18</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>260.1</td>
<td></td>
<td>0.62</td>
<td>0</td>
</tr>
</tbody>
</table>

No candidates.

\[ p \rightarrow \bar{\nu}K^+ \] Lifetime limit (90% CL) combining Method (A) and (B):

\[ > 5.9 \times 10^{33} \text{ yrs @260 kton·yr} \]
5. New modes: $|\Delta(B-L)| = 2$

- ★ Decay to trilepton $p \rightarrow e^+ \nu \nu, \mu^+ \nu \nu$ (will be published soon)
  - Predicted by SO(10) (Pati and Salam): $\tau \approx 10^{30} \sim 10^{33}$ years [6]
  - Single charged lepton in final state $\rightarrow$ check excess in $P$ distribution.


**No significant excesses.** : Lifetime limit (90%CL)

- $p \rightarrow e^+ \nu \nu$: $> 1.7 \times 10^{32}$ years
  (IMB-3: $1.7 \times 10^{31}$ years)

- $p \rightarrow \mu^+ \nu \nu$: $> 2.2 \times 10^{32}$ years
  (Frejus: $2.1 \times 10^{31}$ years)
**Dinucleon decay:** $pp \rightarrow \pi^+\pi^+$, $pn \rightarrow \pi^+\pi^0$, $nn \rightarrow \pi^0\pi^0$

- Search for $\pi$-pair in back-to-back.
- For $nn \rightarrow \pi^0\pi^0$, use total mass and momentum cuts.
- For other modes, difficult to reconstruct total mass and momentum. 
  ➔ Use multi-variable analysis (Boosted Decision Tree).

<table>
<thead>
<tr>
<th>Process</th>
<th>Eff(%)</th>
<th>BG(evts)</th>
<th>Obs(evts)</th>
<th>Limit(yr)</th>
<th>(Frejus)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow \pi^+\pi^+$</td>
<td>5.9</td>
<td>4.5</td>
<td>2</td>
<td>$&gt;7.3 \times 10^{31}$</td>
<td>$7.0 \times 10^{29}$</td>
</tr>
<tr>
<td>$pn \rightarrow \pi^+\pi^0$</td>
<td>10.2</td>
<td>0.8</td>
<td>1</td>
<td>$&gt;1.8 \times 10^{32}$</td>
<td>$2.0 \times 10^{30}$</td>
</tr>
<tr>
<td>$nn \rightarrow \pi^0\pi^0$</td>
<td>21.1</td>
<td>0.1</td>
<td>0</td>
<td>$&gt;4.1 \times 10^{32}$</td>
<td>$3.4 \times 10^{30}$</td>
</tr>
</tbody>
</table>

**Consistent with expected backgrounds.**
6. Summary

- Fruitful nucleon decay results from Super-Kamiokande.
- We could not find any evidences of nucleon decay.
- We calculated nucleon lifetime limits with 90 % C.L.
  \[ p \to e^+\pi^0: > 1.4 \times 10^{34} \text{ yrs} \]
  \[ \nu K^+: > 5.9 \times 10^{33} \text{ yrs} \]
- Other new modes have also been studied.
- BG reduction by neutron tagging is under investigation.
Backup
Future prospects

- Need larger volume detector (Megaton class).
  
  Ex. Hyper-Kamiokande project (fiducial volume 0.56 Mton, 20% photo coverage)

- Sensitivity with HK 10 years run:
  
  $e^+\pi^0$: $1.3 \times 10^{35}$ year
  $\nu_{K^+}$: $2.5 \times 10^{34}$ year

  ➔ Cover most of major models!

Also see ‘Hyper-Kamiokande: A next generation neutrino observatory to search for CP violation in the lepton sector’ in Neutrino session.
Why efficiencies decreased (45 % → 40 %) ➔ Because we have updated π-interaction in Oxygen.

(1) Charge exchange increased to match experimental data.

(2) Kinematics of scattered π changed in P > 500 MeV/c

Input: π 550 MeV/c

Increased in large angle

Final π momentum

Final π angle (degree)

NOTE: Sys.error for π-int → 15 %
On going project: neutron tagging

\[ n+p \rightarrow d+\gamma \ (2.2 \text{ MeV}) \]

- Search for hit cluster N>7 in 10 ns window after prompt signal.
- Eff. 25 %, BKG 1.4 %.
- MC including neutron capture is under developing.

**Preliminary**

neutron after all \( p \rightarrow e^+\pi^0 \) cut (SK4)

Almost 50 % BKG can be rejected!
Recent improvement: \( p \rightarrow \nu K^+, K^+ \rightarrow \pi^+ \pi^0 \)

# of Ring: \( K^+ \rightarrow \pi^+ \pi^0 \)

Judge as 1 ring (~20%) if opening angle of 2 \( \gamma \)s is small or momentum of one \( \gamma \) is small.

Use "\( \pi^0 \) fitter"

• Make likelihood assuming \( \pi^0 \) and search for missing ring.
• It is used for \( \nu_e \) appearance analysis of T2K to reduce BKG.

It makes 1 ring sample available for this analysis!

\( \rightarrow \) Efficiency increased.
Input variables: \( pp \rightarrow \pi^+ \pi^+ \)

### Number of rings
- Signal
- Background
- Data

### Visible energy
- Energy (MeV)
- Events

### Max decay-e length
- Distance (cm)
- Events

### \( \pi^- \)-decay-e ang
- Angle (degrees)
- Events

### Number of decay-e
- Events

### Number of \( \mu \)-like
- Events

### Rtot vector sum
- \( \text{rtot} \) (corrected p.e.)
- Events

### Fraction of dominant ring
- Events

### Max opening ang
- Angle (degrees)
- Events
Input variables: $pn \rightarrow \pi^+\pi^0$

- $\pi^0$ momentum
- $\pi^0-\pi^+$ opening angle
- $\pi^+$ momentum
- Visible energy
- Fraction of dominant ring
- $\pi^0$ mass

Number of decay electrons
Outputs of BDT (SK4 only)

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

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