Search for Nucleon decay in Super-Kamiokande

M. Miura

Kamioka Observatory, ICRR

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1. Introduction

The Standard Model has been successful!
… but why so many parameters?

GUTs: attempt to unify Strong and Electroweak interactions.

GUTs scale: $10^{14-16}$ GeV

Cannot be reached by Accelerators.

Proton decay is permitted!

Lepton and baryon numbers are not conserved.

Nucleon decay experiment is the direct probe for GUTs.
Examples of proton decay model

- Minimal SU(5) model
- Minimal SO(10)
- Minimal SUSY SU(5)
- SUGRA SU(5)
- SUSY SO(10)

Proton lifetime predictions

<table>
<thead>
<tr>
<th>Model</th>
<th>Mode</th>
<th>Prediction (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal SU(5)</td>
<td>p-&gt;e^+π^0</td>
<td>10^{28.5} ~ 10^{31.5} [1]</td>
</tr>
<tr>
<td>Minimal SO(10)</td>
<td>p-&gt;e^+π^0</td>
<td>10^{30} ~ 10^{40} [2]</td>
</tr>
<tr>
<td>Minimal SUSY SU(5)</td>
<td>p-&gt;νK^+</td>
<td>≤ 10^{30} [3]</td>
</tr>
<tr>
<td>SUGRA SU(5)</td>
<td>p-&gt;νK^+</td>
<td>10^{32} ~ 10^{34} [4]</td>
</tr>
<tr>
<td>SUSY SO(10)</td>
<td>p-&gt;νK^+</td>
<td>10^{32}~10^{34} [5]</td>
</tr>
</tbody>
</table>


Super-Kamiokande
- Large Water Cherenkov detector
- Fiducial volume: 22.5 kton
  ⇒ 7 x 10^{33} protons
- Run time ~ 6 years (SK-1+SK2)

Some of them are reachable by Super-Kamiokande!
2. Super-Kamiokande Detector

Location: Kamioka mine, Japan. \(\sim1000\) m under ground.
Size: \(39\) m (diameter) \(\times\) \(42\) m (height), \(50\) kton water.
Optically separated into inner detector (ID) and outer detector (OD, \(\sim2.5\) 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 for SK-1 (4.1\%: SK-2).
Particle ID: Separate into EM shower type (e-like) and muon type (\(\mu\)-like) by Cherenkov ring angle and ring pattern.

\(\mu\)-like (\(\mu^{\pm}\))

\(e\)-like (\(e^{\pm}, \gamma\))
### History of Super-Kamiokande

<table>
<thead>
<tr>
<th>Year</th>
<th>SK-1</th>
<th>SK-2</th>
<th>SK-3</th>
<th>SK-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1997</td>
<td>-</td>
<td>-</td>
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<tr>
<td>1998</td>
<td>-</td>
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<tr>
<td>1999</td>
<td>-</td>
<td>-</td>
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<tr>
<td>2000</td>
<td>-</td>
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<tr>
<td>2001</td>
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<tr>
<td>2002</td>
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<tr>
<td>2003</td>
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<tr>
<td>2004</td>
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<tr>
<td>2005</td>
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<tr>
<td>2006</td>
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<td>-</td>
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<tr>
<td>2007</td>
<td>-</td>
<td>-</td>
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<tr>
<td>2008</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
</tbody>
</table>

- **SK-1**
  - Livetime: 1489.2 days
  - Exposure: 91.7 kton·yr
  - Inner PMT: 11146
  - Photo coverage: 40%
  - p→e⁺π⁰ paper (98')

- **SK-2**
  - Livetime: 798.6 days
  - Exposure: 49.2 kton·yr
  - Inner PMT: 5182
  - Photo coverage: 19%
  - p→νK⁺ paper (05')

- **Newly analyzed (this talk).**
  - p→e⁺π⁰ paper (98')
  - p→νK⁺ paper (05')
MC simulations

Proton decay MC <= Efficiency

8 bounded protons in O:

Fermi momentum, binding energy, various nuclear effects are taken into account.

2 free protons (H): simple two body decay.

Atmospheric $\nu$ MC <= BKG for proton decay

Flux: Primary cosmic rays make $\nu_\mu$ and $\nu_e$.


Event features:

• $e^+$ and $\pi^0$ are back-to-back (459 MeV/c) in nucleon rest frame.
• $\pi^0$ decays into two $\gamma$ s (one $\gamma$ may be missed if direction of the other $\gamma$ is close to $\pi^0$).

$\Rightarrow$ 2 or 3 e-like ring should be observed.
$\Rightarrow$ $\pi^0$ mass should be reconstructed by two ring (3-ring case).

$\Rightarrow$ Proton mass should be reconstructed by all ring and total momentum should be small.

Selection:

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

Clear signal and selected by simple cuts!
Total BKG:
0.31 events / 2288 days

= Still low enough!

Results

<table>
<thead>
<tr>
<th></th>
<th>Obs</th>
<th>BKG</th>
<th>Eff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-1</td>
<td>0</td>
<td>0.20 events / 1489 days</td>
<td>44.6 ± 8.5</td>
</tr>
<tr>
<td>SK-2</td>
<td>0</td>
<td>0.11 events / 799 days</td>
<td>43.5 ± 8.3</td>
</tr>
</tbody>
</table>
1-dim distributions: Data are consistent with Atm. $\nu$ MC.

Lifetime limit (90% C.L): $> 8.2 \times 10^{33}$ yrs @ 141 kton $\cdot$ yr

($=4.7 \times 10^{34}$ proton $\cdot$ yr)

5 times improved!

$> 1.6 \times 10^{33}$ yrs @ 25.5 kton $\cdot$ yr in prev. SK paper, 1998
4. \( p \rightarrow \bar{\nu} + K^+ \) mode

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

Event features:
- Proton \( \rightarrow K^+ \) (below Č thrs.) + \( \nu \).
- \( K^+ \) most likely stops and decays into \( \mu^+ \) (236 MeV/c) + \( \nu \) (Br. 64%).

\[ \Rightarrow \textbf{Monochromatic} \ \mu \]

Selection:
- 1 \( \mu \)-like ring with decay-e (except method-B in next page).
- Fit \( P_\mu \) of data by PDK and Atm MC.

Data are consistent with Atm. \( \nu \) MC.
From upper limit of the fit, lifetime limit can be estimated.
B) $K^+ \rightarrow \mu^+ + \nu_\mu$ with prompt $\gamma$

Event features;
- Proton in $^{16}O$ decays and excited nucleus emits 6 MeV $\gamma$ (Prob. 41%, not clear ring).

$\Rightarrow$ 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
  - $4 < N_\gamma < 30$ hits for SK-2
  - $T_\mu - T_\gamma < 75$ nsec
Even though photo coverage decreased by 50\%,
efficiency in SK-2 keeps 80\% of SK-1.
C) $K^+ \rightarrow \pi^+ + \pi^0$

Event features:
- Br. 21%.
- $\pi^0$ and $\pi^+$ are back-to-back and have 205 MeV/c.
- $P\pi^+$ is just above Č thres. (not clear ring).

$=>$ Search for monochromatic $\pi^0$ with backward activities.

Selection:
- 2 e-like rings with decay-e.
- $85 < M\pi^0 < 185$ MeV.
- $175 < P\pi^0 < 250$ MeV/c.
- $Q_{bk}$: charge sum in 140-180 deg. of $\pi^0$ dir, $Q_{res}$: in 90-140 deg.
  - (SK-1) $40 < Q_{bk} < 100$ pe & $Q_{res} < 70$ pe
  - (SK-2) $20 < Q_{bk} < 50$ pe & $Q_{res} < 35$ pe

$\gamma$  
$\pi^0$  
205 MeV/c
SK-1

Eff.: 6.2±0.5 %
BKG: 0.43 evts
/1489 days
Obs: 0 evts

SK-2

Eff.: 4.8±0.4 %
BKG: 0.31 evts
/799 days
Obs: 0 evts
## Summary of $p \rightarrow \bar{\nu}K^+$

<table>
<thead>
<tr>
<th>K-&gt;</th>
<th>Eff (%)</th>
<th>BKG</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+\nu$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{\mu}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SK-1</td>
<td>37.0±0.4</td>
<td>188.9±5.7</td>
<td>198±14.1</td>
</tr>
<tr>
<td>SK-2</td>
<td>35.7±0.4</td>
<td>95.5±2.0</td>
<td>85±9.2</td>
</tr>
<tr>
<td>Prompt $\gamma$ tag</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SK-1</td>
<td>7.2±1.6</td>
<td>0.16±0.05</td>
<td>0</td>
</tr>
<tr>
<td>SK-2</td>
<td>5.8±1.3</td>
<td>0.08±0.03</td>
<td>0</td>
</tr>
<tr>
<td>$\pi^+\pi^0$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SK1</td>
<td>6.2±0.5</td>
<td>0.43±0.13</td>
<td>0</td>
</tr>
<tr>
<td>SK2</td>
<td>4.8±0.4</td>
<td>0.31±0.10</td>
<td>0</td>
</tr>
</tbody>
</table>

Lifetime limit: $2.8 \times 10^{33}$ yrs $@141$ kton·yr

$\Leftrightarrow 2.3\times 10^{33}$ yrs$@92$kton·yr in prev. paper (05')
5. Other modes

Nucleon => lepton + meson

\[ p \rightarrow e^+ \pi^0, \mu^+ \eta, \pi^+ \rho, \pi^- \rho \]

- Consistent with BKG for all modes.
- Most of them give the most stringent limits in the world.
6. Summary

- We performed nucleon decay search with SK-1 + SK-2 data, 141 kton·yrs in total exposure.
- We could not find any evidences of nucleon decay.
- We calculated nucleon lifetime limits with 90% C.L.
  
  \[ e^+\pi^0: > 8.2 \times 10^{33} \text{ yrs} \implies \text{publish soon!} \]
  \[ \nu K^+: > 2.8 \times 10^{33} \text{ yrs} \]
  \[ \text{Other lepton+meson: } > 6.6 \sim 0.04 \times 10^{33} \text{ yrs} \]
Backup
Future prospects

- BKG for $e^+\pi^0 : 0.3 \text{ events/2288 days}$
  
  $\nu K^+ : 0.2 \text{ events (prompt } \gamma)$

Still low enough!

- SK-3 data will be open soon (~560 days).

- At least, continue until T2K phase-I (>5 years)
  
  $\Rightarrow$ lifetime limit : 2~3 times more.

$\Rightarrow$ Further study: Need to construct larger detector (Hyper-K).
Q. What are BKG for $e^+\pi^0$ mode?

<table>
<thead>
<tr>
<th>Contribution to BG</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE</td>
<td>28%</td>
</tr>
<tr>
<td>CC single $\pi$</td>
<td>32%</td>
</tr>
<tr>
<td>CC multi $\pi$</td>
<td>19%</td>
</tr>
<tr>
<td>other CC</td>
<td>2%</td>
</tr>
<tr>
<td>NC</td>
<td>19%</td>
</tr>
</tbody>
</table>

$\nu + N \rightarrow \text{lepton} + N^*; N^* \rightarrow N' + \text{meson}$

$\nu_e$ CC case, e and $\pi^\pm$, $\pi^0$ are outgoing particles.

$\nu + N \rightarrow \text{lepton} + p$

$\nu_e$ case, e and p are outgoing particles and p interacts in water and make secondary $\pi^0$. 
### Systematic error for $e^+\pi^0$ (Efficiency)

<table>
<thead>
<tr>
<th>Detection Efficiency</th>
<th>SK-I</th>
<th>SK-II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td>19 %</td>
<td>19 %</td>
</tr>
<tr>
<td>Nuclear Effect</td>
<td>15 %</td>
<td></td>
</tr>
<tr>
<td>Energy Scale</td>
<td>0.4 %</td>
<td>1.4 %</td>
</tr>
<tr>
<td>Un-uniformity of Detector Gain</td>
<td>0.7 %</td>
<td>0.5 %</td>
</tr>
<tr>
<td>PID</td>
<td>1.6 %</td>
<td>0.9 %</td>
</tr>
<tr>
<td>decay-e detection efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fermi Momentum</td>
<td>8.2 %</td>
<td>8.7 %</td>
</tr>
<tr>
<td>Fraction of Correlated Decay</td>
<td>6.5 %</td>
<td>6.4 %</td>
</tr>
<tr>
<td>Fiducial Volume</td>
<td>3 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Fitting Biases</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Vertex</td>
<td>2.0 %</td>
<td>1.4 %</td>
</tr>
<tr>
<td>- Cherenkov Opening Angle</td>
<td>0.7 %</td>
<td>0.9 %</td>
</tr>
<tr>
<td>- Ring Counting</td>
<td>0.1 %</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Exposure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Live Time</td>
<td>&lt; 1 %</td>
<td></td>
</tr>
</tbody>
</table>
Q. What are BKG for $\nu K^+$ mode?

$K^+ \rightarrow \nu + \mu$

$\nu + N \rightarrow \text{lepton} + N^*; N^* \rightarrow N' + \text{meson}: 44\%$

Resonance $N^*$ decays into $K^+$.

$\nu + N \rightarrow \text{charged lepton} + P: 17\%$

Low $P$ lepton, High $P$ proton

$\Rightarrow$ VTX mis-reconstructed

$K^+ \rightarrow \pi^+ + \pi^0$

$\nu + N \rightarrow \text{lepton} + N^*; N^* \rightarrow N' + \text{meson}: 63\%$

-Resonance $N^*$ decays into $K^+$.

- $N^*$ decays into $\pi^0$ and charged lepton goes backward of $\pi^0$. 
Q. Why improvement in $\nu K^+$ mode is small?

- Efficiency in SK2 is lower than SK-1 for $\nu K$ mode.
- In SK-1 paper, BKG in prompt g method is 0.7.
- Selection is refined to get max S/N ratio.
- $T_{\text{start}}$ changed from 9 nsec to 11 nsec.

<table>
<thead>
<tr>
<th></th>
<th>Prev.</th>
<th>Now</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eff.(SK1)</td>
<td>8.6%</td>
<td>7.2%</td>
</tr>
<tr>
<td>BKG</td>
<td>0.7</td>
<td>0.16</td>
</tr>
</tbody>
</table>

BKG largely reduced but loose efficiency and limit became worse (2.3->2.0x10^{33} yrs for SK-1).
Contributions of 3 methods in νK⁺ mode

Lifetime limit by single method (10^{33} yrs)

Spectrum fit : 0.6
Prompt γ : 1.2
π⁺π⁰ : 1.1
# Systematic error for νK⁺ (Efficiency)

## μ⁺ν, prompt γ tag

<table>
<thead>
<tr>
<th></th>
<th>SK1</th>
<th>SK2</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ-emission prob.</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Energy scale</td>
<td>2.3</td>
<td>1.2</td>
</tr>
<tr>
<td>Tstart</td>
<td>7.6</td>
<td>8.2</td>
</tr>
<tr>
<td>PID</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Ring count</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td>Water parameter</td>
<td>3.0</td>
<td>2.6</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>22.0</td>
<td>22.0</td>
</tr>
</tbody>
</table>

## π⁺π⁰

<table>
<thead>
<tr>
<th></th>
<th>SK1</th>
<th>SK2</th>
</tr>
</thead>
<tbody>
<tr>
<td>π-N crs in water</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Energy scale</td>
<td>4.1</td>
<td>2.9</td>
</tr>
<tr>
<td>PID</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Ring count</td>
<td>3.6</td>
<td>4.8</td>
</tr>
<tr>
<td>Water parameter</td>
<td>2.4</td>
<td>2.1</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>8.6</td>
<td>8.9</td>
</tr>
</tbody>
</table>
Lifetime limit calculation; Bayesian method

\[ P(\Gamma|n_1, n_2) = \frac{1}{A} \int \int \int \frac{e^{- (\Gamma \lambda_1 \epsilon_1 + b_1)} (\Gamma \lambda_1 \epsilon_1 + b_1)^{n_1}}{n_1!} \times e^{- (\Gamma \lambda_2 \epsilon_2 + b_2)} (\Gamma \lambda_2 \epsilon_2 + b_2)^{n_2}}{n_2!} \times P(\Gamma) P(\delta_\epsilon) P(\delta_\lambda) P(\delta_b) d\delta_\epsilon d\delta_\lambda d\delta_b. \]

\[ CL(0.9) = \int_0^{\Gamma_{\text{limit}}} P(\Gamma|n_1, n_2) d\Gamma \]

Assuming Eff, BKG, exposure are gaussian.

\( \Gamma \): decay rate (=1/\tau)

\( \lambda \): exposure

\( \epsilon \): detection efficiency

\( b \): number of BG events

\( n \): candidate
neutron anti-neutron oscillation

• **motivation**
  - Several types of (B-L)-violating Gauge theories predicts that neutron spontaneously converts to anti-neutron, and vise versa

\[ \equiv n \sim \bar{n} \text{ oscillation} \]

• **expected signal**
  1. anti-neutron annihilates with n or p.

\[ \bar{n} + p \quad \bar{n} + n \]

| \( \pi^+ \pi^- \) | 1% |
| \( \pi^0 \pi^0 \) | 8% |
| \( \pi^0 \pi^0 \pi^0 \pi^0 \) | 10% |
| \( \pi^+ \pi^- \pi^0 \pi^0 \) | 22% |
| \( 2\pi^+ 2\pi^0 \) | 36% |
| \( 2\pi^+ 2\pi^- \) | 16% |
| \( 3\pi^+ 2\pi^- \pi^0 \) | 7% |

| \( \bar{n} + p \) |
| \( \bar{n} + n \) |

2. pions are emitted isotropically with high multiplicity (\( \sim 4\pi \))

Branching ratio derived from Bubble Chamber p + d \( \bar{d} \) data
$n \rightarrow \bar{n}$ transition probability, $P(\Gamma|n)$ is calculated by Bayesian statistics and Bayesian theorem.

$$T_{\text{bound}} = \frac{1}{\Gamma_{\text{limit}}}$$

$> 1.97 \times 10^{32}$ yrs (90% CL) (SK-I) (preliminary)

Bound neutron lifetime can be interpreted to the oscillation time of the free neutron by

$$T_{\text{bound}} = R \times (\tau_{\text{free}})^2$$

$\tau_{\text{free}} > 2.49 \times 10^8$ sec (preliminary)

Previous limits

Kamiokande: $\tau_{\text{free}} > 1.2 \times 10^8$ sec
IMB: $\tau_{\text{free}} > 0.88 \times 10^8$ sec
ILL Beam experiment: $\tau_{\text{free}} > 0.86 \times 10^8$ sec