Recent nucleon decay results from Super-Kamiokande

S. Mine (University of California, Irvine) for Super-Kamiokande collaboration
Super-Kamiokande (Super-K, SK)

Kamioka mine

Japan

- SK total ~ 20 years

![Diagram of Kamioka mine]

<table>
<thead>
<tr>
<th>Phase</th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of PMTs</td>
<td>ID OD</td>
<td>11146 (40%)</td>
<td>5182 (19%)</td>
<td>11129 (40%)</td>
</tr>
<tr>
<td>Anti-implosion container</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>OD segmentation</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Front-end electronics</td>
<td>ATM (ID) OD QTC (OD)</td>
<td>QBEE</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Nucl. Instr. & Meth, A 737C (2014)
Grand Unified Theory (GUT)

- Single symmetry group $G \supset SU(3)_{\text{color}} \times SU(2)_L \times U(1)_{Y}$
  - single coupling constant, quantization of electric charge, etc.

- Popular models:
  - $SO(10)$ GUT
    - 15 fermions and $\nu_R$ in single rep.
  - supersymmetry (SUSY) GUT
    - 3 coupling constants meet at $\sim 10^{16}$GeV

- GUTs predict instability of nucleon:
  - two benchmark decay modes:
    - $e^+\pi^0$ (non-SUSY) and $\nu K^+$ (SUSY)
  - some models predict lifetime $< 10^{34}$ years probed by SK
  - baryon asymmetry of the universe
Nucleon decay searches in SK
(unique way to directly probe GUTs)

• SK has the world’s best sensitivities on nucleon lifetime:
  – large fiducial volume (V)
    • 22.5kt → ~7.5 \times 10^{33} protons and ~6 \times 10^{33} neutrons
  – excellent detector performance (\varepsilon_{\text{sig}}, \#\text{BKG})
    • ex.) *Nucl. Instr. & Meth A 433 (1999)*
  – long stable detector operation since 1996 (T)

• Lifetime sensitivity \propto \begin{cases} \varepsilon_{\text{sig}} / 2.3 \cdot VT \text{ (BKG free)} \\ \varepsilon_{\text{sig}} / \sqrt{\#\text{BKG}} \cdot \sqrt{VT} \text{ (BKG dominant)} \end{cases}
  – important to increase signal efficiency and BKG rejection

• Several new results recently
  – analysis improvements in \( p \rightarrow e^+ \pi^0 \) and \( p \rightarrow \nu K^+ \) (main in this talk)
  – exotic searches (dinucleon decay, etc.)


**Event selections:**
- fully contained
- fiducial volume
- 2 or 3 rings
- all e-like (PID)
- no Michel electrons
- $85 < M_{\pi^0} < 185 \text{MeV}/c^2$ (3-ring)
- $800 < M_p < 1050 \text{MeV}/c^2$
- $P_{\text{tot}} < 100 \text{MeV}/c$, $100 \leq P_{\text{tot}} < 250 \text{MeV}/c$
- no neutrons (SK-IV only)
New: $P_{\text{tot}}$ separation into 2 regions

$P_{\text{tot}}<100\text{MeV}/c$, $100\leq P_{\text{tot}}<250\text{MeV}/c$

(after $p\rightarrow e\pi^0$ selections without $(M_p, P_{\text{tot}})$ cut)

- Total(SKI-IV) expected $\#\text{BKG}(P_{\text{tot}}<100, 100\leq P_{\text{tot}}<250)$: ($\sim0.05$, $\sim0.5$)
- $P_{\text{tot}}<100\text{MeV}/c$: smaller systematic error on signal $\varepsilon$ and almost BKG free → discovery potential and better sensitivity

Sep.9, 2015

S.Mine @ TAUP2015
Neutron tag in SK-IV

- Atm.-ν BKG frequently accompanied by neutron production
- \( n + p \rightarrow d + \gamma(2.2\text{MeV}) \)
- Hit cluster search for \( \gamma \) enabled by QBEE with deadtime-less DAQ + software trigger
  - detection efficiency: 20.5%

\[ \begin{align*}
\text{Atm.-ν MC} & \quad \sim50\% \text{ BKG rejected} \\
\text{Number of events} & \quad (after \ p \rightarrow e\pi^0 \ selections) \\
\text{Number of tagged neutron} & \quad (after \ p \rightarrow e\pi^0 \ selections \ before \ (M_{p'P_{tot}}) \ and \ neutron \ tag) \\
\end{align*} \]
Sensitivities

- The more exposure, the more benefit.
$p \rightarrow e^+ \pi^0$ search result

- **306.3 kton·years (SKI-IV)** (220kt·yrs in PRD 85, 112001 (2012))
- signal $\varepsilon(P_{tot}<250\text{MeV/c})$: $\sim 40\%$
- total(SKI-IV) expected $\#BKG(P_{tot}<250\text{MeV/c}) < 1$
- no data candidate
  - $\tau/B_{p \rightarrow e\pi^0} > 1.67 \times 10^{34}$ years (90% CL)
$p \rightarrow \mu^+\pi^0$ search result

“flipped” SU(5) predicts high branching ratio

(analysis proceeds as with $e^+\pi^0$ with additional requirement of 1 Michel-e)

- 306.3 kton·yrs (SK-I-IV) (220kt·yrs in PRD)
- signal $\varepsilon(P_{tot}<250\text{MeV/c})$: 30-40%
- total expected #BKG:
  - $P_{tot}<100$: $\sim0.05$
  - $100\leq P_{tot}<250$: $\sim0.82$
- no significant data excess
  $\tau/B_{p \rightarrow \mu\pi^0} > 7.78 \times 10^{33}$ years (90% CL)
Event #1

(M_p', P_{tot}) : (902.5, 248.0) MeV
Wall : 466.0 cm
# ring : 2
P_e : 374.9 MeV/c
P_μ : 551.1 MeV/c
\(\theta_{e-\mu} : 157.9^\circ\)

Event #2

(M_p', P_{tot}) : (832.4, 237.9) MeV
Wall : 351.6 cm
# ring : 2
P_e : 460.5 MeV/c
P_μ : 391.3 MeV/c
\(\theta_{e-\mu} : 148.9^\circ\)

(additional ring by manual fit → \(M_\pi^0 : 406 \text{ MeV}/c^2\). See supplement)

<table>
<thead>
<tr>
<th></th>
<th>(P_{tot} &lt; 100 \text{ MeV/c})</th>
<th>(100 \leq P_{tot} &lt; 250 \text{ MeV/c})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total #BKG (SKI-IV)</td>
<td>(~0.05)</td>
<td>(~0.82)</td>
</tr>
<tr>
<td>Data (SKI-IV)</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

- Poisson prob. (\(\geq 2; 0.82\)) : 19.9%
$p \to \nu K^+$ search
(prompt $\gamma$ method)

- event selections:
  - fully contained
  - fiducial volume
  - 1 $\mu$-like (PID)
  - 1 Michel-e
  - $215 < P_\mu < 260 \text{MeV/c}$
  - proton ring rejection
  - $8(4) < N_\gamma < 60(30)$ for SK-I,III,IV(SK-II)
  - $T_\mu - T_\gamma < 75 \text{ns}$
  - no neutrons (SK-IV only)

- no data candidate

(plot from PRD 90, 072005 (2014))
**$p \rightarrow \nu K^+$ search**  
($P_\mu$ spec. method)

- **event selections:**
  - same as $\gamma$ meth. except:
    - no prompt $\gamma$ hits
    - relaxed $P_\mu$ cut
- **no data excess**
p→νK⁺ search

(π⁺π⁰ method)

- event selections:
  - fully contained
  - fiducial volume
  - 1 or 2 e-like rings (PID)
  - 1 Michel-e
  - 85<M_{π⁰}<185MeV/c²,
    175<P_{π⁰}<250MeV/c
  - charge profile likelihood for π⁺
  - 10<E_{bk}<50MeV
  - no neutrons (SK-IV only)
- no data candidate

(plot from *PRD 90, 072005 (2014)*)
p→νK⁺ search result

<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>Exp.(kt·yrs)</td>
<td>91.7</td>
<td>49.2</td>
<td>31.9</td>
<td>133.5</td>
</tr>
<tr>
<td>Prompt γ Eff. (%)</td>
<td>7.9</td>
<td>6.3</td>
<td>7.7</td>
<td>8.5</td>
</tr>
<tr>
<td>BKG</td>
<td>0.08</td>
<td>0.14</td>
<td>0.03</td>
<td>0.14</td>
</tr>
<tr>
<td>OBS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>π⁺π⁰ Eff. (%)</td>
<td>7.8</td>
<td>6.7</td>
<td>7.9</td>
<td>9.0</td>
</tr>
<tr>
<td>BKG</td>
<td>0.18</td>
<td>0.17</td>
<td>0.09</td>
<td>0.12</td>
</tr>
<tr>
<td>OBS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- **306.3 kton·years (SKI-IV)** (260kt·yrs in PRD 90, 072005 (2014))
- signal ε for prompt γ and π⁺π⁻ methods: 6-9%
- total expected #BKG for prompt γ and π⁺π⁰ methods < 1
- no data excess above BKG expectation
  \[ \tau/B_{p\rightarrow\nu K^+} > 6.61 \times 10^{33} \text{ years (90\% CL)} \]
Benchmark searches and theoretical predictions

(Ed Kearns)

- Huge theoretical uncertainty
- Current searches are in interesting ranges
## Summary of recent nucleon decay results in SK

| Decay mode                  | \(|\Delta(B-L)|\) | Lifetime lower limit at 90% CL (years) | Paper (previous result)     |
|-----------------------------|----------------|---------------------------------------|-----------------------------|
| \(p \to e^+\pi^0\)         | 0              | \((^{(*)}1.67 \times 10^{34}\)         | (PRD 85, 112001 (2012))     |
| \(p \to \nu K^+\)          | \(0(\nu), 2(\nu)\) | 6.61 \(\times 10^{33}\)               | (PRD 90, 072005 (2014))     |
| \(p \to \mu^+\pi^0\)      | 0              | \((^{(*)}7.78 \times 10^{33}\)         | (PRD 85, 112001 (2012))     |
| \(p \to e^+//\mu^+(\eta, \rho, \omega)\) | 0               | (0.04-4.2) \(\times 10^{33}\)         | PRD 85, 112001 (2012)       |
| \(p \to \mu^+K^0\)        | 0              | 1.6 \(\times 10^{33}\)                | PRD 86, 012006 (2012)       |
| \(n \to \bar{\nu} \pi^0, p \to \bar{\nu} \pi^+\) | 0               | 1.1 \(\times 10^{33}\), 3.9 \(\times 10^{32}\) | PRL 113, 121802 (2014)      |
| \(p \to e^+//\mu^+\nu\nu\) | \(0(\nu\nu), 2(\nu\nu,\nu\nu)\) | 1.7/2.2 \(\times 10^{32}\)            | PRL 113, 101801 (2014)      |
| \(p \to e^+//\mu^+X\)      | \ (?)          | 7.9/4.1 \(\times 10^{32}\)            | arXiv:1508.05530, accepted by PRL |
| \(n \to v\gamma\)         | \(0(\nu), 2(\nu)\) | 5.5 \(\times 10^{32}\)               | arXiv:1508.05530, accepted by PRL |
| \(pp \to K^+K^+\)          | 2              | 1.7 \(\times 10^{32}\)                | PRL 112, 131803 (2014)      |
| \(pp \to \pi^+\pi^+, pn \to \pi^+\pi^0, nn \to \pi^0\pi^0\) | 2               | 7.22 \(\times 10^{31}\), 1.70 \(\times 10^{32}\), 4.04 \(\times 10^{32}\) | PRD 91, 072009 (2015)       |
| \(np \to (e^+,\mu^+,(\tau^+))\nu\) | \(0(\nu), 2(\nu)\) | \((0.22-5.5) \times 10^{32}\)     | arXiv:1508.05530, accepted by PRL |
| n-n oscillation            | 2              | 1.9 \(\times 10^{32}\)                | PRD 91, 072006 (2015)       |

(* will be published soon)
Next generation: Hyper-Kamiokande (HK)

http://www.hyperk.org/

~20 × Super-K
(detector design will be finalized soon)

J-PARC neutrino beam: CP-δ
Supernova to 2 Mpc
θ_{23}, mass heirarchy by atm. ν
Relic supernova neutrinos
Indirect dark matter

Nucleon decay: reach 10^{35} years

LBL study: PTEP 2015 (2015) 5, 053C02
Nucleon decay searches in HK

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

\[ \tau_p = 1.2 \times 10^{34} \text{yrs} \]

sensitivity (90% CL)
\[ \tau/B_{p \rightarrow e\pi^0} > 1 \times 10^{35} \text{ yrs (HK 10yrs)} \]

\[ p \rightarrow \nu K^+ \]

\[ \tau_p = 4 \times 10^{33} \text{yrs} \]

sensitivity (90% CL)
\[ \tau/B_{p \rightarrow \nu K^+} > 3 \times 10^{34} \text{ yrs (HK 10yrs)} \]
Summary

• Testing baryon number violation is an essential and high priority objective of particle physics

• Nucleon decay searches in Super-Kamiokande:
  – no evidence so far → most stringent lifetime limits in the world
  – keep discovery potential and increase statistics
  – prospect of sensitivity improvements by sophisticated reconstruction algorithm, reducing systematic errors, etc.
  – search new modes

• Hyper-Kamiokande
  – http://www.hyperk.org/
Supplement
Super-Kamiokande Collaboration

1 Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
2 RCCN, ICRResearch, Univ. of Tokyo, Japan
3 University Autonoma Madrid, Spain
4 University of British Columbia, Canada
5 Boston University, USA
6 Brookhaven National Laboratory, USA
7 University of California, Irvine, USA
8 California State University, USA
9 Chonnam National University, Korea
10 Duke University, USA
11 Fukuoka Institute of Technology, Japan
12 Gifu University, Japan
13 GIST College, Korea
14 University of Hawaii, USA
15 KEK, Japan
16 Kobe University, Japan
17 Kyoto University, Japan
18 Miyagi University of Education, Japan
19 STE, Nagoya University, Japan
20 SUNY, Stony Brook, USA
21 Okayama University, Japan
22 Osaka University, Japan
23 University of Regina, Canada
24 Seoul National University, Korea
25 Shizuoka University of Welfare, Japan
26 Sungkyunkwan University, Korea
27 Tokai University, Japan
28 University of Tokyo, Japan
29 Kavli IPMU (WPI), University of Tokyo, Japan
30 Dep. of Phys., University of Toronto, Canada
31 TRIUMF, Canada
32 Tsinghua University, China
33 University of Washington, USA
34 National Centre For Nuclear Research, Poland

~120 collaborators
34 institutions
7 countries
$p \rightarrow e^+ \pi^0$ search
$p \rightarrow \mu^+ \pi^0$ search
Manual fit on $\mu^+\pi^0$ candidate Event #2

Take 3 rings
- $\mu$: 418 MeV/c
- e: 159 MeV/c
- e: 338 MeV/c
- $P_{\text{tot}}$: 294 MeV/c
- $M_{\gamma\gamma}$: 880 MeV
- $M_{\gamma\gamma}$: 406 MeV
Spectral Search for Baryon Number Violation

Momentum distribution of single rings is well modeled by atmospheric neutrinos

Lifetime limits (90%CL): $2 \times 10^{31}$ to $8 \times 10^{32}$ years

(some are novel. 1-2 orders of magnitude improvement over previous results)

PRL 113, 101801 (2014)  
arXiv:1508.05530
**Dinucleon decay** \[ \Delta B = |\Delta(B-L)| = 2 \]

(plots for \( pn \rightarrow \pi^+ \pi^0 \) in SK-IV as example)

**Input variables**

**Boosted Decision Tree Output**

- **Signal-like**

**Table: Frejus limit vs. this analysis**

<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>

**PRD 91, 072009 (2015)**