Nucleon Decay Searches

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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

Lepton and baryon numbers are not conserved.

Nucleon decay experiment is the direct probe for GUTs.

Cannot be reached by Accelerators.

Proton decay is permitted!
Two benchmark decay modes

<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>$p \rightarrow \bar{v}K^+$</td>
<td>$\leq 10^{30}$ [3]</td>
</tr>
<tr>
<td>SUGRA SU(5)</td>
<td>$p \rightarrow \bar{v}K^+$</td>
<td>$10^{32} \sim 10^{34}$ [4]</td>
</tr>
<tr>
<td>SUSY SO(10)</td>
<td>$p \rightarrow \bar{v}K^+$</td>
<td>$10^{32} \sim 10^{34}$ [5]</td>
</tr>
</tbody>
</table>

> $10^{30}$ years!
Need huge detector.

In the late 1970s, several experiments were proposed. 
- minimal SU(5) prediction: $10^{28} \sim 10^{32}$ years 
- 1kt detector expected $10 \sim 10^3$ decays.

Background events for proton decay searches are induced by atmospheric $\nu$ interactions (they were also $\nu$ detectors).

Two types of detector came into fashion (the 1st generation).

Fine-grained iron calorimeter
- Excellent in track reconstruction.
- Cost per ton were expensive.
- KGF (India), Soudan I,II (Minnesota), NUSEX (Italy/France)

Water Cherenkov detector
- Good momentum resolution and PID.
- Cheaper and easier to build larger detectors.
- HPW (Harvard-Purdue-Wisconsin), IMB (Irvine, Michigan, Brookhaven), Kamiokande
Results of Water Cherenkov detector

<table>
<thead>
<tr>
<th>Detector</th>
<th>Period</th>
<th>Mass (ton)</th>
<th>Limit ($e^+\pi^0$, $10^{30}$ yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPW-I</td>
<td>1983-1984</td>
<td>680</td>
<td>1.0</td>
</tr>
<tr>
<td>Kamioka</td>
<td>1983-1997</td>
<td>1040</td>
<td>260</td>
</tr>
<tr>
<td>IMB</td>
<td>1982-1992</td>
<td>3300</td>
<td>540</td>
</tr>
</tbody>
</table>

Results of Iron calorimeter

<table>
<thead>
<tr>
<th>Detector</th>
<th>Period</th>
<th>Mass (ton)</th>
<th>Limit ($e^+\pi^0$, $10^{30}$ yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUSEX</td>
<td>1982-1998</td>
<td>110-130</td>
<td>15</td>
</tr>
<tr>
<td>Frejus</td>
<td>1984-1988</td>
<td>550</td>
<td>70</td>
</tr>
<tr>
<td>Soudan I</td>
<td>1981-1990</td>
<td>16-24</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Could not find evidence. Need more volume. ➔ Super-Kamiokande (The 2nd generation)
3. Present: Super-Kamiokande

**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, ~1/3 comes from IMB).

**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.

μ-like (μ±)  e-like (e±, γ)
History of Super-Kamiokande

- SK has been running more than 20 years (amazingly!)
- Collected 372 kton-year exposure until 2018
- Many of the current limits come from SK.
Water Cherenkov Detector for Nucleon Decay searches

• **Easy to construct large detector.**
  - Need huge number of nucleons.
  - SK: 22.5kton in fiducial = 7x10^{33} protons.

• **High efficiency and low uncertainty.**
  - Mesons from proton decay in oxygen suffer from nuclear interactions (absorption, scattering, charge exchange …) which are dominant sources of inefficiency.
  - 2 hydrogens in water act as free proton, free from nuclear interactions.

• **Backgrounds (atmospheric ν) are well understood.**
  - SK is the world largest Neutrino Detection Experiment.
3-1. $p \rightarrow e^+\pi^0$, $\mu^+\pi^0$ mode

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

**Selection:**
- Fully contained, VTX in fiducial volume.
- 2 or 3 ring

**$e^+\pi^0$ case:**
- all e-like, w/o decay-e.

**$\mu^+\pi^0$ case:**
- one $\mu$-like with decay-e.

- $85 < M_{\pi^0} < 185$ MeV (for 3-ring event).
- $800 < M_P < 1050$ MeV & $P_{\text{tot}} < 250$ MeV/c

Selected by simple cuts!
New technique 1: Neutron tag

- Most of atmospheric ν BKG are accompanied by neutrons.
- A neutron is captured by a hydrogen (~200μsec) and emits γ ray:
  \[ n+p \rightarrow d+\gamma \text{ (2.2 MeV)} \]
- New electronics installed in SK4 enables us to record all hits including this γ ray.
- Search for hit cluster \( N \geq 7 \) in 10 ns window after prompt signal, and neutrons are selected by neural network.
- Eff. 20.5 %, BKG 1.8 %.
- About half of the background events can be rejected by requiring no neutron.

Time difference from prompt signal
New technique 2: two box analysis

- Signal box defined by 800<\textit{M}_{\text{tot}}<1050\text{ MeV/c}^2 and \textit{P}_{\text{tot}}<250\text{MeV/c} is divided into two regions;
  ① Lower box: \textit{P}_{\text{tot}}<100\text{ MeV/c}
    ✓ Signal: Dominated by free proton (H) decay, free from nuclear effects → Almost BKG free.
  ② Higher box: 100\leq\textit{P}_{\text{tot}}<250\text{ MeV/c}
    ✓ Signal: Dominated by bound proton (O) decay, more uncertainty due to nuclear effects. More BKG.

- Achieve better sensitivity.
Results


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

<table>
<thead>
<tr>
<th></th>
<th>Eff. (%)</th>
<th>BKG</th>
<th>OBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low ( P_{\text{tot}} )</td>
<td>18.7</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>High ( P_{\text{tot}} )</td>
<td>19.9</td>
<td>0.58</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>38.6</td>
<td>0.63</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Eff. (%)</th>
<th>BKG</th>
<th>OBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low ( P_{\text{tot}} )</td>
<td>18.0</td>
<td>0.07</td>
<td>0</td>
</tr>
<tr>
<td>High ( P_{\text{tot}} )</td>
<td>16.7</td>
<td>0.65</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>34.7</td>
<td>0.72</td>
<td>1</td>
</tr>
</tbody>
</table>

Lifetime limit (90% CL, 365 kton \( \cdot \) yrs data)

\[ p \rightarrow e^+ \pi^0: > 2.0 \times 10^{34} \text{ years} \]
\[ p \rightarrow \mu^+ \pi^0: > 1.2 \times 10^{34} \text{ years} \]
3-2. $N \rightarrow$ charged anti-lepton + meson

- Several decay modes in which a nucleon decays into a charged lepton and a meson (not only $\pi^0$) are proposed.
- Those searches have been studied systematically with 316kt⋅year data.

Also improved in analysis:
- Reduce BKG in SK4 by neutron tag.
- Two box analysis for $p \rightarrow e^+/\mu^+ + \eta^0$, $\eta^0 \rightarrow 2\gamma$
- And so on.
Event selection

1) Select rings

<table>
<thead>
<tr>
<th>$N \rightarrow$ lepton</th>
<th>meson</th>
<th>meson decay mode</th>
<th>(Br.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow e^+ (\mu^+)$</td>
<td>$\pi^0$</td>
<td>$\pi^0 \rightarrow 2\gamma$</td>
<td>(98.8%)</td>
</tr>
<tr>
<td>$p \rightarrow e^+ (\mu^+)$</td>
<td>$\eta$</td>
<td>$\eta \rightarrow 2\gamma$</td>
<td>(39.3%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\eta \rightarrow 3\pi^0$</td>
<td>(32.6%)</td>
</tr>
<tr>
<td>$p \rightarrow e^+ (\mu^+)$</td>
<td>$\rho^0$</td>
<td>$\rho^0 \rightarrow \pi^+\pi^-$</td>
<td>($\sim$100%)</td>
</tr>
<tr>
<td>$p \rightarrow e^+ (\mu^+)$</td>
<td>$\omega$</td>
<td>$\omega \rightarrow \pi^0\gamma$</td>
<td>(8.9%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\omega \rightarrow \pi^+\pi^-\pi^0$</td>
<td>(89.2%)</td>
</tr>
<tr>
<td>$n \rightarrow e^+ (\mu^+)$</td>
<td>$\pi^-$</td>
<td>$\rho^- \rightarrow \pi^-\pi^0$</td>
<td>($\sim$100%)</td>
</tr>
</tbody>
</table>

- Primary e/μ ring and
  - 2 e-like rings
  - 2 e-like rings
  - 4, 5 e-like rings
  - 2 μ-like rings
  - 2,3 e-like rings
  - 2 e-like and 1 μ-like
  - 2-ellike and 1 μ-like

2) Reconstruct meson mass

- $\eta$: 480 ~ 620 MeV/c²
- $\rho^0, \rho^-$: 600 ~ 900 MeV/c²
- $\omega$: 650 ~ 900 MeV/c²

3) Reconstruct nucleon mass and momentum

- mass: 800 ~ 1050 MeV/c²
  - (600~800MeV for $p \rightarrow e\omega$, 450~700MeV for $p \rightarrow \mu\omega$)
- momentum: < 250 MeV/c
  - (<150 MeV/c for $p \rightarrow e\eta(3\pi^0), e\rho, e\omega(\pi^0\gamma)$,
  - <200 MeV/c for $p \rightarrow e/\mu\omega(\pi^+\pi^-\pi^0)$)
Summary of $\text{N} \rightarrow \text{anti-lepton} + \text{meson}$

- Some candidates have been observed, but consistent with expected background.
- Lifetime limits in most modes are improved by factor 2~3 since the previous publication (SK1+2).
3-3. $p \rightarrow \bar{\nu} K^+$ mode

General features

- $\bar{\nu}$ cannot be detected = we cannot reconstruct proton mass and momentum.
- Momentum of $K^+ \sim 339\text{MeV}/c$: below Cherenkov threshold and not visible by SK.
- $K^+$ stops in water and decay with $\tau = 12\text{ns}$:
  - $K^+ \rightarrow \nu\mu^+$: Br. 64 % (Method A)
  - $K^+ \rightarrow \pi^+\pi^0$: Br. 21 % (Method B)
- In these two body decay case, decayed particles have monochromatic momentum.
Method (A) \( K^+ \rightarrow \mu^+ \nu_\mu \)

**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).
- **\( \Rightarrow \) Tag** \( \gamma \) to eliminate BKG.

**Selection:**
- 1 \( \mu \)-like ring with decay-e.
- \( 215 < P_\mu < 260 \text{ MeV/c} \)
- 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
- No neutrons (only for SK-4)
**Method (B)**  
\[ K^+ \rightarrow \pi^+ + \pi^0 \]

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).

\[ \Rightarrow \text{Search for monochromatic } \pi^0 \text{ with backward activities.} \]

**Selection:**
- 1 or 2 e-like rings with decay-e.
- \( 85 < M\pi^0 < 185 \text{ MeV} \).
- \( 175 < P\pi^0 < 250 \text{ MeV}/c. \)
- \( E_{\text{bk}} \): visible energy sum in 140-180 deg. of \( \pi^0 \) dir.
- \( E_{\text{res}} \): in 90-140 deg,
- \( L_{\text{shape}} \): Likelihood based on charge profile
  - \( 10 < E_{\text{bk}} < 50 \text{ MeV} \)
  - \( E_{\text{res}} < 12 \text{ MeV} \) (20 MeV for 1 ring)
  - \( L_{\text{shape}} > 2.0 \) (3.0 for 1 ring)
- No neutrons
No Candidate observed.

<table>
<thead>
<tr>
<th></th>
<th>SK1</th>
<th>SK2</th>
<th>SK3</th>
<th>SK4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eff (%)</td>
<td>BG (ev)</td>
<td>Obs (ev)</td>
<td>Eff (%)</td>
<td>BG (ev)</td>
</tr>
<tr>
<td>Pr.γ</td>
<td>7.9 ± 0.1</td>
<td>0.078</td>
<td>0</td>
<td>6.5 ± 0.1</td>
</tr>
<tr>
<td>(\pi^+\pi^0)</td>
<td>7.8 ± 0.1</td>
<td>0.21</td>
<td>0</td>
<td>6.5 ± 0.1</td>
</tr>
</tbody>
</table>

\[p \rightarrow \nu K^+ \text{ Lifetime limit (90\% CL)} : > 8.2 \times 10^{33} \text{ yrs (365 kton} \cdot \text{yr exposure)}\]
Di-nucleon decays: $NN \rightarrow ll, p \rightarrow l\gamma$

- Search for di-nucleon decay with only leptons or $\gamma$s in final state
  - $NN \rightarrow$ e-like+e-like ($pp \rightarrow e^+e^+, nn \rightarrow e^+e^-, nn \rightarrow \gamma\gamma$).
  - $NN \rightarrow$ e-like+$\mu$-like ($pp \rightarrow e^+\mu^+, nn \rightarrow e^+\mu^-, nn \rightarrow e^+\mu^+$).
  - $NN \rightarrow$ $\mu$-like+$\mu$-like ($pp \rightarrow \mu^+\mu^+, nn \rightarrow \mu^+\mu^-$).

- Also proton decay: $p \rightarrow e^+\gamma, \mu^+\gamma$

- 5 of 8 Di-nucleon decay: $\Delta(B-L)=-2$.

- First trial to investigate those mode in SK, expect to improve the current PDG world limits by Frejus and IMB.

$pp \rightarrow e^+\mu^+$

Publish soon.
• Select FCFV 2R (ee, em, μμ) without tagged neutron, and apply total mass and total momentum cut as same as p → e+π0.

• High selection efficiency (~80%).

• Low expected background
  - < 0.1 events for NN decay.
  - 0.1 events for p → e+γ, 0.7 events for p → μ+γ.

• Two candidates observed in p → μ+γ, consistent with background.

• Lifetime limits are improved by some orders of magnitude from the current PDG limits.
3-5. Summary of the current results

- Most of modes have been investigated with $> 0.3 \text{ Mton} \cdot \text{year exposure}$ (red and green in the left figure).
- Super-Kamiokande can cover large number of decay modes.
- Many of them are the most stringent limits on nucleon lifetime.
- We observed some candidates, but still consistent with expected backgrounds and no evidence of nucleon decay has been observed.
4. Future prospects

• Still no evidence has been found. Major decay modes are explored up to around $10^{34}$ years.

• Proton lives longer, $\sim 10^{35}$ years?
  - Run SK 10 times more (~200 years)? $\rightarrow$ Impossible.
  - Need “the 3rd generation” detectors.

• Several projects are moving forward.
  - Water Cherenkov: Hyper-Kamiokande (HK)
    - Well established and stable.
    - Larger volume.
    - Can cover several decay modes.
  - New wave: DUNE (LAr), JUNO (L-Scintillator)
    - Excellent event reconstruction.
    - High efficiency, low background.
Comparison with Predictions

Future experiments will open the door to GUTs!
Backup
N (NN) $\rightarrow$ charged lepton +X

- **Search for**
  - $p \rightarrow e^+/\mu^+ + X$, $n \rightarrow \gamma + X$ (X: invisible massless particle, $\Delta B=1$)
  - $pn \rightarrow e^+/\mu^+/\tau^+ + \nu$ (di-nucleon decay, $\Delta B=2$)
- **Test momentum distributions of single ring events.**

- **Data and Atm.$\nu$ MC agree well.**
- **Lifetime limits:** fit data by Atm.$\nu$ and signal MC.
  - $p \rightarrow e^+X$: $> 7.9 \times 10^{32}$ yrs
  - $p \rightarrow \mu^+X$: $> 4.1 \times 10^{32}$ yrs
  - $n \rightarrow \gamma X$: $> 5.5 \times 10^{32}$ yrs
  - $pn \rightarrow e^+\nu$: $> 2.6 \times 10^{32}$ yrs
  - $pn \rightarrow \mu^+\nu$: $> 2.2 \times 10^{32}$ yrs
  - $pn \rightarrow \tau^+\nu$: $> 2.9 \times 10^{32}$ yrs
Di-nucleon decays: \( NN \rightarrow \pi\pi \)

- Search for \( ^{16}\text{O}(pp) \rightarrow ^{14}\text{C}\pi^+\pi^+ \), \( ^{16}\text{O}(pn) \rightarrow 14N\pi^+\pi^0 \), \( ^{16}\text{O}(nn) \rightarrow ^{14}\text{O}\pi^0\pi^0 \).
- \( \Delta B=2 \)
- Tag pions in back-to-back. Pions are affected by nuclear interactions in nucleus and water.
  - Use Boosted Decision Tree for \( pp \rightarrow \pi^+\pi^+ \) and \( pn \rightarrow \pi^+\pi^0 \)
- For \( nn \rightarrow \pi^0\pi^0 \), use total mass and total momentum cuts, as same as \( p \rightarrow e^+\pi^0 \).

<table>
<thead>
<tr>
<th>Mode</th>
<th>Eff. (%)</th>
<th>BKG</th>
<th>Obs</th>
<th>Limit (10^{32} \text{yr})</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp ( \rightarrow \pi^+\pi^+ )</td>
<td>5.9</td>
<td>4.5</td>
<td>2</td>
<td>0.72</td>
</tr>
<tr>
<td>pn ( \rightarrow \pi^+\pi^0 )</td>
<td>10.2</td>
<td>0.75</td>
<td>1</td>
<td>1.7</td>
</tr>
<tr>
<td>nn ( \rightarrow \pi^0\pi^0 )</td>
<td>21.1</td>
<td>0.14</td>
<td>0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Observation is consistent with BKG.
Observed events (2-ring events)

<table>
<thead>
<tr>
<th>TotMass (MeV/c^2)</th>
<th>TotMom. (MeV/c)</th>
<th>Pe (MeV/c)</th>
<th>Pμ (MeV/c)</th>
<th>Ang. (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>903</td>
<td>248</td>
<td>375</td>
<td>551</td>
<td>158</td>
</tr>
</tbody>
</table>

Note1: Cut: Ptot <250MeV/c, they were really close to boundary.
Note2: The 2^{nd} event in the paper went out from signal box with updated gain correction.
Systematic errors

### Lifetime limit (90% CL) with 365kton \cdot yrs data

\[
p \rightarrow e^+\pi^0 \\
> 2.0 \times 10^{34} \text{ years}
\]

\[
p \rightarrow \mu^+\pi^0 \\
> 1.2 \times 10^{34} \text{ years}
\]

### Coming soon: Improved reconstruction tool.
- Current one: decide step by step: VTX, # of rings, PID, Mom …
- New method: Fit everything at once by maximum likelihood.
- Higher resolution \(\Rightarrow\) Expect to improve discovery potential.
Meson mass can be reconstructed with same quality for all period. Use two box analysis as same as $p \rightarrow e^+\pi^0$. Two candidates (expected BG: 0.9 events)
## Results of $N \rightarrow l+m$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Eff. (Av,%)</th>
<th>BKG</th>
<th>Obs.</th>
<th>Poisson Prob $\geq$Obs (%)</th>
<th>Lifetime limit ($10^{33}$yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow e^+\eta$</td>
<td>25.8</td>
<td>0.78</td>
<td>0</td>
<td>-</td>
<td>10.0 (prev.4.2)</td>
</tr>
<tr>
<td>$p \rightarrow e^+\rho^0$</td>
<td>3.7</td>
<td>0.64</td>
<td>2</td>
<td>13.5</td>
<td>0.72 (0.71)</td>
</tr>
<tr>
<td>$p \rightarrow e^+\omega^0$</td>
<td>4.9</td>
<td>1.35</td>
<td>1</td>
<td>74.1</td>
<td>1.6 (0.32)</td>
</tr>
<tr>
<td>$n \rightarrow e^+\pi^-$</td>
<td>12.7</td>
<td>0.41</td>
<td>0</td>
<td>-</td>
<td>5.3 (2.0)</td>
</tr>
<tr>
<td>$n \rightarrow e^+\rho^-$</td>
<td>1.4</td>
<td>0.87</td>
<td>4</td>
<td>1.2</td>
<td>0.03 (0.07)</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+\eta$</td>
<td>21.1</td>
<td>0.85</td>
<td>2</td>
<td>20.9</td>
<td>4.7 (1.3)</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+\rho^0$</td>
<td>1.8</td>
<td>1.30</td>
<td>1</td>
<td>72.7</td>
<td>0.57 (0.16)</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+\omega^0$</td>
<td>6.7</td>
<td>1.09</td>
<td>0</td>
<td>-</td>
<td>2.8 (0.78)</td>
</tr>
<tr>
<td>$n \rightarrow \mu^+\pi^-$</td>
<td>12.2</td>
<td>0.77</td>
<td>1</td>
<td>53.7</td>
<td>3.5 (1.0)</td>
</tr>
<tr>
<td>$n \rightarrow \mu^+\rho^-$</td>
<td>1.1</td>
<td>0.96</td>
<td>1</td>
<td>61.7</td>
<td>0.06 (0.036)</td>
</tr>
</tbody>
</table>

Consistent with BKG, lifetime limits improved factor 2~3 in most of modes.
n̅n oscillation

- ΔB=2
- n̅ annihilates immediately.
- Apply total momentum ($P_{\text{tot}} < 450$ MeV/c) and total mass cut ($750 < M_{\text{tot}} < 1800$ MeV/c$^2$) to multi-ring.
- Use only SK1 data (91.7kton • yr).
  - Eff. 12.1 %
  - BKG: 24.1 events
  - Observed: 21 event
- Lifetime limit: > 1.9x10$^{32}$ yrs
→ oscillation time (free neutron):
  > 2.7x10$^8$ sec

(using nuclear suppressing factor by Freedman&Gil, PRD 78, 016002(2008), with 20~30% theoretical error)
Hyper-Kamiokande

- Tank size: 60m (H)x74m(D), 186 kton, upright cylindrical.
- Start budget request for the first tank.
- 40% photo coverage by new Box&Line PMT (photon counting eff. $\times 2$, ½ time resolution than SK PMT).
- Can achieve better neutron tagging efficiency which rejects Atm.$\nu$ BG.

DUNE

- Liquid Ar TPC, start from 10 kton, increased up to 40 kton later.
- Can reconstruct $K^+$ track.
- Efficiency for $p \rightarrow \nu K^+$: 97%, ~4 times more than HK.
- Efficiency for $p \rightarrow e^+\pi^0$ is limited by $\pi$ interaction in nucleus and similar to HK.
$3\sigma$ discovery potential by future detectors

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

$p \rightarrow \bar{\nu}K^+$

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<tr>
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<th>Eff(%)</th>
<th>BG/Mton</th>
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<td>HK</td>
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<tr>
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<th>Eff(%)</th>
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# Numbers are taken from Design Report.
# Systematic error included only in HK case.
3-4 Other decay modes

Di-nucleon decays: NN → ℓℓ, p → ℓγ

- Search for di-nucleon decay: pp → ℓ⁺ ℓ⁺, nn → ℓ⁺ ℓ⁻, nn → γγ, without any meson in final states and ΔB=2 (ℓ = e or μ)
- Also proton decay: p → ℓ⁺ γ
- First trial to investigate those mode in SK.
- Use total mass and momentum cut as same as p → e⁺π⁰.
- Consistent with background expectation and updates lifetime limits.

Publish soon.