Searches for Baryon Number Violation

Ed Kearns     Boston University

From the Cosmos to the LHC

May 15-18, 2017

Cleveland, USA
Origins: baryon number conservation formulated by:
Weyl (1929), Stueckelberg (1938),
Wigner (1949), Lee & Yang (1950) to explain stability of matter.

It is conceivable, for instance, that a conservation law for the number of heavy particles (protons and neutrons) is responsible for the stability of the protons in the same way as the conservation law for charges is responsible for the stability of the electron. Without the conservation law in question, the proton could disintegrate, under emission of a light quantum, into a positron, just as the electron could disintegrate, were it not for the conservation law for the electric charge, into a light quantum and a neutrino. E. Wigner

Conserved in the Standard Model*

*imperfectly due to anomalies, but with irrelevantly long lifetimes

but the Standard Model is incomplete …
Baryon number violation

**BNV:** anticipated for BAU (Sakharov Condition #1)

**BNV:** natural consequence of Grand Unified Theories
– nucleon decay
– violation of B and L

**BNV:** possible consequence of new physics below the GUT scale
– nnbar oscillation
– di-nucleon decay
– violate B only

Other new physics: dark matter induced BNV, extra dimensions, dark sector, better not to assume too much and just look?

The Standard Model is incomplete.
**Some BNV processes studied with accelerators**

<table>
<thead>
<tr>
<th>Category</th>
<th>Example</th>
<th>Branching fraction</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z decays</td>
<td>$Z \rightarrow p\ e$</td>
<td>$&lt; 1.8 \times 10^{-6}$</td>
<td>OPAL</td>
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<tr>
<td>tau decays</td>
<td>$\tau \rightarrow p\bar{\tau} \gamma$</td>
<td>$&lt; 10^{-5} – 10^{-7}$</td>
<td>LHCb, CLEO, Belle</td>
</tr>
<tr>
<td>Heavy meson decay</td>
<td>$B^0 \rightarrow \Lambda^0 \ e^+$</td>
<td>$&lt; 10^{-5} – 10^{-8}$</td>
<td>CLEO, BaBar</td>
</tr>
<tr>
<td>Heavy baryon decay</td>
<td>$\Lambda^0 \rightarrow \pi^- \ e^+$</td>
<td>$&lt; 10^{-5} – 10^{-7}$</td>
<td>CLAS</td>
</tr>
<tr>
<td>Top quark</td>
<td>$t\bar{t} \rightarrow b\ u\ e^-$</td>
<td>$&lt; 10^{-3}$</td>
<td>CMS</td>
</tr>
</tbody>
</table>

But arguably (Marciano, 1995) some of these processes may be better constrained by nucleon decay.

**nucleon decay is most constraining**

Hou, Nagashima, Soddu hep-ph/0509006
\[ \Delta B = 2 \] violates B-L, needed for BAU

nnbar oscillation
(free neutron or inside nucleus)

\[ \delta m_{n\bar{n}} = \frac{1}{\tau_{n\bar{n}}} = \langle \bar{n} | L_{\Delta B=2} | n \rangle = \frac{1}{M^5} \langle \bar{n} | UDDUDD | n \rangle \approx \frac{\Lambda^6}{M^5} \]

\[ \Lambda \approx 200 \text{ MeV} \]
\[ \tau \approx 10^8 \text{ s} \]
\[ M > 10^6 \text{ GeV} \]
Future Free Neutron Oscillation Experiment

Quasi-free conditions: vacuum, magnetic field $\leq 10$ nT

More neutrons, 200 m oscillation channel
Sensitivity $\propto N_n t^2$
Improvement over previous free nnbar limit by factor by 500 – 1000


construction finish in 2019

theory and experiment plenary talks tomorrow (Mohapatra, Snow)
nnbar in nuclei

Liquid Argon TPC parallel talks (Josh Barrow, Jeremy Hewes), Result from SNO (Marc Bergevin)

(and plenary talks – Snow, Mohapatra)
Grand Unified Theories

assume the Standard Model, $\text{SU}(3) \otimes \text{SU}(2) \otimes \text{U}(1)$, is part of a larger symmetry group, e.g. $\text{SU}(5)$:

$$
\bar{5} = \begin{pmatrix}
\bar{d}_g \\
\bar{d}_r \\
\bar{d}_b \\
e^- \\
-\nu_e
\end{pmatrix}_{L} 
= \begin{pmatrix}
0 & \bar{u}_b & \bar{u}_g & \bar{d}_g \\
0 & \bar{u}_g & \bar{u}_r & \bar{d}_r \\
0 & \bar{u}_b & \bar{d}_b & 0 \\
0 & -e^+ & 0
\end{pmatrix}_{L}
$$

Consequences:

- Single (unified) coupling
- Charge quantization: $Q_d = Q_e / 3$, $Q_u = -2Q_d$ ⇒ $Q_p = -Q_e$
- New gauge interactions ($X$, $Y$ bosons) ⇒ proton decay
- Other predictions of $\text{SU}(5)$: magnetic monopoles, value of weak mixing angle (poor), massless neutrinos (oops!)
- There are other groups, e.g. $\text{SO}(10)$ that accommodate massive neutrinos
Circumstantial Evidence

\[ \tau(e^+\pi^0) = 4.5 \times 10^{29.17} \text{ years (predicted)} \]

\[ \tau(e^+\pi^0) > 5.5 \times 10^{32} \text{ years (IMB/1990)} \]
SUSY GUTs

Unification scale pushed up ✔

τ(e^+π^0) ≈ 10^{35-38} years

But new modes now present (D=5)

τ(νK^+) ≈ 10^{29-35} years
Benchmark Proton Decay Signatures

Water Cherenkov
Super-Kamiokande
Hyper-Kamiokande

Liquid Scintillator
KamLAND
JUNO
ASDC/THEIA

Liquid Argon TPC
DUNE

most massive – superior for $e^+\pi^0$
 broad search capabilities
kaons below Cherenkov threshold

fine grained detail
visible kaon track
heavy nucleus, no free protons

clean timing signature
specialize in charged kaon
(also invisible mode)
e+ π0 search in Super-K

- Fully contained
- Fiducial volume
- 2 or 3 rings
- All rings are EM showers
- π0 mass 85-185 MeV/c²
- No μ-decay electrons
- Mass range 800-1050 MeV/c²
- Net momentum < 250 MeV/c
- SK-IV only: veto event if n-capture

New “two box” strategy.
Low momentum associated with free proton.
No nuclear effects,
Lower background

<table>
<thead>
<tr>
<th>Signal Efficiency (%)</th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV w. n cap.</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 &lt; ( p_{\text{net}} ) &lt; 200 MeV/c</td>
<td>20.4 ± 3.1</td>
<td>20.2 ± 3.1</td>
<td>20.5 ± 3.2</td>
<td>19.4 ± 1.2</td>
</tr>
<tr>
<td>( p_{\text{net}} ) &lt; 100 MeV/c</td>
<td>18.8 ± 0.9</td>
<td>18.3 ± 1.0</td>
<td>19.6 ± 1.3</td>
<td>18.7 ± 1.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Background (evts)</th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV w. n cap.</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 &lt; ( p_{\text{net}} ) &lt; 200 MeV/c</td>
<td>0.22 ± 0.06</td>
<td>0.12 ± 0.04</td>
<td>0.06 ± 0.02</td>
<td>0.15 ± 0.05</td>
</tr>
<tr>
<td>( p_{\text{net}} ) &lt; 100 MeV/c</td>
<td>0.03 ± 0.01</td>
<td>0.01 ± 0.003</td>
<td>0.003 ± 0.001</td>
<td>0.02 ± 0.01</td>
</tr>
</tbody>
</table>

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Nuclear Physics of Proton Decay

- Effective mass in $^{16}\text{O}$
- Correlation with other nucleons
- Fermi motion – by shell
- Initial position (Woods-Saxon)
- Nuclear de-excitation $\gamma$
- Pion-nuclear interactions
  - Elastic Scattering
  - Charge Exchange
  - Absorption

<table>
<thead>
<tr>
<th>Hole</th>
<th>Residual</th>
<th>States</th>
<th>$(k)$</th>
<th>$E_\gamma$</th>
<th>$E_p$</th>
<th>$E_n$</th>
<th>$B(k)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(p_{1/2})_p^{-1}$</td>
<td>g.s.</td>
<td>$\frac{1}{2}^-$</td>
<td>$^{15}\text{N}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.25</td>
</tr>
<tr>
<td>$(p_{3/2})_p^{-1}$</td>
<td>6.32</td>
<td>$\frac{3}{2}^-$</td>
<td>$^{15}\text{N}$</td>
<td>6.32</td>
<td>0</td>
<td>0</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>9.93</td>
<td>$\frac{5}{2}^-$</td>
<td>$^{15}\text{N}$</td>
<td>9.93</td>
<td>0</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>10.70</td>
<td>$\frac{7}{2}^-$</td>
<td>$^{15}\text{N}$</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>$(s_{1/2})_p^{-1}$</td>
<td>g.s.</td>
<td>$\frac{1}{2}^+$</td>
<td>$^{14}\text{N}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\sim 20$</td>
</tr>
<tr>
<td></td>
<td>7.03</td>
<td>$2^+$</td>
<td>$^{14}\text{N}$</td>
<td>7.03</td>
<td>0</td>
<td>0</td>
<td>$\sim 13$</td>
</tr>
<tr>
<td></td>
<td>g.s.</td>
<td>$\frac{3}{2}^+$</td>
<td>$^{13}\text{C}$</td>
<td>0</td>
<td>1.6</td>
<td>0</td>
<td>$\sim 11$</td>
</tr>
<tr>
<td></td>
<td>7.01</td>
<td>$2^+$</td>
<td>$^{13}\text{C}$</td>
<td>7.01</td>
<td>$\sim 21$</td>
<td>0</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>g.s.</td>
<td>$\frac{1}{2}^+$</td>
<td>$^{13}\text{C}$</td>
<td>0</td>
<td>$\sim 11$</td>
<td>$\sim 2$</td>
<td>0.03</td>
</tr>
<tr>
<td>$(j)_p^{-1}$</td>
<td>others</td>
<td>many states</td>
<td>$\leq 3-4$</td>
<td>0</td>
<td></td>
<td></td>
<td>0.16</td>
</tr>
</tbody>
</table>
Neutron capture on hydrogen

Capture time

Atmospheric neutrino background is frequently accompanied by neutron production

Detection efficiency = 20.5%
Can increase to ~90% with capture on Gd

SK-Gd construction in 2018 or 2019
Super-Kamiokande I-IV $p \rightarrow e^+\pi^0$ MC

Super-Kamiokande I-IV atm $\nu$ MC

$\tau/B(p \rightarrow e^+\pi^0) > 1.6 \times 10^{34}$ years

Super-Kamiokande I-IV Signal MC

Super-Kamiokande I-IV data

$\tau/B(p \rightarrow \mu^+\pi^0) > 7.7 \times 10^{33}$ years

Super-K Data (306 kt y)
antilepton plus other mesons

<table>
<thead>
<tr>
<th>Modes</th>
<th>Background (events)</th>
<th>Candidate (events)</th>
<th>Probability (%)</th>
<th>Lifetime Limit (×10^{33} years) at 90% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>p → e^+\eta</td>
<td>0.78±0.30</td>
<td>0</td>
<td>-</td>
<td>10.</td>
</tr>
<tr>
<td>p → \mu^+\eta</td>
<td>0.85±0.23</td>
<td>2</td>
<td>20.9</td>
<td>4.7</td>
</tr>
<tr>
<td>p → e^+\rho^0</td>
<td>0.64±0.17</td>
<td>2</td>
<td>13.5</td>
<td>0.72</td>
</tr>
<tr>
<td>p → \mu^+\rho^0</td>
<td>1.30±0.33</td>
<td>1</td>
<td>72.7</td>
<td>0.57</td>
</tr>
<tr>
<td>p → e^+\omega</td>
<td>1.35±0.43</td>
<td>1</td>
<td>74.1</td>
<td>1.6</td>
</tr>
<tr>
<td>p → \mu^+\omega</td>
<td>1.09±0.52</td>
<td>0</td>
<td>-</td>
<td>2.8</td>
</tr>
<tr>
<td>n → e^+\pi^-</td>
<td>0.41±0.13</td>
<td>0</td>
<td>-</td>
<td>5.3</td>
</tr>
<tr>
<td>n → \mu^+\pi^-</td>
<td>0.77±0.20</td>
<td>1</td>
<td>53.7</td>
<td>3.5</td>
</tr>
<tr>
<td>n → e^+\rho^-</td>
<td>0.87±0.26</td>
<td>4</td>
<td>1.2</td>
<td>0.03</td>
</tr>
<tr>
<td>n → \mu^+\rho^-</td>
<td>0.96±0.28</td>
<td>1</td>
<td>61.7</td>
<td>0.06</td>
</tr>
<tr>
<td>total</td>
<td>8.6</td>
<td>12</td>
<td>15.7</td>
<td>-</td>
</tr>
</tbody>
</table>

Phys. Rev. D in preparation (19 p.) ready to submit very soon!
\[ p \rightarrow e^+ \pi^0 \]
\[ n \rightarrow e^+ \pi^+ \]
\[ p \rightarrow \mu^+ \pi^0 \]
\[ n \rightarrow \mu^+ \pi^+ \]
\[ p \rightarrow \nu \pi^+ \]
\[ n \rightarrow \nu \pi^0 \]
\[ p \rightarrow e^+ \eta \]
\[ p \rightarrow \mu^+ \eta \]
\[ n \rightarrow \nu \eta \]
\[ p \rightarrow e^+ \rho^0 \]
\[ n \rightarrow e^+ \rho^- \]
\[ p \rightarrow \mu^+ \rho^0 \]
\[ n \rightarrow \mu^+ \rho^- \]
\[ p \rightarrow \nu \rho^+ \]
\[ n \rightarrow \nu \rho^0 \]
\[ p \rightarrow e^+ \omega \]
\[ p \rightarrow \mu^+ \omega \]
\[ n \rightarrow \nu \omega \]
\[ p \rightarrow e^+ K^0 \]
\[ n \rightarrow e^+ K^- \]
\[ n \rightarrow e^- K^+ \]
\[ p \rightarrow \mu^+ K^0 \]
\[ n \rightarrow \mu^+ K^- \]
\[ n \rightarrow \mu^ - K^+ \]
\[ p \rightarrow \nu K^+ \]
\[ n \rightarrow \nu K^0 \]
\[ p \rightarrow e^+ K^*_{(892)^0} \]
\[ p \rightarrow \nu K^*_{(892)^+} \]
\[ n \rightarrow \nu K^*_{(892)^0} \]

antilepton plus meson conserves (B-L)

non-strange mesons

strange mesons
Hyper-Kamiokande

Two tank – staging strategy
Each tank:
   260 kton total, 188 kton fiducial mass
   40000 50-cm high QE PMTs
   74 m $\phi$ x 60 m high
   1800 mwe overburden

Maximize detector performance – less mass than originally discussed
Proton decay signal (at SK limit)

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

\[ p \rightarrow K^+ \nu \] with \( \gamma \) tag
Tick tock protons!!!

Sensitivity curves by Hyper-K group (preliminary)
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<tbody>
<tr>
<td>ProtoDUNEes</td>
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<td>Cavern excavation</td>
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<td>Cryostat Construction</td>
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<td>Far Detector Installation</td>
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<tr>
<td>Far Detector commissioning</td>
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</table>
LAr Shines for Many Modes

- Modes with charged kaon in final state (SUSY)
- Modes with displaced vertices ⇒
- Multi-prong modes with no neutrino
- nnbar background rejection
  - No recoil proton allowed
  - No CC electron (or muon)
- Lepton + light meson likely no better than water due to nuclear absorption of the light meson.

\[ p \rightarrow \mu^+ K^0 \]
<table>
<thead>
<tr>
<th>Mode</th>
<th>Efficiency</th>
<th>BG Rate (/Mt y)</th>
<th>Efficiency</th>
<th>BG Rate (/Mt y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁺π⁰</td>
<td>38%</td>
<td>0.7</td>
<td>45%</td>
<td>1</td>
</tr>
<tr>
<td>ν K⁺</td>
<td>22.5%</td>
<td>1.6</td>
<td>97%</td>
<td>1</td>
</tr>
<tr>
<td>μ⁺ K⁰</td>
<td>10%</td>
<td>5-10</td>
<td>47%</td>
<td>&lt;2</td>
</tr>
<tr>
<td>μ⁻ π⁺ K⁺</td>
<td>?</td>
<td>?</td>
<td>97%</td>
<td>1</td>
</tr>
<tr>
<td>e⁻ K⁺</td>
<td>10%</td>
<td>3</td>
<td>96%</td>
<td>&lt;2</td>
</tr>
<tr>
<td>n n̄</td>
<td>12%</td>
<td>260</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Rough and unofficial
SK efficiency & BG
or from HK Design Report

Work underway
to reevaluate these for DUNE
Using full reconstruction
Progress in Event Reconstruction

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

See talk by A. Higuera, CoS SURF 2017
This color is at current SK limit

Nominal LArTPC
97% efficient
1 evt/Mt y

Super-K
17.5% efficient
2 evt/Mt y
(new! with neutron tag)

Work Underway to Understand Signal vs Background for LArTPC

A. Bueno et al. hep-ph/0701101
The decade ahead almost a decade from now

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Conclusions

- Testing Baryon Number Violation is an essential and high priority objective of particle physics.

- Proton decay experiments have been negative so far, and severely constraining of theory. But the ongoing searches are in potentially fruitful territory.

- We have hitched our star to a big neutrino program.

- $10^{35}$ by 2035 !!!! – still (barely) possible
Summary of Recent Exotic Searches

- Generally more than an order of magnitude improvement
- Some searches are entirely new
$p \rightarrow \nu K^+$

Kaon is below Cherenkov threshold. This is a search for kaon decay at rest.

![Diagram of the reaction $p \rightarrow \nu K^+$]

<table>
<thead>
<tr>
<th>$\gamma$-tag plus $\pi^+\pi^0$</th>
<th>SK1</th>
<th>(20% coverage) SK2</th>
<th>SK3</th>
<th>(new electronics) SK4 $\rightarrow$ w. n-cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>15.7 %</td>
<td>13.0 %</td>
<td>15.6 %</td>
<td>18.9 % $\rightarrow$ 17.5 %</td>
</tr>
<tr>
<td>Background rate (ev/100 kty)</td>
<td>0.28</td>
<td>0.63</td>
<td>0.38</td>
<td>0.4 $\rightarrow$ 0.19</td>
</tr>
</tbody>
</table>

No candidates, 306 kton yr (SK 1+2+3+4 w. n-cap):

$$\frac{\tau}{B} > 6.61 \times 10^{33} \text{ y}$$

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