Thanks to all the contributors

Searches for Baryon Number Violation in Neutrino Experiments: A White Paper


1 Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, Missouri 63130, USA
2 Department of Physics, University of Houston, Houston, Texas 77204, USA
3 University of California, Berkeley, Department of Physics, California 94720, Berkeley, USA
4 Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720-8153, USA
5 The Massachusetts Institute of Technology, Department of Physics, 77 Massachusetts Avenue, Building 4, Room 304, Cambridge, Massachusetts 02139, USA
6 Tel Aviv University, Tel Aviv 6997801, Israel
7 Argonne National Laboratory, Argonne, Illinois 60439, USA
8 Department of Physics, Boston University, Boston, MA 02215, USA
9 Department of Physics and Astronomy, University of California, Irvine, California 92697, USA
10 Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland
11 School of Physics and Astronomy, University of Minnesota, University of Minnesota 55455, USA
12 Department of Physics and Astronomy, University of California Davis, Davis, California 95616 USA
13 Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794, USA
14 RIKEN-BNL Research Center, Brookhaven National Lab, Upton, New York 11973, USA
15 School of Fundamental Physics and Mathematical Sciences, Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China
16 International Centre for Theoretical Physics Asia-Pacific, Beijing/Hangzhou, China
Overview

● This paper will summarize the experimental and theoretical aspects of baryon number violation searches performed in neutrino detectors.

● ~40 pages so far

● Topic overlap with RF04: Baryon and Lepton Number Violating Processes
  ○ Our understanding is that their whitepaper does not focus on experimental prospects

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Theoretical Motivation

- Baryon number is an accidental symmetry of the SM.
- Expected to be violated in many well-motivated BSM scenarios with *quark-lepton* symmetry, such as Pati-Salam, SU(5) and SO(10) GUTs.
- GUT scale is too high to be directly probed in the lab.
- **But there is a smoking gun signal:** proton decay.

- Historical context: Kamioka Nucleon Decay Experiment (Kamiokande).
- Kamiokande-II (SN1987A, solar neutrino deficit)
- Super-Kamiokande (neutrino oscillation)
- The most stringent bounds on proton decay also come from Super-K.

- **Goal of the whitepaper:** Illustrate the importance of experiments *simultaneously searching for BNV and studying neutrino properties.*
Proton Decay in GUTs

Non-SUSY: dimension-6 operator

SUSY: dimension-5 operator

Georgi, Glashow ‘74; Sakai, Yanagida ‘82; Weinberg ‘82; Babu, Mohapatra ‘93; Bajc, Senjanovic ‘06; Dev, Mohapatra ‘10; Dev, Dutta, Mohapatra, Severson ‘12; Dutta, Mimura, Mohapatra ‘13; Babu, Khan ‘15; Perez, Murgui ‘16; Ellis et al ‘19; Dorsner, Saad 20; … Recent review by Hisano, 2202.01404
Non-SUSY GUTs
SUSY GUTs

$p \rightarrow \bar{\nu} k^+$: Theory predictions

- Minimal SUSY SU(5)
- Super-K (ruled out)
- SUSY SU(5) [CMSSM: $c \neq 0$]
- SUSY SU(5) [super-GUT: $c = 0$]
- Mini-split SUSY SO(10)
- Extended SUSY SO(10) [type-I seesaw]
- Extended SUSY SO(10) [type-II seesaw]
- SUSY SO(10) x $U_{PQ}(1)$

Future projections:
- JUNO (10 yrs)
- Hyper-K (10 yrs)
- DUNE (10 yrs)
- JUNO (20 yrs)
- Hyper-K (20 yrs)
- DUNE (20 yrs)
Other BNV Processes

Mohapatra, Marshak (PRL '80); Pati, Salam, Sarkar (PLB '83)
Neutron-Antineutron Oscillation

Mohapatra, Marshak (PRL ‘80)
Upper Limit on n-nbar

Babu, Dev, Fortes, Mohapatra, 1303.6918
Expt lines drawn by J. Barrow
Connection to Other BSM Physics: Majorana Neutrinos

\[ p \rightarrow e^+ \pi^0 \]
\[ \Delta (B - L) = 0 \]

\[ n - \bar{n} \text{ oscillation} \]
\[ \Delta (B - L) = -2 \]

Neutrinoless double beta decay
Connection to Gravitational Waves

King, Pascoli, Turner, Zhou, 2106.15634
Lattice Developments

For n-nbar matrix elements,

<table>
<thead>
<tr>
<th>Operator</th>
<th>$\mathcal{M}^{\text{MS}}_{J_1}(2 \text{ GeV})$,</th>
<th>$\mathcal{M}^{\text{MS}}_{J_1}(700 \text{ TeV})$,</th>
<th>$\mathcal{M}^{\text{MS}}_{J_1}(2 \text{ GeV})$</th>
<th>$\mathcal{M}^{\text{MS}}_{J_1}(2 \text{ GeV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_1$</td>
<td>$-46(13) \times 10^{-5} \text{ GeV}^6$</td>
<td>$-26(7) \times 10^{-5} \text{ GeV}^6$</td>
<td>4.2</td>
<td>5.2</td>
</tr>
<tr>
<td>$Q_2$</td>
<td>$95(17) \times 10^{-5} \text{ GeV}^6$</td>
<td>$144(26) \times 10^{-5} \text{ GeV}^6$</td>
<td>7.5</td>
<td>8.7</td>
</tr>
<tr>
<td>$Q_3$</td>
<td>$-50(12) \times 10^{-5} \text{ GeV}^6$</td>
<td>$-47(11) \times 10^{-5} \text{ GeV}^6$</td>
<td>5.1</td>
<td>6.1</td>
</tr>
<tr>
<td>$Q_5$</td>
<td>$-1.06(48) \times 10^{-5} \text{ GeV}^6$</td>
<td>$-0.23(10) \times 10^{-5} \text{ GeV}^6$</td>
<td>-0.84</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Rinaldi et al, 1901.07519

Yoo et al, 2111.01608
Theory Summary

- Observation of BNV will be a clear signal of BSM physics.
- Synopsis of the expected nucleon lifetimes in a wide class of GUT models.
- Comparison with experimental projections.
- Importance of other BNV processes like n-nbar oscillation.
- Connection to other BSM physics: neutrino mass, baryogenesis, dark matter, gravitational waves, flavor physics.
- Lattice developments in the calculation of the hadronic form factors.

To-do list:
- Include lattice update for n-nbar
- Comment on other nucleon decay and di-nucleon decay modes
- Anything else missing?
Current and Future Experiments

Currently running experiments:

- Super-K: A bit on history, brief summary of published limits nucleon decay limits as well as neutron-antineutron transformation limit
- NOvA: Summary of NOvA analysis for neutron-antineutron transformation search

Planned and proposed detectors:

- Hyper-K: contribution expected soon
- DUNE: Brief summary of published sensitivities for nucleon decay ($p \rightarrow \bar{\nu}K$ and $n \rightarrow e^+K^+$) and neutron-antineutron transformations
- JUNO: Brief summary of $p \rightarrow \bar{\nu}K$ sensitivity analysis
- THEIA: Comparisons of sensitivities for Theia, Hyper-K, JUNO, DUNE, DUNE+Theia ($p \rightarrow \bar{\nu}K$ and $p \rightarrow e^+\pi^0$)

*Sections are in no particular order.*
Other Experimental Considerations (both DUNE-adjacent)

Effect of Different Nuclear Model Configurations on Sensitivity to Intranuclear Neutron-Antineutron Transformations

- Highlights the impact of nuclear model choices on calculated sensitivities
- Specific examples for DUNE, but generally relevant

LArTPC

- Considering the impact of the detection of nuclear de-excitation gammas and precise timing from photon detectors on nucleon decay sensitivities in LArTPCs
Experimental Summary

Anything missing? Ideas on what to emphasize? What is important to communicate to people outside the neutrino community on this topic?