Theories of Baryon and Lepton Number Violation

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Snowmass Community Planning Meeting
October 5 – 8, 2020
RF4 has actively organized several meetings on $B$ and $L$ Violation

Conveners: Pavel Fileviez Perez and Andrea Pocar

- **BLV circa 2020**
  
  https://artsci.case.edu/blv2020/timetable/

- **Prospects for $B$ Violation by 2 Units**
  
  https://indico.fnal.gov/event/44472/timetable/

- **Rare Processes and Precision Frontier Town Hall Meeting**
  
  https://indico.fnal.gov/event/45713/sessions/16419/

31 LOI submitted to $B$ & $L$ Violation Subgroup RF4
Plan

- $B$-Violation: Proton Decay $\Delta(B - L) = 0$
- $B$-Violation: $n - \bar{n}$ oscillations $\Delta(B - L) = -2$
- $L$-Violation: Neutrinoless double beta decay $\Delta(B - L) = -2$
- Connections with Baryon Asymmetry of the Universe
- Remarks on Collider Signals
Baryon Number Violation

- Baryon number postulated to be a symmetry of Nature to stabilize matter
  - Weyl (1929), Stuckelberg (1939), Wigner (1949)

- Unlike electric charge, which guarantees stability of electron, $B$ is not a fundamental symmetry

- Weak interactions violate $B$ non-perturbatively
  - 't Hooft (1977)

- Quantum gravity is suspected to violate all global symmetries including $B$

- $B$ violation essential to create baryon asymmetry of the Universe
  - Skaharov (1967)

- Most extensions of the Standard Model, notably quark-lepton unified theories and Grand Unified Theories, lead to $B$ violation
### Unification of Matter in $SO(10)$

16 members of a family fit nicely into a spinor of $SO(10)$

<table>
<thead>
<tr>
<th>$u_r$ : ${-+++-}$</th>
<th>$d_r$ : ${-+++-}$</th>
<th>$u^c_r$ : ${+-+-+}$</th>
<th>$d^c_r$ : ${+-+-+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_b$ : ${+-+-+-}$</td>
<td>$d_b$ : ${+-+-+-}$</td>
<td>$u^c_b$ : ${+-+-+-}$</td>
<td>$d^c_b$ : ${+-+-+-}$</td>
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<tr>
<td>$u_g$ : ${++-+-}$</td>
<td>$d_g$ : ${++-+-}$</td>
<td>$u^c_g$ : ${++-+-}$</td>
<td>$d^c_g$ : ${++-+-}$</td>
</tr>
<tr>
<td>$v$ : ${-+-+-}$</td>
<td>$e$ : ${-+-+-}$</td>
<td>$v^c$ : ${+++-+}$</td>
<td>$e^c$ : ${+++-+}$</td>
</tr>
</tbody>
</table>

First 3 spins refer to color, last two are weak spins

\[
Y = \frac{1}{3} \Sigma(C) - \frac{1}{2} \Sigma(W)
\]

- Pati, Salam (1974) – Quark-lepton unification
- Georgi, Glashow (1974) – $SU(5)$ unification
- Georgi (1975); Fritzsch, Minkowski (1975) – $SO(10)$ unification
- Georgi, Quinn, Weinberg (1974) – Gauge coupling unification
Unification of gauge couplings

![Diagrams showing the unification of gauge couplings in Standard Model (SM) and MSSM.](image)
Without SUSY, SO(10) can break to SM via intermediate chains.
Intermediate Pati-Salam symmetry

\[ \alpha_{1Y}^{-1}, \alpha_{2L}^{-1}, \alpha_{3c}^{-1}, \alpha_{2L/R}^{-1}, \alpha_{4c}^{-1} \]

- \( 54_H \) breaking of \( SO(10) \) to \( SU(4)_c \times SU(2)_L \times SU(2)_R \times P \)
Pati-Salam symmetry without Parity

\[ 210_H \text{ breaking of } SO(10) \text{ to } SU(4)_c \times SU(2)_L \times SU(2)_R \]
Gauge coupling evolution with threshold

\[ p \rightarrow e^+ \pi^0 \text{ lifetime } \leq 2 \times 10^{35} \text{ yrs.} \]
Proton Decay in GUTs

- Mediated by super-heavy X and Y gauge bosons of GUT
- Effective operator has dimension 6:

\[ \mathcal{L}_{\text{eff}} = \frac{g^2}{2M_X^2}(\bar{u}^c \gamma_\mu u)(\bar{e}^c \gamma^\mu d) \]

- Leads to \( p \rightarrow e^+ \pi^0 \) decay
Proton Decay in GUTs (cont.)

\[ \tau_p < 2 \times 10^{35} \text{ yrs.} \]

\[ \Gamma^{-1}(p \rightarrow e^+ \pi^0) \approx (8.2 \times 10^{34} \text{ yr}) \times \left( \frac{\alpha_H}{0.0122 \text{ GeV}^3} \right)^{-2} \left( \frac{\alpha_G}{1/34.7} \right)^{-2} \left( \frac{A_R}{3.35} \right)^{-2} \left( \frac{M_X}{10^{16} \text{ GeV}} \right)^4 \]
Proton Decay in SUSY GUTs

- New decays open up, mediated by color triplet Higgsino
- Decay rate depends on SUSY particle masses
- Dominant decay is $p \rightarrow \bar{\nu} K^+$
- For TeV scale SUSY scalars, $\tau \approx 10^{32} \text{ yrs.}$
Proton Decay in SUSY SU(5)

\[ \tau(p \rightarrow \bar{p} K^+) \] (years)

\[ m_{0,1,2} \text{ (TeV)} \]

Winberg, Sakai, Yanagida, Murayama, Hisano, Yanagida, Perez, Nath Gogoladze, Un, KB (2020), Ellis et.al. (2019)
Neutron-Antineutron Oscillation

- Neutron can oscillate into anti-neutron ($\Delta B = -2$ process)
- Probes energy scale of $10^6$ GeV: Complementary to proton decay
- $B$ violation with $\Delta B = -2$ can generate baryon asymmetry of the universe at low energy scale $\ n - \bar{n} \leftrightarrow B$ asymmetry
- Time evolution of $n - \bar{n}$ system governed by:

$$\mathcal{M}_B = \begin{pmatrix} m_n - \overline{\mu}_n \cdot \vec{B} - i\lambda/2 & \delta m \\ \delta m & m_n + \overline{\mu}_n \cdot \vec{B} - i\lambda/2 \end{pmatrix}$$

Here $1/\lambda = \tau_n = 880$ sec., $m_n$ is neutron mass.

$$\mathcal{L} = m_n \bar{n} n + \frac{\delta m}{2} n^T C n$$

$\delta m$ violates $B$ by 2 units. ($\delta m = 0$ in standard model)
- Discovery of $n - \bar{n}$ oscillations would prove violation of baryon number
$n \rightarrow \bar{n}$ Oscillation Phenomenology

- $n \rightarrow \bar{n}$ transition probability:
  
  $$P(n \rightarrow \bar{n}) = \sin^2(2\theta) \sin^2(\Delta E t/2) e^{-\lambda t}$$

  $$\Delta E \simeq 2|\vec{\mu}_n.\vec{B}|$$, \hspace{1em} \tan(2\theta) = -\frac{\delta m}{\vec{\mu}_n.\vec{B}}$$

- Quasifree condition holds:
  
  $$|\vec{\mu}_n.\vec{B}| t \ll 1$$

  $$P(n \rightarrow \bar{n}) \simeq [(\delta m) t]^2 = [t/\tau_{n-\bar{n}}]^2$$

- Number of $\bar{n}$ created after time $t$ is
  
  $$N_{\bar{n}} = P(n \rightarrow \bar{n}) N_n \simeq \phi T_{\text{run}} [t/\tau_{n-\bar{n}}]^2$$

- Best limit on free neutron oscillation: $\tau_{n-\bar{n}} > 8.6 \times 10^7$ sec.
  Baldo-ceolin et. al., ILL (1994)
\( n - \bar{n} \) Oscillation Phenomenology (cont.)

- \( n - \bar{n} \) transition can occur in nuclei. However, energy difference is of order 30 MeV, suppressing oscillation by a large factor:

\[
\tau_{Nuc} = R\tau_{n\bar{n}}^2, \quad R \simeq 5 \times 10^{22} \text{sec}^{-1}
\]

Chetyrkin et. al (1981); Dover, Gal, Richards (1995); Kopeliovich et. al. (2012),...

- Best limit from SuperK: \( \tau_{n\bar{n}} > 3.5 \times 10^8 \text{ sec} \).

\( \Rightarrow \delta m < 10^{-23} \text{ eV} \)

- For free neutron oscillations degaussing of earth’s magnetic field to level nano-Tesla required for improved determination
Models of $n - \bar{n}$ oscillations

- Effective $\Delta B = 2$ operator that mediates neutron oscillation is:

$$\mathcal{L}_{\text{eff}} = \frac{(udd)^2}{\Lambda^5}$$

- High dimension implies oscillations probe scale of $\Lambda \sim 10^6$ GeV
- This operator naturally arises in quark-lepton unified theories based on $SU(2)_L \times SU(2)_R \times SU(4)_C$ as partners of seesaw mechanism for neutrinos. Mohapatra, Marshak (1980)
- $\Delta$ fields are color sextet scalars, which do not mediate proton decay. $\mathcal{L}_{\text{eff}} = (\lambda f^3 v_{BL})/M^6$
The quark level Lagrangian needs to be converted to nucleon level $\delta m$

MIT bag model calculations showed $\delta m \simeq \Lambda_{QCD}^6/\Lambda^5$ with $\Lambda_{QCD} \simeq 200$ MeV Shrock-Rao (1982)

Recent lattice calculations show enhancement of oscillation probability by an order of magnitude Rinaldi et. al. (2018)

For $n - \bar{n}$ transition in nuclei, nuclear physics calculations have been improving Friedman, Gal (2008)
Post-Sphaleron Baryogenesis

• A scalar ($S$) or a pseudoscalar ($\eta$) decays to baryons, violating $B$

• $\Delta B = 1$ is strongly constrained by proton decay and cannot lead to successful post-sphaleron baryogenesis

• $\Delta B = 2$ decay of $S/\eta$ can generate baryon asymmetry below $T = 100$ GeV: $S/\eta \rightarrow 6 q; \quad S/\eta \rightarrow 6 \bar{q}$

• Decay violates CP, and occurs out of equilibrium

• Naturally realized in quark-lepton unified models, with $S/\eta$ identified as the Higgs boson of $B - L$ breaking

• $\Delta B = 2 \Rightarrow$ connection with $n - \bar{n}$ oscillation

• Quantitative relationship exists in quark-lepton unified models based on $SU(2)_L \times SU(2)_R \times SU(4)_C$
At $T = T_d$, scalar starts decaying: $200 \text{ MeV} < T_d < 100 \text{ GeV}$
Prediction for $n - \bar{n}$ oscillation

In a specific quark-lepton symmetric model Dev, Fortes, Mohapatra, Babu (2013)

Figure: The likelihood probability for a particular value of $\tau_{n-\bar{n}}$ as given by the model parameters.
EFT for $n - \bar{n}$ oscillations and baryogenesis

- Recently Grojean, Shakya, Wells, Zhang (2018) have proposed a minimal EFT for baryogenesis.
- They assume two couplings: $uddX_1$ and $uddX_2$ where $X_i$ are singlet Majorana fermions.
- This is sufficient to induce baryon asymmetry.
Other models of $n - \bar{n}$ oscillations

- Supersymmetry with R-parity violation Goity, Sher (1995); Mohapatra, Babu (2001); Csaki, Grossman, Heidenreinich (2012),...
- GUT with TeV-scale colored scalars Mohapatra, Babu (2012); Aswathi, Parida, Sahu (2014),...
- Flavor geography with TeV scale $B$ violation Nussinov, Shrock (2002); Winslow, Ng (2010); Dvali, Gabadadze
- TeV scale $B$ violating theories (Arnold, Fornal, Perez, Wise, Gu, Sarkar,...)
Neutrinoless double beta decay

- Double beta decay without neutrinos violates $L$ by two units
- Discovery would establish neutrinos to be Majorana particle
- Would suggest leptogenesis as a source of baryon asymmetry
- Most studied mechanism is light Majorana neutrino mass $m_{\beta\beta0\nu}$

$$m_{\beta\beta0\nu} = \left| \sum_i U_{ei}^2 m_i \right|$$

- Inverted neutrino hierarchy gives larger contributions
- Normal mass hierarchy would require very high sensitivity (kiloton) experiments
Neutrinoless double beta decay via $m_\nu$

- Currently lightest neutrino mass is unknown
- Mass ordering is also unknown
- Whether neutrino is Majorana or Dirac particle is unknown

![Diagram showing the mass hierarchy for neutrinoless double beta decay](image)
Introduction

- Very sensitive probe of lepton number violation
- Stringently constrained experimentally

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<tr>
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<th>$T^{0\nu}_{1/2}(^{76}\text{Ge})$</th>
<th>$T^{0\nu}_{1/2}(^{130}\text{Te})$</th>
<th>$T^{0\nu}_{1/2}(^{136}\text{Xe})$</th>
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<tr>
<td>$\geq 9 \cdot 10^{25}$ yr</td>
<td>$&gt; 3.2 \cdot 10^{25}$ yr</td>
<td>$&gt; 1.1 \cdot 10^{26}$ yr</td>
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- To be improved by 1-2 orders

Measurement would tell us:

- There’s physics beyond the SM
- Neutrinos are Majorana particles

Have implications for

- Neutrino mass mechanism
- Leptogenesis

Not which LNV source is responsible

- Many possible mechanisms:

Schechter, Valle, `82

From Wouter Dekens
Complementarity with collider physis

- TeV scale new physics can contribute to $\beta\beta 0\nu$
- In this case, new particles may be searched for at colliders
- Same-sign dilepton signal from heavy right-handed neutrino of left-right symmetric models: (Keung, Senjanovic)
Summary

- Proton decay discovery would be monumental, and will strongly support grand unification.

- Neutron-antineutron oscillations have very high potential to probe fundamental physics to an intermediate scale, and may be related to baryon asymmetry of the universe.

- Neutrinoless double beta decay discovery would establish the Majorana nature of neutrino, and will support leptogenesis mechanism.