# Theories of Baryon and Lepton Number Violation


**K.S. Babu**

Oklahoma State University


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 $SO(10)$

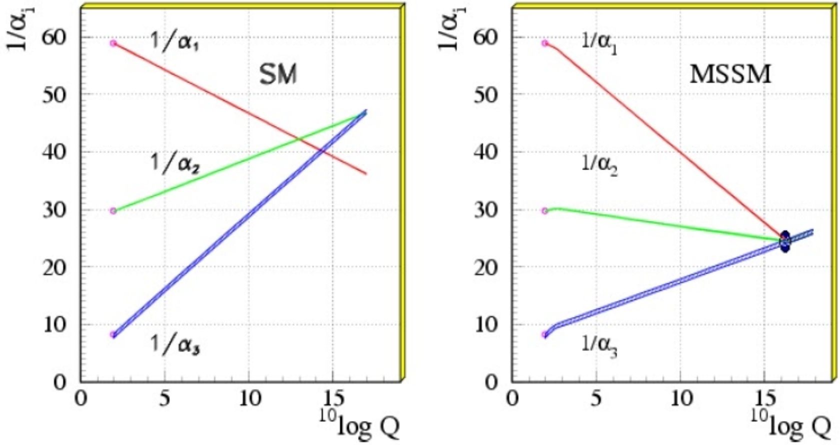
| | | | |
|---|---|---|---|
| $u_r : \{-++\ +-\}$ | $d_r : \{-++\ -+\}$ | $u_r^c : \{+--\ ++\}$ | $d_r^c : \{+--\ --\}$ |
| $u_b : \{+-+\ +-\}$ | $d_b : \{+-+\ -+\}$ | $u_b^c : \{-+-\ ++\}$ | $d_b^c : \{-+-\ --\}$ |
| $u_g : \{++-\ +-\}$ | $d_g : \{++-\ -+\}$ | $u_g^c : \{--+\ ++\}$ | $d_g^c : \{--+\ --\}$ |
| $\nu : \{---\ +-\}$ | $e : \{---\ -+\}$ | $\nu^c : \{+++\ ++\}$ | $e^c : \{+++\ --\}$ |

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

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

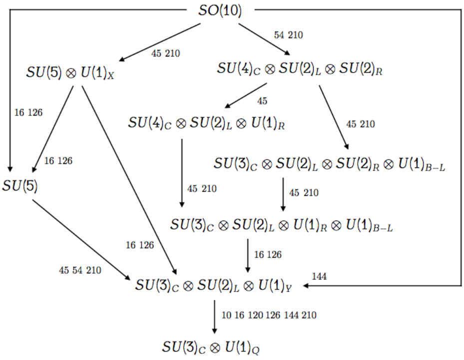
Pati, Salam (1974) – Quark-lepton unification
Georgi, Glashow (1974) – $SU(5)$ unification
Georgi (1975); Fritzsch, Minkowski (1975) – $SO(10)$ unification
Georgi, Quinn, Weinberg (1974) – Gauge coupling unification

# Unification of gauge couplings

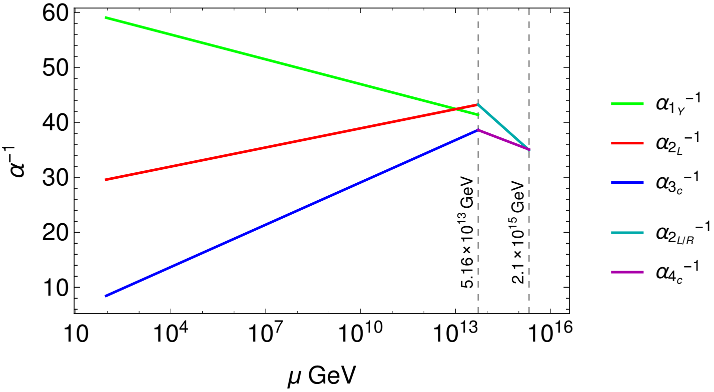


# Gauge coupling unification without SUSY

- Without SUSY $SO(10)$ can break to SM via intermediate chains

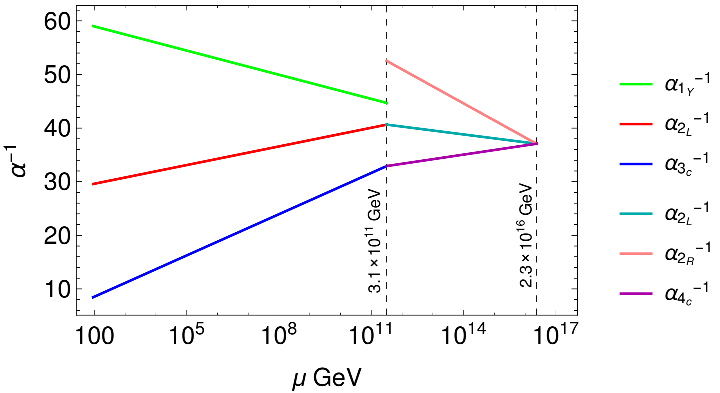


# Intermediate Pati-Salam symmetry



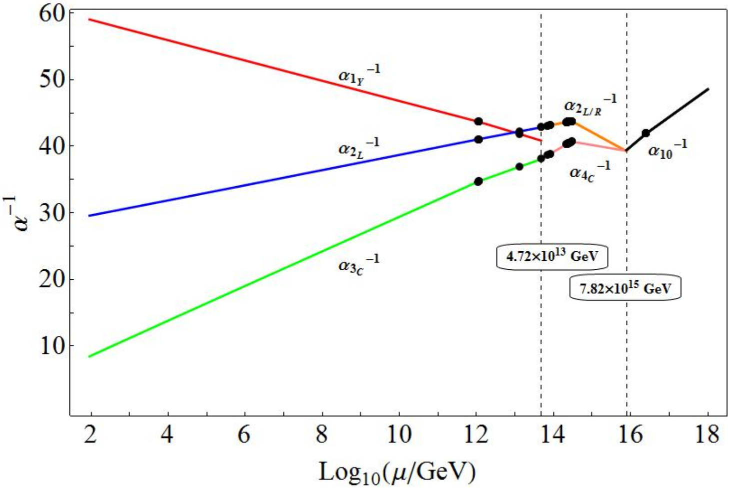

- $54_H$ breaking of $SO(10)$ to $SU(4)_c \times SU(2)_L \times SU(2)_R \times P$

# Pati-Salam symmetry without Parity




$210_H$ breaking of $SO(10)$ to $SU(4)_c \times SU(2)_L \times SU(2)_R$

# Gauge coupling evolution with threshold




- $p \to e^+\pi^0$ lifetime $\leq 2 \times 10^{35}$ yrs.

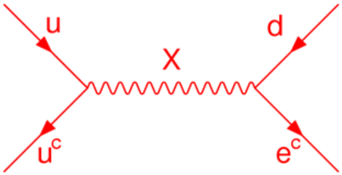
Babu, Khan (2015)

# Proton Decay in GUTs

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

$$\mathcal{L}_{\rm eff} = \frac{g^2}{2M_X^2}(\overline{u^c}\gamma_\mu u)(\overline{e^c}\gamma^\mu d)$$

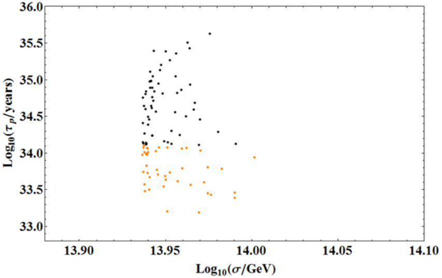
- Leads to $p \to e^+\pi^0$ decay



# Proton Decay in GUTs (cont.)

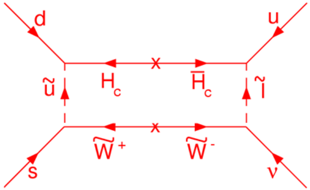
$$\tau_p < 2 \times 10^{35} \text{ yrs.}$$

$$\Gamma^{-1}(p \to e^+\pi^0) \approx (8.2 \times 10^{34} \text{ yr}) \times \left(\frac{\alpha_H}{0.0122 \text{ GeV}^3}\right)^{-2} \left(\frac{\alpha_G}{1/34.7}\right)^{-2} \left(\frac{A_R}{3.35}\right)^{-2} \left(\frac{M_X}{10^{16} \text{ GeV}}\right)^{4}$$

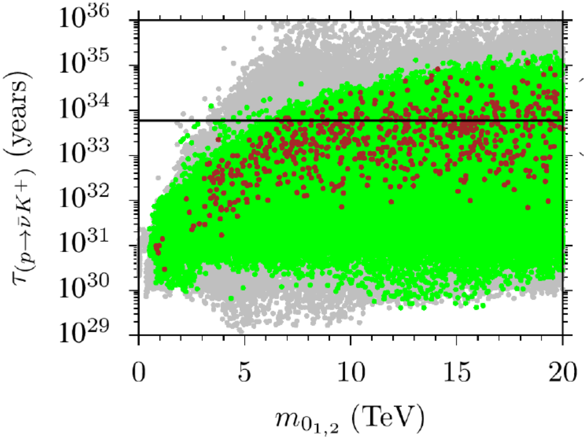


# Proton Decay in SUSY GUTs

- New decays open up, mediated by color triplet Higgsino
- Decay rate depends on SUSY particle masses
- Dominant decay is $p \to \overline{\nu} K^{+}$
- For TeV scale SUSY scalars, $\tau \approx 10^{32}$ yrs.



# Proton Decay in SUSY SU(5)




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:

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

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

# $n - \bar{n}$ Oscillation Phenomenology

- $n \to \bar{n}$ transition probability:

$$P(n \to \bar{n}) = \sin^2(2\theta)\sin^2(\Delta E t/2)e^{-\lambda t}$$
$$\Delta E \simeq 2|\vec{\mu_n}.\vec{B}|, \quad \tan(2\theta) = -\frac{\delta m}{\vec{\mu_n}.\vec{B}}$$

- Quasifree condition holds:

$$|\vec{\mu_n}.\vec{B}|t << 1$$

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

- Number of $\bar{n}$ created after time $t$ is

$$N_{\bar{n}} = P(n \to \bar{n})N_n \simeq \phi T_{\rm run}[t/\tau_{n-\bar{n}}]^2$$

- 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:

$$\tau_{Nuc} = R\tau^2_{n\bar{n}}, \quad R \simeq 5 \times 10^{22}\,\mathrm{sec}^{-1}$$

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

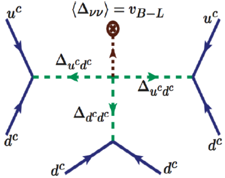
- Best limit from SuperK: $\tau_{n\bar{n}} > 3.5 \times 10^8$ sec.
- $\Rightarrow \delta m < 10^{-23}$ eV
- For free neutron oscillations degaussing of earth's magnetic field to level nano-Tesla required for improved determination

# Models of $n - \bar{n}$ oscillations

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

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

- 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. $\mathcal{L}_{\rm eff} = (\lambda f^3 v_{BL})/M^6$



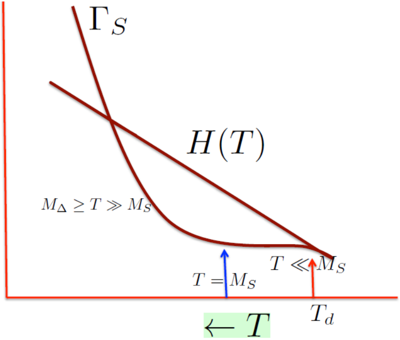
# From quarks to nucleons

- The quark level Lagrangian needs to be converted to nucleon level $\delta m$
- MIT bag model calculations showed $\delta m \simeq \Lambda^6_{QCD}/\Lambda^5$ 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: $S/\eta \to 6\,q; \quad S/\eta \to 6\,\overline{q}$
- 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 $n - \overline{n}$ oscillation
- Quantitative relationship exists in quark-lepton unified models based on $SU(2)_L \times SU(2)_R \times SU(4)_C$

# Thermal history of scalar decay




At $T = T_d$, scalar starts decaying: $200\ \mathrm{MeV} < T_d < 100$ GeV

# Prediction for $n - \bar{n}$ oscillation

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

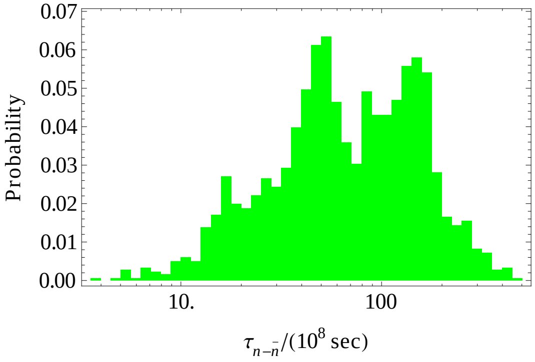
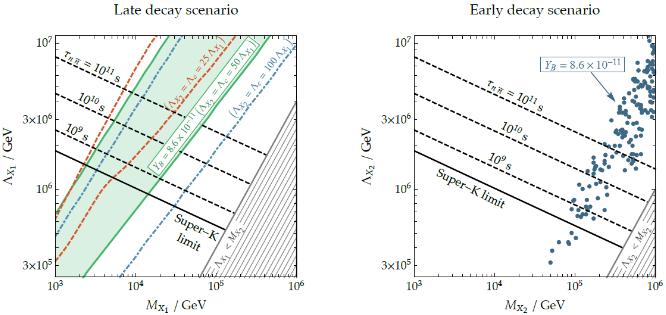



Figure: The likelihood probability for a particular value of $\tau_{n-\bar{n}}$ as given by the model parameters.

# 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

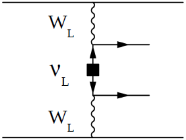
- Supersymmetry with R-parity violation Goity, Sher (1995); Mohapatra, Babu (2001); Csaki, Grossman, Heidenreinch (2012),...
- GUT with TeV-scale colored scalars Mohapatra, Babu (2012); Aswathi, Parida, Sahu (2014),...
- Flavor geography with TeV scale $B$ violation Nussinov, Shrock (2002); Winslow, 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 $m_{\beta\beta 0\nu}$

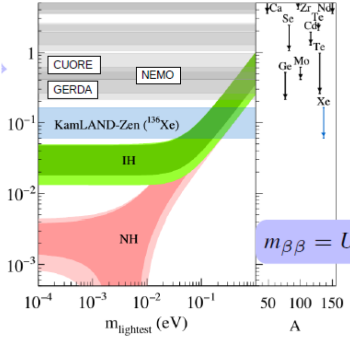
$$m_{\beta\beta 0\nu} = \left| \sum_i U_{ei}^2 m_i \right|$$

- 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

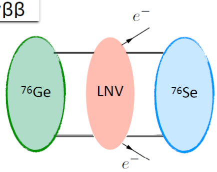



$m_{\beta\beta} = U_{ei}^2 m_i$

# Introduction



## 0νββ




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

| $T^{0\nu}_{1/2}(^{76}\mathrm{Ge})$ | $T^{0\nu}_{1/2}(^{130}\mathrm{Te})$ | $T^{0\nu}_{1/2}(^{136}\mathrm{Xe})$ |
|---|---|---|
| $> 9 \cdot 10^{25}$ yr | $> 3.2 \cdot 10^{25}$ yr | $> 1.1 \cdot 10^{26}$ yr |

- To be improved by 1-2 orders

### Measurement would tell us:

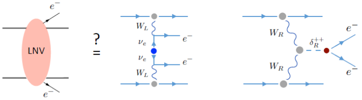
- There's physics beyond the SM
- Neutrinos are Majorana particles

Have implications for

- Neutrino mass mechanism
- Leptogenesis

### Not which LNV source is responsible

- Many possible mechanisms:




Light $\nu_L$?   Left-Right model?

- Hard to disentangle using 0νββ alone

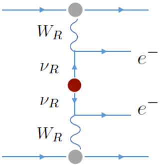
Schechter, Valle, `82

From Wouter Dekens

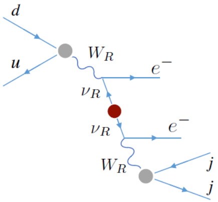
# Complementarity with collider physis

- 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)

0νββ




Collider



# 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.