A Simple Model for Low Scale Baryogenesis and Neutron-Antineutron Oscillation

BHUPAL DEV

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talk based on

BD and R. N. Mohapatra, Phys. Rev. D **92**, 016007 (2015)
[arXiv:1504.07196 [hep-ph]]

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B Violation

- An essential ingredient for successful baryogenesis. [Sakharov (1967)]
- Some pertinent questions in effective field theories of $\not{B}$:
  - Selection rules for ΔB?
  - Scale of B-violation?
  - Experimental tests?
- $\Delta B = 1 \Longrightarrow$ proton decay.
- Induced by either dim-5 or dim-6 operators.
- $\tau_p \gtrsim 10^{34}$ yr implies $\Lambda \gtrsim 10^{15}$ GeV.
- $\Delta B = 2 \Longrightarrow n - \bar{n}$ oscillation and di-nucleon decay.
- Dim-9 operator, so amplitude $\propto \Lambda^{-5}$.
- $\Lambda \gtrsim$ few TeV is enough to satisfy the existing constraints.

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Highlights of the Talk

- A simple model with TeV-scale $\Delta B = 2$.
- A concrete low-scale baryogenesis mechanism.
- Testable predictions for $n - \bar{n}$ oscillation.
- Explains neutrino mass by a radiative mechanism.
- Stability of the proton is connected to small neutrino mass.
- Testable consequences at the LHC.

Ingredients

- Work within the SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$.
- Extend the particle content by adding
  - At least two singlet fermions, to serve as RH neutrinos (N_a).
  - A second Higgs doublet (η).
  - A color-triplet scalar (χ) with $Y = +4/3$.
- Impose an additional Z_2-symmetry:

Fields	Z_2 charge
Q, u_R, d_R, N, η	$-$
L, e_R, ϕ, χ	$+$

- The relevant part of the Yukawa Lagrangian is

$$\mathcal{L}_Y = h_{\nu,ai}\overline{N}_a \eta L_i + \frac{1}{2} M_{ab} N_a^{\mathsf{T}} C^{-1} N_b + \lambda_{aj}\overline{N}_a \overline{\chi}_\alpha u_{R,\alpha j} + \lambda'_{ij}\epsilon^{\alpha\beta\gamma}\chi_\alpha d_{R,\beta i} d_{R,\gamma j} + \text{H.c.}$$

- The Majorana mass term breaks both B and L by two units.

Constraints on λ and λ'

- Let us assume $M_\chi \sim 10$ TeV and $M_N \sim 1$ TeV as a benchmark.
- Constraints on the λ' couplings from FCNC:

$$K_L - K_S : \lambda'_{13}\lambda'_{23} \lesssim 10^{-3/2}$$
$$B_d - \overline{B}_d : |\lambda'_{32}\lambda'_{12}| \lesssim 10^{-1}$$
$$B_s - \overline{B}_s : |\lambda'_{31}\lambda'_{12}| \lesssim 10^{-1}$$

- Conservative FCNC limits: $\lambda'_{12}, \lambda'_{32} \leq 10^{-2}$ which leaves λ'_{13} unconstrained.
- Constraints from di-nucleon decay $pp \to KK$: $\lambda'_{12}\lambda_{a1} \lesssim 10^{-4}$.
- Can choose $\lambda'_{12} \leq 10^{-4}$, while keeping λ_{a1} unconstrained.
- Single proton decay due to $(udd)l$ operator is forbidden by Z_2 symmetry.
- Same Z_2 symmetry also forbids the Dirac neutrino mass term $\overline{L}\phi N$.

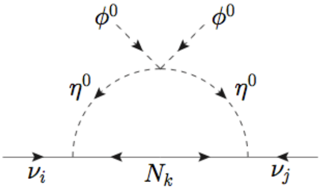
Neutrino Mass

- Higgs potential: [Ma, Phys. Rev. D **73**, 077301 (2006)]

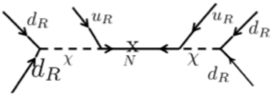
$$V(\phi,\eta) = -m_1^2|\phi|^2 + m_2^2|\eta|^2 + \lambda_1|\phi|^4 + \lambda_2|\eta|^4 + \lambda_3|\phi|^2|\eta|^2 + \lambda_4|\phi^\dagger\eta|^2 + \left[\frac{\lambda_5}{2}(\phi^\dagger\eta)^2 + \mathrm{H.c.}\right],$$

  where $\langle\phi^0\rangle = v_{\rm wk} \equiv 174$ GeV and $\langle\eta\rangle = 0$.
- One-loop neutrino mass:

$$(\mathcal{M}_\nu)_{ij} \simeq \frac{\lambda_5 v_{\rm wk}^2}{8\pi^2 M_\eta^2} h_{\nu,ai} h_{\nu,aj} M_a$$



$n - \bar{n}$ Oscillation



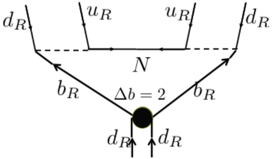
- The starting effective $\not{B}$ operator is $N_a u_R d_R d_R$.

  [Babu, Mohapatra and Nasri, Phys. Rev. Lett. **98**, 161301 (2007)]

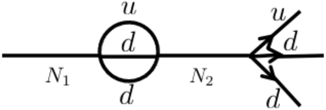
$$\mathcal{L}_I = \frac{\lambda_{ai}\lambda'_{jk}}{M_\chi^2} N_a u_{R,i} d_{R,j} d_{R,k} + \text{H.c.}$$

- Due to color-antisymmetry, only $j \neq k$ terms are non-zero.
- Induces $n - \bar{n}$ oscillation at one-loop.

$$G_{n-\bar{n}} \simeq \frac{(\lambda_{a1}\lambda'_{13})^2 M_{N_a}}{16\pi^2 M_\chi^4 \Lambda^2} \ln\left(\frac{\Lambda^2}{M_N^2}\right) .$$

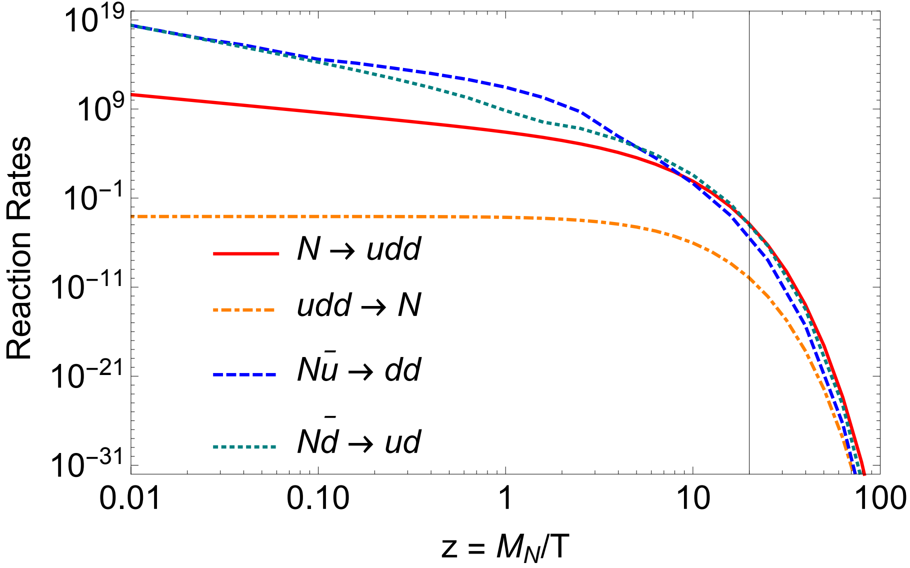


Baryogenesis



- Interference of tree- and loop-contributions to $N \to u_R d_R d_R$ mediated by χ.
- In quasi-degenerate limit, dominant self-energy contribution to CP-asymmetry. [Flanz, Paschos and Sarkar, Phys. Lett. B**345**, 248 (1995); Covi, Roulet and Vissani, Phys. Lett. B**384**, 169 (1996); Pilaftsis, Phys. Rev. D **56**, 5431 (1997)]
- Resonant baryogenesis mechanism, similar to resonant leptogenesis [Pilaftsis and Underwood, Nucl. Phys. B **692**, 303 (2004)].
- Does not rely on sphaleron processes.
- Can realize both high- and low-scale baryogenesis.
- A concrete model of post-sphaleron baryogenesis. [Babu, Mohapatra and Nasri, Phys. Rev. Lett. **97**, 131301 (2006); Babu, BD and Mohapatra, Phys. Rev. D **79**, 015017 (2009); Babu, BD, Fortes and Mohapatra, Phys. Rev. D **87**, 115019 (2013)]

Reaction Rates

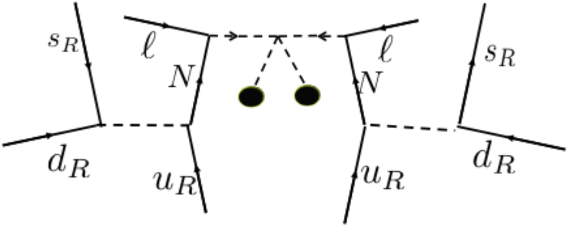


Conclusion and Outlook

- Presented a simple model for TeV-scale B violation.
- Allows successful low-scale baryogenesis.
- The stability of proton is linked to the smallness of neutrino masses.
- Only allows $\Delta B = 2$ processes.
- Predicts $n - \bar{n}$ oscillation lifetime $\tau_{n-\bar{n}} \sim 10^{10}$ sec within reach of next-generation experiments.
- Also testable via di-nucleon decays such as $pp \to KK$.
- Collider signals:

$$pp \to \bar{q}N \to 4j$$
$$pp \to \eta^+\eta^- \to \ell^+\ell^- N_1 N_2 \to \ell^+\ell^- + 4j + 2b$$

Di-nucleon Decay



CP Asymmetry and Reaction Rates

$$\varepsilon \simeq \frac{3}{512\pi^3} \frac{\sum_{i,j,k} \mathrm{Im}[\lambda_{1i}\lambda'_{jk}\lambda^*_{2i}\lambda'^*_{jk}]}{\sum_{i,j,k}(|\lambda_{1i}\lambda'_{jk}|^2 + |\lambda_{2i}\lambda'_{jk}|^2)} \frac{M_N^6(M_{N_1}^2 - M_{N_2}^2)}{M_\chi^4[(M_{N_1}^2 - M_{N_2}^2)^2 + M_N^2\Gamma_N^2]} ,$$

$$\Gamma_{N_a} = \frac{3}{256\pi^3} \frac{\sum_{i,j,k} |\lambda_{ai}\lambda'^*_{jk}|^2}{M_{N_a}^3} \int_0^{M_{N_a}^2} ds \frac{M_{N_a}^6 - 3M_{N_a}^2 s^2 + 2s^3}{(s - M_\chi^2)^2 + M_\chi^2\Gamma_\chi^2}$$

$$\simeq \frac{3}{512\pi^3} \frac{\sum_{i,j,k} |\lambda_{ai}\lambda'^*_{jk}|^2 M_{N_a}^5}{M_\chi^4}$$

$$\gamma_D = \frac{M_N^3}{\pi^2 z}\Gamma_N K_1(z) ,$$

$$\gamma_S = \frac{M_N^4}{64\pi^4 z}\int_1^\infty dx\sqrt{x}K_1(z\sqrt{x})\hat{\sigma}(x) ,$$

where

$$\hat{\sigma}(s) = \frac{3\sum_{i,j,k} |\lambda_{ai}\lambda'^*_{jk}|^2 (M_{N_a}^2 - s)^2(M_{N_a}^2 + 2s)}{4\pi s[(s - M_\chi^2)^2 + M_\chi^2\Gamma_\chi^2]} .$$

Boltzmann Equations

$$\frac{d\eta_{N_a}}{dz} = -\left(\frac{\eta_{N_a}}{\eta_{N_a}^{\rm eq}} - 1\right)(D_a + S_a),$$
$$\frac{d\eta_B}{dz} = \sum_a \left(\frac{\eta_{N_a}}{\eta_{N_a}^{\rm eq}} - 1\right)\varepsilon D_a - \eta_B \sum_a S_a\,,$$

In the strong washout regime,

$$\frac{d\eta_B}{dz} = \frac{1}{2\zeta(3)} z^2 K_1(z) \sum_a \varepsilon \frac{D_a}{D_a + S_a} - \eta_B \sum_a S_a\,.$$

Successful baryogenesis $\eta_B(T_0) \sim 6 \times 10^{-10}$ possible with $M_N \sim 1$ TeV and $M_\chi \sim 10$ TeV.