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

BHUPAL DEV

The University of Manchester & Technische Universität München

talk based on

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

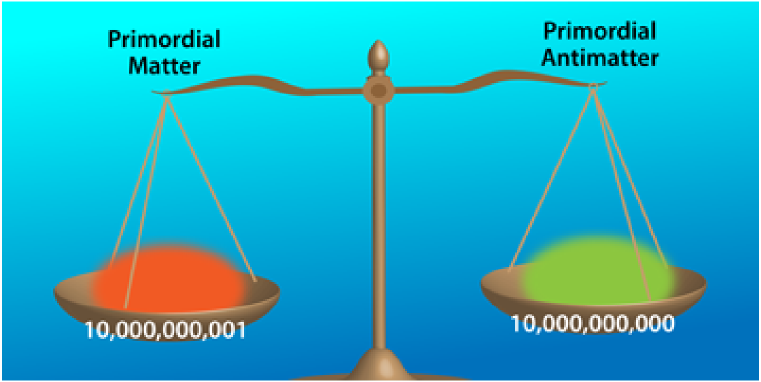
Université libre de Bruxelles
Brussels, Belgium

The University of Manchester

October 2, 2015

Matter-Antimatter Asymmetry

$$\eta^{\Delta B} \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = \left(6.105^{+0.086}_{-0.081}\right) \times 10^{-10} \qquad \text{[Planck (2015)]}$$



Baryogenesis

- Dynamical generation of baryon asymmetry.
- Basic **Sakharov conditions:** [Sakharov '67]
  - B violation: There must exist $X(B=0) \to Y_1(B=0) + Y_2(B \neq 0)$.
  - C *and* CP violation.
    Otherwise, $\Gamma(X \to Y_1 + Y_2) = \Gamma(\bar{X} \to \bar{Y}_1 + \bar{Y}_2) \Longrightarrow$ No net effect!
  - Out-of-equilibrium dynamics.
    Otherwise, $\Gamma(X \to Y_1 + Y_2) = \Gamma(Y_1 + Y_2 \to X) \Longrightarrow$ No net effect!
- Necessary but not sufficient.

$+$

$\neq$

Baryogenesis in the SM and beyond

- Standard Model has all the ingredients!
  - B violation through non-perturbative effects.
  - Maximal C violation due to weak interactions.
  - CP violation in the quark sector due to the CKM phase.
  - Departure from thermal equilibrium at the electroweak phase transition.
- But
  - CKM CP violation is too small.
  - No strong first-order phase transition.
- **Requires some New Physics**:
  - New sources of CP violation.
  - A departure from equilibrium (in addition to EWPT) or modify the EWPT itself.
  - May be new sources of B or L violation?

Baryogenesis in the SM and beyond

- Standard Model has all the ingredients!
  - B violation through non-perturbative effects.
  - Maximal C violation due to weak interactions.
  - CP violation in the quark sector due to the CKM phase.
  - Departure from thermal equilibrium at the electroweak phase transition.
- But
  - CKM CP violation is too small.
  - No strong first-order phase transition.
- **Requires some New Physics**:
  - New sources of CP violation.
  - A departure from equilibrium (in addition to EWPT) or modify the EWPT itself.
  - May be new sources of B or L violation?

Motivations

- Numerous models of baryogenesis, some of which are testable in foreseeable laboratory experiments.
- Examples:
  - Electroweak baryogenesis: baryon creation in the EWPT.
  - Leptogenesis: baryon asymmetry from lepton asymmetry.
  - Other recent ideas involving dark matter, such as WIMPy baryogenesis and Asymmetric DM.
- MSSM EW baryogenesis is severely constrained.
- Vanilla leptogenesis requires an energy scale $> 10^9$ GeV $\Longrightarrow$ problems with naturalness and gravitino bound.
- Resonant leptogenesis might be testable, but requires some fine-tuning.
- Alternative low-scale baryogenesis mechanisms?

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.

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.

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.

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 $\overline{L}\phi N$.

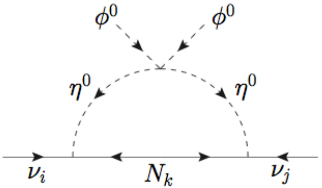
Neutrino Mass

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

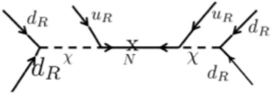
$$V(\phi,\eta) = -m_1^2|\phi|^2 + m_2^2|\eta|^2 + \lambda_1|\phi|^4 + \lambda_2|\eta|^4 + \lambda_3|\phi|^2|\eta|^2 + \lambda_4|\phi^\dagger\eta|^2 + \left[\frac{\lambda_5}{2}(\phi^\dagger\eta)^2 + \mathrm{H.c.}\right],$$

  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



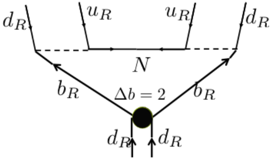
- The starting effective $\not{B}$ operator is $N_a u_R d_R d_R$.

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

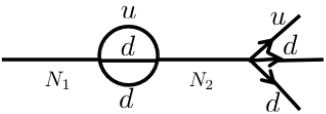
$$\mathcal{L}_I = \frac{\lambda_{ai}\lambda'_{jk}}{M_\chi^2} N_a u_{R,i} d_{R,j} d_{R,k} + \text{H.c.}$$

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

$$G_{n-\bar{n}} \simeq \frac{(\lambda_{a1}\lambda'_{13})^2 M_{N_a}}{16\pi^2 M_\chi^4 \Lambda^2} \ln\left(\frac{\Lambda^2}{M_N^2}\right) \lesssim 10^{-28}\ \text{GeV}^{-5}\,.$$



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)]

CP Asymmetry

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

- For the couplings satisfying FCNC, can get $\varepsilon \sim 10^{-4}$ even with a 1% degeneracy.
- Due to FCNC and diproton constraints, the dominant contribution comes from diagrams with bdu, bdc, bdt loops.
- In principle, possible to improve by considering both ε and ε' effects for a suitable set of model parameters.

Reaction Rates

- For $M_\eta, M_\chi \gg M_N$, the dominant decay mode is $N \to u_R \chi^* \to u_R d_R d_R$.

$$
\begin{aligned}
\Gamma_{N_a} &= \frac{3}{256\pi^3} \frac{\sum_{i,j,k} |\lambda_{ai} \lambda'^*_{jk}|^2}{M^3_{N_a}} \int_0^{M^2_{N_a}} ds \frac{M^6_{N_a} - 3M^2_{N_a} s^2 + 2s^3}{(s - M^2_\chi)^2 + M^2_\chi \Gamma^2_\chi} \\
&\simeq \frac{3}{512\pi^3} \frac{\sum_{i,j,k} |\lambda_{ai} \lambda'^*_{jk}|^2 M^5_{N_a}}{M^4_\chi}
\end{aligned}
$$

- Washout effects mainly due to inverse decay and $2 \leftrightarrow 2$ scatterings.

$$
\begin{aligned}
\gamma_{D_a} &= \frac{T M^2_{N_a}}{\pi^2} \Gamma_{N_a} K_1(M_{N_a}/T) , \\
\gamma_{I_a} &= \frac{1}{2} \gamma_{D_a} \frac{\eta^{\rm eq}_{N_a}}{\eta^{\rm eq}_B} , \\
\gamma_{S_a} &= \frac{T}{64\pi^4} \int_{m^2_{N_a}}^\infty ds \sqrt{s}\, \hat{\sigma}_a(s)\, K_1(\sqrt{s}/T) ,
\end{aligned}
$$

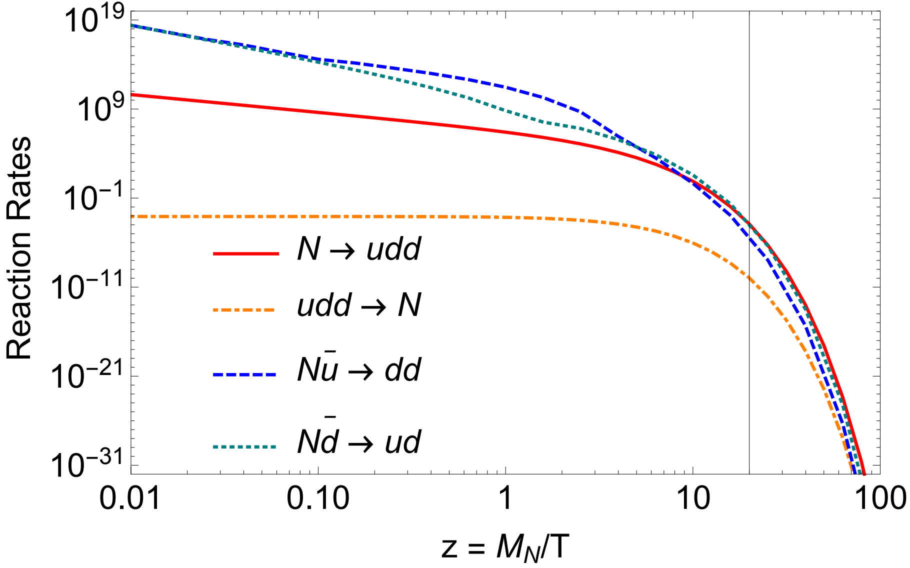
Reduced Cross Sections

$$\hat{\sigma}(s) = \frac{1}{8\pi s}\int_{t_{\min}}^{t_{\max}} dt \sum_{\text{spins}} |\mathcal{M}|^2 ,$$

The dominant processes are $N_a \bar{u}_R \to d_R d_R$ and $N_a \bar{d}_R \to u_R d_R$, for both of which $t_{\min} = M_{N_a}^2 - s$ and $t_{\max} = 0$.

$$\begin{aligned}
\hat{\sigma}_{a1}(s) &= \frac{3}{2\pi}\sum_{i,j,k} |\lambda_{ai}\lambda'_{jk}|^2 \frac{(s - M_{N_a}^2)^2}{[(s - M_\chi^2)^2 + M_\chi^2 \Gamma_\chi^2]} , \\
\hat{\sigma}_{a2}(s) &= \frac{3}{2\pi s}\sum_{i,j,k} |\lambda_{ai}\lambda'_{jk}|^2 \left[\frac{(s - M_{N_a}^2)(s + 2M_\chi^2)}{s + M_\chi^2} \right. \\
&\qquad \left. - 2M_\chi^2 \log\left(1 + \frac{s}{M_\chi^2}\right) \right] .
\end{aligned}$$

Reaction Rates



Boltzmann Equations

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

- 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.
- In general, possible to have baryogenesis for $M_N \sim$ GeV–TeV range.

Collider Signals

- No $\nu - N$ mixing unlike in usual seesaw.
- RH neutrinos can only be produced at colliders from $\eta^{\pm} \to \ell^{\pm} N$.
- η's can be pair-produced in Drell-Yan process.

- In the usual inert doublet model, for $M_N \leq M_\eta$, the final state N would go undetected as a missing energy.
- In our model, $\eta \to \ell N \to \ell jjb$ (induced by $Nudd$ operator).
- Promising collider signals:

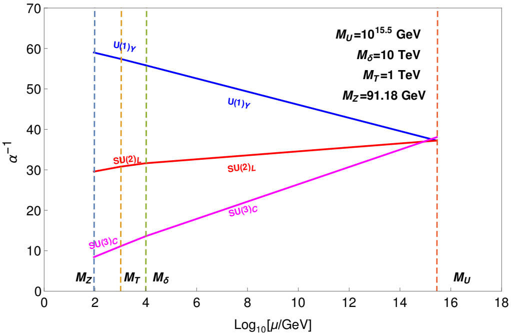
$$pp \to \bar{q}N \to 4j$$
$$pp \to \eta^+\eta^- \to \ell^+\ell^- N_1 N_2 \to \ell^+\ell^- + 4j + 2b$$

GUT Embedding

- Explored two options: $SU(5)$ and $SU(2)_L \times SU(2)_R \times SU(4)_c$.
- For $SU(5)$ embedding, we need an additional Z_4 symmetry and the following multiplets:

$$\text{Fermion}: T_{10}(+i), \quad \bar{F}_{\bar{5}}(+i), \quad N(-i),$$
$$\text{Scalar}: \Sigma_{24}(+1), \quad H_5(-1), \quad \eta_5(+1), \quad \chi_{10}(-1), \quad \chi'_{10}(+1)$$

- $SU(5) \to G_{\rm SM}$ by $\langle \Sigma_{24}(\mathbf{1},\mathbf{1},0)\rangle$ and he EWSB by $H(\mathbf{1},\mathbf{2},1/2)$.



GUT Embedding

- For G_{224}, we choose the Higgs sector to have the following multiplets:

$$\chi(\mathbf{1},\mathbf{2},\mathbf{4}), \quad \phi_0(\mathbf{2},\mathbf{2},\mathbf{1}), \quad \phi_{15}(\mathbf{2},\mathbf{2},\mathbf{15}), \quad \Delta_R(\mathbf{1},\mathbf{3},\mathbf{10}), \quad \Sigma(\mathbf{1},\mathbf{1},\mathbf{15}).$$

- $\langle\Sigma\rangle \neq 0$ breaks $G_{224} \to G_{2213}$, which is subsequently broken to $G_{\rm SM}$ by $\langle\chi_R\rangle$ and $\langle\Delta_R^0\rangle$.
- In the effective Lagrangian, generate terms like

$$d_R N \chi^*_{-1/3} + u_R N \chi^*_{2/3} + \chi_{-1/3} u_R^{\mathsf{T}} C d_R$$

  Integrating out $\chi_{-1/3}$ leads to the $N u_R d_R d_R$ operator.
- Unification may be possible! [BD, R. N. Mohapatra, S. Patra (ongoing)]

Why G_{224}?

NEUTRINO MASS HIERARCHY, NEUTRON-ANTINEUTRON ... PHYSICAL REVIEW D **79,** 015017 (2009)

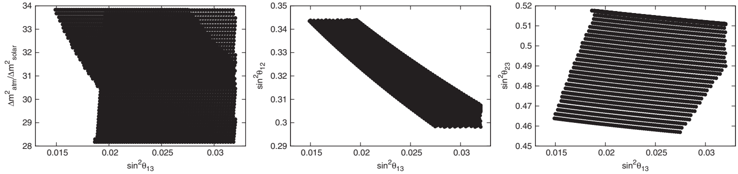
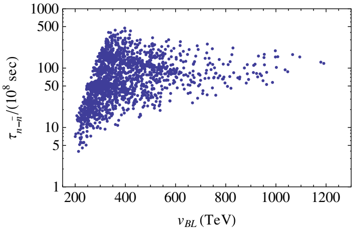


FIG. 1. We give the predictions for neutrino oscillation parameters for the allowed ranges of the diquark scalar couplings in our model. Note the lower limit on the θ_{13} of about 0.1.

[Babu, BD and Mohapatra, PRD **79**, 015017 (2009)]



Connection between neutrino mass, baryogenesis and $n - \bar{n}$ oscillation. [Babu, BD, Fortes and Mohapatra, PRD **87**, 115019 (2013)]

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 $pp \to KK$.
- Interesting signals at the LHC.
- Possible GUT embedding.

Di-nucleon Decay