Baryon asymmetry in the early Universe in SM extensions of the lepton sector

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Introduction

It is observed that in the present Universe

$$\eta_B = \frac{n_B}{n_\gamma} = (6.5^{+0.4}_{-0.3}) \times 10^{-10} \qquad \text{(WMAP)} \qquad (1)$$

Necessary conditions for generation of observed baryon asymmetry of the universe (BAU) (Sakharov conditions) (Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5, 1967)

- violation of the baryon number
- C and CP-violation
- deviation from thermal equillibrium

In the SM the CPV effects are possible via a single phase in the Cabibbo–Kobayashi–Maskawa (CKM) quark mixing matrix, however it is insufficient to explain (1).

There are many possibilities to explain the BAU in different extentions of the SM, however the mechanism of baryon asymmetry generation has not yet been determined

We will consider the extensions of the SM by right-handed neutrinos (HNL, sterile neutrinos)

- 3 generations of HNLs, νMSM
- Left-right simmetric models based on the group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, MLRM (new particles are $N_{1,2,3}$ and $Z_2, W_2^{\pm}$, 13 Higgs bosons with masses >11 TeV)

because

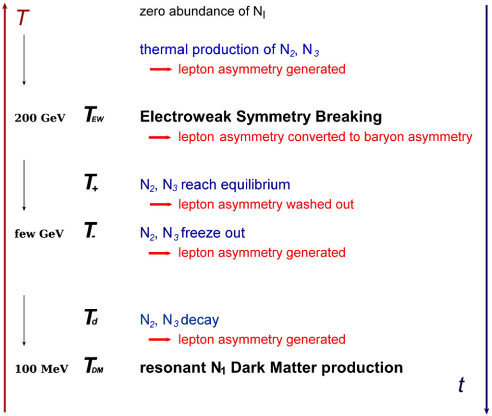
- symmetry between right- and left-handed neutrinos is restored
- natural way to obtain the smallness of m_ν by seesaw mechanism, type I or type II, and neutrino oscillations
- presence of DM as the lightest HNL (N_1)

In the following we will assume that N_1 is warm DM (Dubinin, F., Kazarkin, Pepan Letters 22, 5, 2025)

$$\begin{aligned} \tau_{N_1} &\sim 3 \times 10^{22} \left(\frac{M_1}{1\ \text{keV}}\right)^{-4} \left(\frac{m_D^{dm}}{1\ \text{eV}}\right)^{-1} \text{sec} \ > \ H_0^{-1} \simeq 10^{17}\ \text{sec}, \\ &> 10^{25}\ \text{sec}\ \ (\text{from nonobservation of } N_1 \to \gamma\nu), \qquad (2) \\ \Omega_{N_1} h^2 &\simeq \left(\frac{m_D^{dm}}{10^{-5}\ \text{eV}}\right)\left(\frac{M_1}{10\ \text{keV}}\right) \le \Omega_{DM} h^2 = 0.12 \qquad (3) \end{aligned}$$

Thermal history of the Universe

In the work Canetti, Drewes, Frossard, Shaposhnikov, Phys. Rev. D 87 (2013) 093006 (νMSM), it was assumed and found out that



$M_1 \sim \mathcal{O}(\text{keV})$

N_2, N_3 are responsible for
– mass generation of ν
– baryogenesis with $M_2 \simeq M_3$

$M_{2,3} \geq 1$–2 GeV

$\frac{\delta M}{M} \lesssim 10^{-13}$

At such temperatures new states W_2, Z_2, H_i are decoupled, so MLRM can be considered as νMSM-like effective theory

Neutrino sector

Flavour basis

$$\mathcal{L} \supset (\overline{\nu_L} \;\; \overline{\nu_R^c}) M_\nu \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}, \tag{4}$$

$$\text{where} \quad M_\nu^{\nu\texttt{MSM}} = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \quad \text{or} \quad M_\nu^{\texttt{MLRM}} = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix},$$

$$\nu\text{MSM}: \qquad M_D = h\langle H\rangle, \tag{5}$$

$$\text{MLRM}: \qquad M_D = \frac{h_L k_1 + \tilde{h}_L k_2}{\sqrt{2}}, \quad M_L = \sqrt{2} h_M v_L, \quad M_R = \sqrt{2} h_M v_R \;\; (v_L \ll v_R)$$

$$(k_1^2 + k_2^2)^{1/2} = 246 \text{ GeV}, \quad v_L = \frac{1}{v_R} \frac{\beta_2 k_1^2 + \beta_1 k_1 k_2 + \beta_3 k_2^2}{(2\rho_1 - \rho_3)}$$ VEV seesaw

Mass basis (after SSB)

$$\mathcal{U}^\dagger M_\nu \mathcal{U}^* = \begin{pmatrix} \hat{m} & 0 \\ 0 & \hat{M} \end{pmatrix}, \qquad \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} = P_L \mathcal{U} \begin{pmatrix} \nu \\ N \end{pmatrix} \tag{6}$$

where $\hat{m} = \text{diag}(m_1, m_2, m_3)$, $\hat{M} = \text{diag}(M_1, M_2, M_3)$,

$$\mathcal{U} = W \cdot \begin{pmatrix} U_\nu & 0 \\ 0 & U_N^* \end{pmatrix}, \qquad \text{where} \quad W = \exp\begin{pmatrix} 0 & \theta \\ -\theta^\dagger & 0 \end{pmatrix}, \; \theta < I$$

$$W^\dagger M_\nu W^* = \begin{pmatrix} m_\nu & 0 \\ 0 & M_N \end{pmatrix} \equiv \tilde{\mathcal{M}} \qquad (7)$$

$(m_\nu)_{ee} < 2$ eV, $\quad (m_\nu)_{\mu\mu} < 0.19$ MeV, $\quad (m_\nu)_{\tau\tau} < 18.2$ MeV, $\quad \sum_i m_{\nu_i} < 0.2 - 1.0$ eV

K. Olive, et al., Review of particle physics, Chin. Phys. C 38 (2014) 090001; 1602.04816v2 [hep-ph]

	Standard approach (LO)	Nonminimal approach[1] (NLO)
W	$\begin{pmatrix} 1-\frac{1}{2}\theta\theta^\dagger & \theta \\ -\theta^\dagger & 1-\frac{1}{2}\theta^\dagger\theta \end{pmatrix}$	$\begin{pmatrix} 1-\frac{1}{2}\theta\theta^\dagger & \theta-\frac{1}{6}\theta\theta^\dagger\theta \\ -\theta^\dagger+\frac{1}{6}\theta^\dagger\theta\theta^\dagger & 1-\frac{1}{2}\theta^\dagger\theta \end{pmatrix}$
In the case of $M_L \simeq 0$		
$\tilde{\mathcal{M}}_{12}$	$\theta \simeq M_D M_R^{-1}$	$M_R - \frac{1}{2}M_R\theta^T\theta^* - \frac{1}{6}\theta^\dagger\theta M_R \simeq$ $\theta^{-1}M_D\left(1-\frac{1}{2}\theta^T\theta^*\right) - \frac{1}{2}\theta^\dagger M_D - M_D^T\theta^*$
$\tilde{\mathcal{M}}_{11}$	$m_\nu \simeq -M_D M_M^{-1} M_D^T$	$m_\nu \simeq -\theta M_D^T$
$\tilde{\mathcal{M}}_{22}$	$M_N \simeq M_R + \frac{1}{2}(\theta^\dagger\theta M_R + M_R^T\theta^T\theta^*)$ $\simeq (\theta^{-1}+\theta^\dagger)M_D$	$M_N \simeq M_R + (\theta^\dagger M_D + M_D^T\theta^*)$ $-\frac{1}{2}(\theta^\dagger\theta M_R + M_R\theta^T\theta^*)$ $\simeq \left(\theta^{-1}-\frac{1}{3}\theta^\dagger\right)M_D$

[1] Dubinin, Fedotova, Symmetry 15, 3, 2023

Casas-Ibarra-like parametrization of the mixing matrix Θ

$$\nu_L \simeq U_{\rm PMNS}\nu_L + \Theta N_L, \quad \text{where} \quad U_{\rm PMNS} \simeq \left(1 - \frac{1}{2}\theta\theta^\dagger\right) U_\nu, \quad \Theta \simeq \theta U_N^* \tag{8}$$

From $I = M_N M_N^{-1}$ one can find	Standard approach	Nonminimal approach
M_D	$-iU_{\rm PMNS}\sqrt{\hat{m}}\Omega_{\rm m}\sqrt{\hat{M}}U_N^\dagger$	$+iU_{\rm PMNS}\sqrt{\hat{m}}\Omega_{\rm nm}\sqrt{\hat{M}}U_N^\dagger$
Θ	$-iU_{\rm PMNS}\sqrt{\hat{m}}\Omega_{\rm m}\sqrt{\hat{M}^{-1}}$	$-iU_{\rm PMNS}\sqrt{\hat{m}}(\Omega_{\rm nm}^{-1})^T\sqrt{\hat{M}^{-1}}$
where Ω	$\Omega_{\rm m}^T\Omega_{\rm m} = I$	$\Omega_{\rm nm}^{-1} = \Omega_{\rm nm}^T + \frac{1}{3}\hat{M}^{-1}(\Omega_{\rm nm}^{-1})^*\hat{m}$

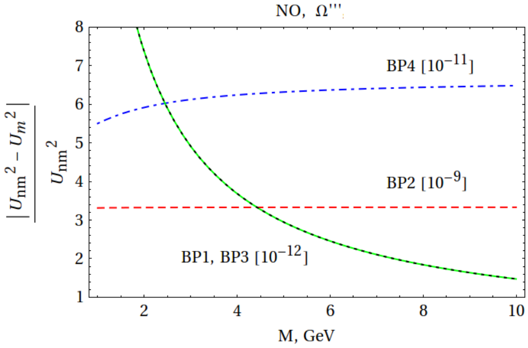
Casas J., Ibarra A., Nucl.Phys.B 618 (2001) 171; Dubinin, Fedotova, Symmetry 15, 3, 2023.

It is interesting to note that $m_\nu \simeq U_{\rm PMNS}\hat{m}U_{\rm PMNS}^T$ in both approximations.

Phenomenologically convenient quantities – mixing parameters:

$$U_{\alpha i}^2 = |\Theta_{\alpha I}|^2, \qquad U_i^2 = \sum_\alpha U_{\alpha I}^2, \qquad U^2 = \sum_i U_i^2 \tag{9}$$

The sensitivity of mixing parameter



$$\mathrm{NO}: \Omega_{\mathrm{nm}} = \mathrm{diag}(\omega_1, \omega_2, \omega_3),$$
$$\omega_i = \sqrt{1 - \frac{1}{3}\frac{m_i}{M_i}}$$

$m_1 \setminus M_1$	1 keV	50 keV
0	BP1	BP3
10^{-5} eV	BP2	BP4

Thus, from the phenomenological point of view the LO is a very good approximation

However, for successful baryogenesis ΔM crusially depends on $\mathcal{O}(\theta^2)$. As was demonstrated above new terms of $\mathcal{O}(\theta^2)$ arise in the NLO approximation

$$M_N^{\mathrm{LO}} - M_N^{\mathrm{NLO}} = \frac{4}{3}\theta^\dagger M_D \tag{10}$$

Conclusion

We considered the next order in the decomposition of the rotation matrix W in neutrino sector of the SM extensions – νMSM and MLRM

- The contributions of the order of $\mathcal{O}(\theta M_D)$ coming from the expansion of rotation matrix W up to $\mathcal{O}(\theta^3)$ terms to the mass matrix M_N are of the same order as for the case $W \sim \mathcal{O}(\theta^2)$.

- The absolute value of relative difference of the mixing parameter in LO and NLO approximations is negligible for phenomenology on accelerators.

- The shift of ΔM needed for successful baryogenesis is approximately

$$M_N^{\text{LO}} - M_N^{\text{NLO}} = \frac{4}{3}\theta^\dagger M_D$$

Thank you for your attention