A new leptogenesis scenario with predictions on $\sum m_\nu$ and $J_{CP}$

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In an $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_L \times U(1)_R$ left-right symmetric framework with spontaneous breaking $U(1)_L \times U(1)_R \rightarrow U(1)_{B-L}$, we present a new leptogenesis scenario to predict low limits on neutrinos’ mass scale $\sum m_\nu$ and CP violation $J_{CP}$. Benefited from a softly broken parity symmetry, which is motivated by solving the strong CP problem without introducing an unobserved axion, the dimensionless couplings of the mirror fields charged under $SU(2)_R \times U(1)_R$ are mapped to the couplings of the ordinary fields charged under $SU(2)_L \times U(1)_L$. The mirror Dirac neutrinos can have a heavy mass matrix proportional to the seesaw-suppressed mass matrix of the ordinary Dirac neutrinos. Through the $SU(2)_R$ gauge interactions, the mirror neutrinos can decay to generate a lepton asymmetry in the mirror muons and an opposite lepton asymmetry in the mirror electrons. Before the $SU(2)_L$ sphaleron processes go out of equilibrium, the mirror muons rather than the mirror electrons can efficiently decay into the ordinary right-handed leptons with some dark matter scalars and hence the mirror muon asymmetry can be partially converted to an expected baryon asymmetry.

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I. INTRODUCTION

People have proposed various baryogenesis mechanisms to understand the cosmic matter-antimatter asymmetry which is as same as a baryon asymmetry. The leptogenesis [1,2] in seesaw [3,4] context has become one of the most attractive baryogenesis mechanisms because it can simultaneously explain the generation of baryon asymmetry and the smallness of neutrino masses. However, the conventional leptogenesis scenario contains many free parameters so that it cannot give the exact dependence of the baryon asymmetry on the neutrino mass matrix unless we do some assumptions on the texture of the relevant masses and couplings. For example, we can expect a successful leptogenesis in the canonical seesaw model even if the neutrino mass matrix doesn’t contain any CP phases [3].

In this paper we shall propose a new leptogenesis scenario in an $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_L \times U(1)_R$ left-right symmetric [2] model to give some predictions on the mass scale $\sum m_\nu$ and the CP violation $J_{CP}$ of the Dirac neutrinos. Motivated by solving the strong CP problem without introducing an unobserved axion [2,13], we will consider a softly broken parity symmetry under which the dimensionless couplings of the $SU(2)_R \times U(1)_R$ mirror fields are identified to the couplings of the $SU(2)_L \times U(1)_L$ ordinary fields. The mirror Dirac neutrinos can have a heavy mass matrix proportional to the seesaw-suppressed [14] mass matrix of the ordinary Dirac neutrinos. Through the $SU(2)_R$ gauge interactions, the mirror neutrinos can decay to produce a lepton asymmetry in the mirror muons and an opposite lepton asymmetry in the mirror electrons. Both of the mirror muons and electrons can decay into the ordinary right-handed leptons with some dark matter scalars. But the lifetime of the mirror muons can be shorter than that of the mirror electrons. This means the mirror electron asymmetry can be expected not to participate in the $SU(2)_L$ sphaleron processes. In other words, only the mirror muon asymmetry can be partially converted to a baryon asymmetry.

II. THE MODEL

The $SU(2)_{L(R)} \times U(1)_{L(R)}$ charged fields include the following fermions,

$$q_L(2, +\frac{1}{6}), \, d_R(1, -\frac{1}{3}), \, u_R(1, +\frac{2}{3}), \, l_L(2, -\frac{1}{2}), \, e_R(1, -1);$$
$$q_R(2, +\frac{1}{6}), \, d'_R(1, -\frac{1}{3}), \, u'_R(1, +\frac{2}{3}), \, l'_R(2, -\frac{1}{2}), \, e'_R(1, -1);$$

(1)

and the following scalars,

$$\phi(2, -\frac{1}{2}), \, \eta(2, -\frac{1}{2}); \, \phi'(2, -\frac{1}{2}), \, \eta'(2, -\frac{1}{2}).$$

(2)

Here the ordinary fields without prime are charged under the $SU(2)_L \times U(1)_L$ gauge groups while the mirror fields with prime are charged under the $SU(2)_R \times U(1)_R$ gauge symmetry. We also have three $SU(2)_R \times SU(2)_L$-singlet scalars which are nontrivial under the $U(1)_L \times U(1)_R$ symmetries,

$$\chi_d(-\frac{1}{2}, +1), \, \chi_u(+\frac{2}{3}, -\frac{2}{3}), \, \chi_e(-1, +1),$$

(3)

with the brackets being the $U(1)_L \times U(1)_R$ charges. Furthermore, we introduce the ordinary right-handed neutrinos and the mirror left-handed neutrinos,

$$\nu_R, \, \nu'_L \text{ with } Q_N = +1,$$

(4)

which are $SU(2)_{L,R} \times U(1)_{L,R}$ singlets but carry a quantum number $Q_N = +1$ under an additional $U(1)_N$ gauge

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symmetry. The scalars \( (\phi, \phi') \) and \( (\eta, \eta') \) can be distinguished as they are assumed to have the \( U(1)_X \) charges \( Q_\chi = 0 \) and \( Q_N = -1 \), respectively. The parity invariant Yukawa interactions involving the above fields then can be written down,

\[
\mathcal{L} = -y_d(q_L^\dagger \phi d_R + \tilde{q}_R^\dagger \tilde{\phi} d_L) - y_u(q_L^\dagger \phi u_R + \tilde{q}_R^\dagger \tilde{\phi} u_L) - y_\chi(q_L^\dagger \chi d_R + \tilde{q}_R^\dagger \tilde{\chi} d_L - f_x \chi \epsilon e^L + \text{H.c.}) \tag{5}
\]

The ordinary fermions(scalars) are odd(even) under a \( Z_2 \) discrete symmetry while the mirror fermions(scalars) are odd(even) under a \( Z'_2 \) discrete symmetry. This \( Z_2 \times Z'_2 \) symmetry will not be broken at any scales. Thus the scalars \( \chi_{d,u,e} \) will not acquire any nontrivial vacuum expectation values. At least two of the scalars \( \chi_{d,u,e} \) can keep stable because of their couplings,

\[
V \ni \kappa_2 \chi_{d,u,e}^2 \chi_{d,u,e}^2 + \kappa_3 \chi_{d,u,e}^3 + \text{H.c.} \tag{6}
\]

We can consider an \([SU(2)_L \times SU(2)_R]\)-singlet scalar \( \omega \) with a proper \( U(1)_L \times U(1)_R \) charge such as \((-3, +3)\) to spontaneously break the present \( U(1)_L \times U(1)_R \) down to the usual \( U(1)_B-L \). Subsequently, the \([SU(2)_L\)-doublet scalar \( \eta' \) and the \([SU(2)_L\)-doublet scalar \( \phi \) will develop their vacuum expectation values. At least two of the scalars \( \chi_{d,u,e} \) can get a heavy mass matrix proportional to the seesaw-suppressed mass matrix of the ordinary Dirac neutrinos. For the following demonstration, we also give the charged gauge boson masses

\[
m_{W_L} = g \sqrt{\frac{(\phi)^2 + (\eta)^2}{2}} \simeq \frac{g}{\sqrt{2}} \phi, \\
m_{W_R} = g \sqrt{\frac{(\phi')^2 + (\eta')^2}{2}} \tag{12}
\]

as well as the PMNS matrix which now doesn’t contain any Majorana phases,

\[
U = \begin{pmatrix}
\epsilon_{12}^{13} & \epsilon_{13}^{12} & \epsilon_{13}^{12} \\
-\epsilon_{12}^{13} & -\epsilon_{12}^{13} & -\epsilon_{12}^{13}
\end{pmatrix} \tag{13}
\]

III. MIRROR LEPTON ASYMMETRIES

The mirror neutrinos can have the two-body and three-body decay modes as shown in Fig. 1 when their masses are in the following range,

\[
M_{\nu'} + M_{W_R} < M_{\nu'} < M_{\nu'} + M_{W_R}. \tag{14}
\]

We calculate the decay width at tree level,

\[
\Gamma_{\nu'} = \Gamma(\nu'_{\nu} \to \mu^- + W_R^+) + \Gamma(\nu'_{\nu} \to e^- + W_R^+) + \sum_{\alpha}\sum_{\beta\gamma} \Gamma(\nu'_{\nu} \to \nu'_{\alpha} + q_{\beta}^{+1/3} + q_{\gamma}^{+2/3})
\]

\[
\simeq \frac{3g^4}{256\pi^3} M_{\nu'} \left[1 + \frac{4\pi^2}{g^2} (|U_{e\nu}|^2 + |U_{\mu\nu}|^2) \right] \xi^2 \tag{15}
\]

where the parameter \( \xi \) is given by

\[
\xi = \frac{M_{\nu'}^2 - M_{W_R}^2}{M_{\nu'}^2} < \frac{(M_{\nu'} + M_{W_R})M_{\nu'}}{M_{\nu'}^2} \simeq \frac{2M_{\nu'}}{M_{W_R}} = \frac{2m_{\tau}}{m_{W_L}} \sin \beta' = 0.044 \sin \beta' \leq 0.031 
\]

for \( \sin \beta' = \frac{\sqrt{\langle \phi' \rangle^2 + \langle \eta' \rangle^2}}{\langle \phi' \rangle^2 + \langle \eta' \rangle^2} \leq \frac{1}{\sqrt{2}} \). \tag{16}

Although the mirror neutrino decays exactly conserve the lepton number, they can generate a lepton asymmetry in the mirror muons and an opposite lepton asymmetry in the mirror electrons at one-loop level,

\[
\varepsilon_{\nu'} = \frac{\Gamma(\nu'_{\nu} \to \mu^- + W_R^+) - \Gamma(\nu'_{\nu} \to e^- + W_R^+)}{\Gamma_{\nu'}} \tag{17a}
\]

\[
\varepsilon_{\nu'} = \frac{\Gamma(\nu'_{\nu} \to \mu^- + W_R^+) - \Gamma(\nu'_{\nu} \to e^- + W_R^+)}{\Gamma_{\nu'}} \tag{17b}
\]
In the presence of the scalars $\chi_{d,u,e}$, the induced mirror electron and muon asymmetries will be immediately cancelled each other if the decaying and scattering processes shown in Fig. 3 are very fast. We expect such processes to go into equilibrium at some low temperatures such as $T_{\text{sph}} \sim 100$ GeV where the $SU(2)_L$ sphaleron processes have not been active no longer. For this purpose we can require the interaction rates smaller than the Hubble constant at the crucial temperature $T_{\text{sph}}$

$$\Gamma_D^{\mu^+\rightarrow e^+} = \sum_{\alpha\beta} \Gamma(\mu^+ \rightarrow e^+ + e^- + e^+)$$
$$= \left(\frac{f_1 f_3}{m_\mu^+ m_\mu^-} \right) \frac{M_\mu^+}{M \chi_e} \frac{T^5}{4 \pi^3} < H(T) \left| T_{\text{sph}} \right.$$  

(23a)

$$\Gamma_s^{\mu^+\rightarrow e^+} = \sum_{\alpha\beta} \Gamma(\mu^+ \rightarrow e^+ + e^- + e^+)$$
$$\approx \frac{3}{4} \left(\frac{f_1 f_3}{m_\mu^+ m_\mu^-} \right) \frac{T^5}{4 \pi^3} < H(T) \left| T_{\text{sph}} \right.$$  

(23b)

$$\Gamma_t^{\mu^+\rightarrow e^+} = \sum_{\alpha\beta} \Gamma(\mu^+ \rightarrow e^+ + e^- + e^+)$$
$$\approx \frac{3}{4} \left(\frac{f_1 f_3}{m_\mu^+ m_\mu^-} \right) \frac{T^5}{4 \pi^3} < H(T) \left| T_{\text{sph}} \right.$$  

(23c)

$$\Gamma_t^{\mu^+\rightarrow e^+} = \sum_{\alpha\beta} \Gamma(\mu^+ \rightarrow e^+ + e^- + e^+)$$
$$\approx \frac{3}{4} \left(\frac{f_1 f_3}{m_\mu^+ m_\mu^-} \right) \frac{T^5}{4 \pi^3} < H(T) \left| T_{\text{sph}} \right.$$  

(23d)

Here the Hubble constant is given by

$$H(T) = \left(\frac{8 \pi^3 g_*}{90} \right)^{\frac{1}{2}} \frac{T^2}{M_{\text{Pl}}}$$

(24)

with $M_{\text{Pl}} \simeq 1.22 \times 10^{19}$ GeV being the Planck mass and $g_* = 106.75$ being the relativistic degrees of freedom.

IV. ORDINARY BARYON ASYMMETRY

It is well known we can obtain a baryon asymmetry from a lepton asymmetry produced before the $SU(2)_L$ sphaleron processes stop working at a temperature around $T_{\text{sph}} \sim 100$ GeV [13]. On the other hand, we have already got a lepton asymmetry stored in the mirror muons and an opposite lepton asymmetry stored in the mirror electrons. These mirror muons and electrons will decay into the ordinary right-handed leptons.
and electrons both decay efficiently above the scale $T_{\text{sph}}$, the mirror muon and electron asymmetries will both participate in the sphalerons. In consequence, we will fail in getting a nonzero baryon asymmetry from the induced mirror lepton asymmetries. However, it is allowed that the mirror muons can have a shorter life time while the mirror electrons can have a longer life time, i.e.

$$\Gamma_{\mu'} = \sum_{\alpha} \left[ \Gamma(e_{\alpha}' \rightarrow e_{\alpha}^* + \chi_d^* + \chi_d + \chi_d^*) \ight.$$  

$$\left. + \Gamma(e_{\alpha}' \rightarrow e_{\alpha} + \chi_d^* + \chi_d + \chi_d^*) \right]$$

$$= \frac{(f_e f_{\nu})_{\nu'\mu'}}{32768\pi^5} \left( |\kappa_3|^2 + \frac{1}{3} |\kappa_2|^2 \right) \frac{M_{\mu'}^3}{M_{\chi}^4} H(T_{\text{sph}}) , (25a)$$

$$\Gamma_{e'} = \sum_{\alpha} \left[ \Gamma(e_{\alpha}' \rightarrow e_{\alpha}^* + \chi_d + \chi_d^* + \chi_d^*) \ight.$$  

$$\left. + \Gamma(e_{\alpha}' \rightarrow e_{\alpha} + \chi_d + \chi_d^* + \chi_d^*) \right]$$

$$= \frac{(f_e f_{\nu})_{\nu'\mu'}}{32768\pi^5} \left( |\kappa_3|^2 + \frac{1}{3} |\kappa_2|^2 \right) \frac{M_{\mu'}^5}{M_{\chi}^4} < H(T_{\text{sph}}) . (25b)$$

In this case, similar to the left-handed lepton asymmetry and the opposite right-handed neutrino asymmetry in the neutrinosynthesis scenario [17], the mirror muon asymmetry rather than the mirror electron asymmetry will be partially converted to an ordinary baryon asymmetry through the sphalerons [18].

$$\eta_B \approx \frac{28}{79}$$

Here we have taken the weak washout condition

$$\Gamma_{\nu_{i}'} < H(T) \left| T = M_{\nu_{i}'} \right. , (27)$$

into account. This can be achieved by choosing the mirror neutrinos heavy enough.
By inputting the cosmic baryon asymmetry \[ n_B = 5.91 \times 10^{-10}, \]
and the neutrino oscillation data \[ \Delta m_{21}^2 = 7.54 \times 10^{-5} \text{eV}^2, \Delta m_{31}^2 = 2.43 \times 10^{-3} \text{eV}^2, \]
s\[ s_{12} = 0.308, s_{23} = 0.437, s_{13} = 0.0234; \]
or
\[ \Delta m_{21}^2 = 7.54 \times 10^{-5} \text{eV}^2, \Delta m_{31}^2 = -2.38 \times 10^{-3} \text{eV}^2, \]
s\[ s_{12} = 0.308, s_{23} = 0.455, s_{13} = 0.0240, \]
we can drive a low limit on the CP violation for the quasi degenerate neutrinos,
is the original QCD phase while
\[ \bar{\theta} = \theta + \text{ArgDet}(M_u M_d). \]
where \( \theta \) is the original QCD phase while \( M_u \) and \( M_d \) are the mass matrices of the ordinary and mirror down- and up-type quarks, respectively,
\[ \mathcal{L} \supset -[\bar{d}_L, \bar{d}_L] M_d \left[ \begin{array}{c} d_R \\ u_R \end{array} \right] - [\bar{u}_L, \bar{u}_L] M_u \left[ \begin{array}{c} u_R \\ d_R \end{array} \right] + \text{H.c. with} \]
\[ M_u = \left[ \begin{array}{cc} y_d \langle \phi \rangle & 0 \\ 0 & y_u \langle \phi \rangle \end{array} \right], \quad M_d = \left[ \begin{array}{cc} y_u \langle \phi \rangle & 0 \\ 0 & y_d \langle \phi \rangle \end{array} \right]. \]

When the \( \theta \)-term is removed as a result of the parity invariance, the real determinants \( \text{Det}(M_d) \) and \( \text{Det}(M_u) \) will lead to a zero \( \text{ArgDet}(M_u M_d) \). We hence can obtain a vanishing strong CP phase \( \theta \).

The model also contains two stable scalars \( \chi_d \) and \( \chi_u \) because of the unbroken \( Z_2 \times Z_2 \) symmetry. These scalars can annihilate into the ordinary species through their Yukawa interactions and Higgs portal. For a proper choice of their masses and couplings, they can obtain a right relic density to explain the dark matter puzzle. This type of scalar dark matter has been studied in a lot of literatures [21].

VI. SUMMARY

In this paper we have proposed a new leptogenesis scenario in the left-right symmetric framework to predict the low limits on the neutrino mass scale and CP violation from the cosmic baryon asymmetry. These predictions may be verified by future neutrino oscillation experiments and cosmological observations. Our model contains a softly broken parity to solve the strong CP problem without introducing an unobserved axion. The Dirac neutrinos obtain a seesaw-suppressed mass matrix. Some dark matter scalars also participate in the leptogenesis processes.

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