I. INTRODUCTION

There is an $SU(2)_L$ global anomaly \cite{1} violating the baryon ($B$) and lepton ($L$) numbers by an equal amount in the $SU(3)_C \times SU(2)_L \times U(1)_Y$ - standard model (SM). At the finite temperatures $100 \text{ GeV} \lesssim T \lesssim 10^{12} \text{ GeV}$, the anomalous process becomes strong due to an instanton-like solution, the so-called sphalerons \cite{2}. During the sphaleron epoch, neither the baryon asymmetry nor the lepton asymmetry can survive if the baryon and lepton asymmetries are equal. However, the sphaleron processes will not affect any primordial $B - L$ asymmetry and will convert the $B - L$ asymmetry to a baryon asymmetry and a lepton asymmetry \cite{2}. So, a successful baryogenesis mechanism working above the weak scale should require a $B - L$ number violation which is a pure baryon number violation, a pure lepton number violation or a combined baryon and lepton violation.

The baryon and/or lepton number violation can lead to other interesting phenomena. For example, we can obtain a Majorana neutrino mass term by a lepton number violation of two units, a neutron-antineutron oscillation by a baryon number violation of two units, as well as a two-body proton decay by a baryon number violation of one unit and a lepton number violation of one unit.

The simplest grand unified theories (GUTs), a baryon asymmetry and an equal lepton asymmetry can be simultaneously produced at the GUT scale through some baryon and lepton number violating interactions, which are also responsible for generating a $B - L$ conserving proton decay. In this GUT baryogenesis scenario, the baryon and lepton asymmetries will be both wiped out by the sphaleron processes.

In this paper we shall show it is possible to realize the baryogenesis and the proton decay by same interactions. For this purpose, we shall extend the SM by an isotriplet and two isosinglet leptoquark scalars, two isotriplet Higgs scalars as well as three right-handed neutrinos. The Majorana masses of the right-handed neutrinos will softly break the lepton number while the trilinear scalar couplings involving the Higgs triplets will softly break both of the baryon and lepton numbers. The $B - L$ number violating processes involving the right-handed neutrinos will be assumed to decouple before the out-of-equilibrium decays of the Higgs triplets. So, the $B - L$ asymmetry from the decays of the Higgs triplets into the leptoquarks can explain the baryon asymmetry in the universe. After the Higgs triplets pick up their seesaw-suppressed vacuum expectation values, the leptoquarks with TeV-scale masses can mediate a testable proton decay.

II. THE MODEL

For simplicity, we do not write down the full lagrangian. Instead, we only give the terms as below,

\begin{align}
\mathcal{L} & \supset -y_{ik} \bar{l}_i \phi N_R_k - \frac{1}{2} M_{N_k} \bar{N}^c N_R_k - f_{ij} \bar{e}_L i \tau_2 \Omega_{Q_L} L_j \\
& - f_{ij}^c \delta_{a} \bar{e}_L i \tau_2 q_L_j - h_{ij} \delta_{a} \bar{e}_L u_R_j - \mu_a \phi^T i \tau_2 \Sigma_a \phi \\
& - \kappa_{ij} \delta_{a} \frac{1}{2} \text{Tr} (\Sigma_a \Omega) + \text{H.c.} \\
& = -y_{ik} (\bar{\nu}_{L_i} \phi^0 + \bar{e}_{L_i} \phi^-) N_R_k - \frac{1}{2} M_{N_k} \bar{N}^c N_R_k \\
& - f_{ij}^c \omega^{-2/3} \bar{e}_L u_{L_j} - \frac{1}{\sqrt{2}} \omega^{1/3} (\bar{\nu}_{L_i} d_{L_j} + \bar{e}_L u_{L_j}) \\
& - \omega^{+4/3} \bar{e}_L d_{L_j} - f_{ij} \delta_{a} (\bar{\nu}_{L_i} d_{L_j} + \bar{e}_L u_{L_j}) \\
& - h_{ij} \delta_{a} \bar{e}_L u_{L_j} - \mu_a (\sigma_a^0 \phi^0 \phi^0 + \sqrt{2} \sigma_a^+ \phi^0 \phi^- \\
& - \sigma_a^+ \phi^- \phi^- - \kappa_a \frac{1}{2} \omega^{-2/3} (\sigma_a^0 + \sigma_a^+ + \sigma_a^-) + \text{H.c.},
\end{align}
with the SM quarks, leptons and Higgs scalar:

\[ q_L(3, 2, +\frac{1}{6}) = \begin{bmatrix} u_L \\ d_L \end{bmatrix}, \quad u_R(3, 1, +\frac{2}{3}), \]

\[ l_L(1, 2, -\frac{1}{2}) = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix}, \quad e_R(1, 1, -1), \]

\[ \phi(1, 2, -\frac{1}{2}) = \begin{bmatrix} \phi^0 \\ \phi^- \end{bmatrix}, \]  

(2)

the gauge-singlet right-handed neutrinos:

\[ N_R(1, 1, 0), \]  

(3)

the [SU(2)]-singlet and triplet leptoquark scalars:

\[ \delta_a(3, 1, \frac{1}{3}) = \delta^{+1/3}_a, \]

\[ \Omega(3, 3, \frac{1}{3}) = \begin{bmatrix} \frac{1}{\sqrt{2}} \omega^{+1/3} & \omega^{+4/3} \\ \omega^{-2/3} & -\frac{1}{\sqrt{2}} \omega^{+1/3} \end{bmatrix}, \]  

(4)

and the [SU(2)]-triplet Higgs scalars:

\[ \Sigma_a(1, 3, 1) = \begin{bmatrix} \frac{1}{\sqrt{2}} \sigma_a^+ & \sigma_a^{+1} \\ \sigma_a^0 & -\frac{1}{\sqrt{2}} \sigma_a^- \end{bmatrix}. \]  

(5)

We assign the baryon and lepton numbers as below,

\[ (\frac{1}{3}, 0) \text{ for } q_L \text{ and other SM quarks}, \]

\[ (0, +1) \text{ for } N_R, \ l_L \text{ and other SM leptons}, \]

\[ (B, L) = \begin{cases} (-\frac{1}{3}, -1) \text{ for } \Omega \text{ and } \delta, \\ (-1, -3) \text{ for } \Sigma, \\ (0, 0) \text{ for } \phi. \end{cases} \]  

(6)

In Eq. (1), the Majorana masses of the right-handed neutrinos break the lepton number, the trilinear couplings of the Higgs scalars break both the baryon number and the lepton number, while other terms conserve the baryon and lepton numbers. Clearly, the Majorana masses and the trilinear scalar couplings also break the lepton number, while other terms conserve the baryon number and lepton numbers. The Higgs doublet will develop a VEV:

\[ \langle \phi^0 \rangle \simeq 174 \text{ GeV}, \]  

(7)

to spontaneously break the electroweak symmetry. The Higgs triplets \[ \Sigma_a \] then can pick up their seesaw-suppressed VEVs:

\[ \langle \sigma_a^0 \rangle \simeq -\mu_a \langle \phi^0 \rangle^2 \frac{M_{\Sigma_a}}{M_{\Sigma_a}} \ll \langle \phi^0 \rangle, \]  

(8)

like the Higgs triplets in the type-II seesaw model [3].

### III. NEUTRINO MASSES

Although the Yukawa couplings of the Higgs triplets to the lepton doublets are absent from Eq. (1), they can appear at one-loop order as shown in Fig. II. We calculate the effective Yukawa couplings to be

\[ \mathcal{L} \supset -\frac{1}{2} (g_a)_{ij} \bar{\ell}_L^i \Sigma \ell_L^j + \text{H.c.} \]

\[ = -\frac{1}{2} (g_a)_{ij} (\sigma_a^0 \nu_e \nu_L^i + \sqrt{2} \sigma_a \nu_e \nu_L^i - \sigma_a^{+1} \nu_e \nu_L^i) \]

\[ + \text{H.c.}. \]  

(9)

with

\[ (g_a)_{ij} \simeq \frac{1}{4 \pi^2} \frac{\mu_a}{M_{\Sigma_a}^2} \left( \frac{M_{\Sigma_a}^2}{M_N^2} + i \pi \right) \]

\[ \frac{1}{M_N} \frac{\mu_a (m_\nu^2)_{ij}}{\sigma_a} \text{ for } M_{\Sigma_a}^2 \ll 1. \]  

(10)

Here the canonical type-I seesaw [3] formula have been adopted,

\[ \mathcal{L} \supset -\frac{1}{2} m_{\nu} \bar{\nu}_L \nu_L + \text{H.c.} \]  

with \[ m_\nu = -y_\nu \langle \phi^0 \rangle^2 \frac{g_a}{M_N}. \]  

(11)

The effective Yukawa couplings (10) will also contribute to the neutrino masses through the type-II seesaw mechanism,

\[ \langle \delta m_\nu \rangle_{ij} = (g_a)_{ij} \sum_a (\sigma_a^0) \simeq -\frac{i}{4 \pi} \sum_a |\mu_a|^2 (m_\nu)_{ij}. \]  

(12)

Clearly, the type-I seesaw could dominate over the type-II seesaw,

\[ \delta m_\nu \ll m_\nu \]  

for \[ |\mu_a|^2 \ll M_{\Sigma_a}^2. \]  

(13)

The neutrino mass matrix can be diagonalized by

\[ m_\nu = U \text{diag}(m_1, m_2, m_3) U^T, \]  

(14)

where \[ m_{1,2,3} \] are the mass eigenvalues while \[ U \] is the mixing matrix with three mixing angles, one Dirac CP phase and two Majorana CP phases. The neutrino oscillation experiments have given some information on the neutrino masses and mixing such as

\[ m_2^2 - m_1^2 = (7.09 - 8.19) \times 10^{-5} \text{ eV}^2; \]  

(15a)

\[ m_3^2 - m_1^2 = \begin{cases} -(2.08 - 2.64) \times 10^{-3} \text{ eV}^2, \\ (2.18 - 2.73) \times 10^{-3} \text{ eV}^2. \end{cases} \]  

(15b)

Furthermore, the cosmological observations [3] have put an upper bound on the sum of the neutrino mass eigenvalues,

\[ \sum_i m_i < 0.58 \text{ eV}. \]  

(16)
FIG. 1: The effective Yukawa couplings of the Higgs triplets to the lepton doublets. The CP conjugation is not shown for simplicity.

IV. BARYOGENESIS

We assume that the lepton number violating processes involving the right-handed neutrinos will decouple before the decays of the Higgs triplets and then the final $B - L$ asymmetry should be generated by the decays of the Higgs triplets. Below the seesaw scale $M_L$, the $\Delta L = 2$ scattering processes should have the rate [9]:

\[
\Gamma_A = \frac{1}{\pi} \sum_i m_i^2 |\langle \phi^i \rangle|^4 T^3. \tag{17}
\]

By requiring

\[
\Gamma_A < H(T), \tag{18}
\]

where the Hubble constant is given by

\[
H(T) = \left( \frac{8\pi^3 g_*}{90} \right)^{1/2} \frac{T^2}{M_{Pl}}, \tag{19}
\]

with $M_{Pl} = 1.22 \times 10^{19}$ GeV being the Planck mass and $g_* = 106.75 + 30 = 136.75$ being the relativistic degrees of freedom (the SM fields plus an isorighttriplet and two isosinglet leptoquark scalars), the lepton number violating processes will decouple when the temperature falls down to

\[
T \simeq 2 \times 10^{13} \text{GeV} \left( \frac{2.5 \times 10^{-3} \text{eV}^2}{\sum_i m_i^2} \right). \tag{20}
\]

In the following demonstration, we hence shall consider the mass spectrum as below,

\[
M_{\Sigma_{1,2}} < 10^{13} \text{GeV} < M_N. \tag{21}
\]

As shown in Fig. 2, the Higgs triplets have the following decay modes:

\[
\begin{align*}
\Sigma & \rightarrow \delta_1 \delta_2 \, \Omega, \quad \phi^* \phi^* \, l_L^c l_L^c; \\
\Sigma^* & \rightarrow \delta_1^* \delta_2^* \, \Omega^*, \quad \phi \, \phi \, \, l_L^c l_L^c.
\end{align*} \tag{22}
\]

Therefore, the decays of the Higgs triplets can produce a $B - L$ asymmetry in the leptoquarks and the leptons if CP is not conserved. To quantify the $B - L$ asymmetry, we can define a CP asymmetry in the decays of the Higgs triplets $\Sigma_a$,

\[
\varepsilon_{a_L} = \varepsilon_a^L \hat{\delta}_2 \hat{\delta}_1 \Omega^* + \varepsilon_a^l l_L^c, \tag{23}
\]

with

\[
\begin{align*}
\varepsilon_a^L & = \frac{\Gamma_{\Sigma_a \rightarrow \delta_1 \delta_2 \Omega} - \Gamma_{\Sigma_a \rightarrow \delta_1^* \delta_2^* \Omega^*}}{\Gamma_a}, \tag{24a} \\
\varepsilon_a^l & = \frac{\Gamma_{\Sigma_a \rightarrow \delta_1 \delta_2 \Omega} - \Gamma_{\Sigma_a \rightarrow \delta_1^* \delta_2^* \Omega^*}}{\Gamma_a}. \tag{24b}
\end{align*}
\]

Here

\[
\begin{align*}
\Gamma_a & = \Gamma_{\Sigma_a \rightarrow \delta_1 \delta_2 \Omega} + \Gamma_{\Sigma_a \rightarrow \phi^* \phi^*} + \Gamma_{\Sigma_a \rightarrow \delta_1 \delta_2 \Omega} \\
& = \Gamma_{\Sigma_a \rightarrow \delta_1 \delta_2 \Omega} + \Gamma_{\Sigma_a \rightarrow \phi^* \phi^*} + \Gamma_{\Sigma_a \rightarrow \delta_1 \delta_2 \Omega} \tag{25}
\end{align*}
\]

is the decay width. We can calculate the tree-level decay width:

\[
\begin{align*}
\Gamma_a & = \frac{1}{8\pi} \left( 1 \frac{\mu_a}{M_{\Sigma_a}^2} + \frac{1}{64\pi^2} \frac{\mu_a^2 (\sum_i m_i^2)}{\langle \phi^i \rangle^4} \right) \times M_{\Sigma_a}, \tag{26}
\end{align*}
\]

and the one-loop CP asymmetries:

\[
\begin{align*}
\varepsilon_a^L & = -\frac{1}{128\pi^3} \left( \frac{1}{\mu_a^2} M_{\Sigma_a}^2 - M_{\Sigma_a}^2 \right) \times \left( \frac{1}{64\pi^2} |\kappa_a|^2 + \frac{1}{64\pi^2} |\mu_a|^2 \sum_i m_i^2 \langle \phi^i \rangle^4 \right) \tag{27a} \\
\varepsilon_a^l & = -\frac{1}{128\pi^3} \left( \frac{1}{\mu_a^2} M_{\Sigma_a}^2 - M_{\Sigma_a}^2 \right) \times \left( \frac{1}{64\pi^2} |\kappa_a|^2 + \frac{1}{64\pi^2} |\mu_a|^2 \sum_i m_i^2 \langle \phi^i \rangle^4 \right). \tag{27b}
\end{align*}
\]

When the Higgs triplets $\Sigma_a$ go out of equilibrium, their CP violating decays can generate a $B - L$ asymmetry in the leptoquarks $\Omega$ and $\delta_{1,2}$ as well as the leptons $l_L$. For
example, we consider the weak washout region, where the out-of-equilibrium condition can be described by the following quantity,

$$K_a = \frac{\Gamma_a}{H} \bigg|_{T=M_{\Sigma_a}} \lesssim 1.$$ (28)

The induced $B-L$ asymmetry then can approximate to

$$\frac{n_{B-L}}{s} \sim 3 \times \frac{\varepsilon_a}{g_*} \text{ for } K_a \lesssim 1,$$ (29)

where the factor 3 means the three components of the decaying Higgs triplets. If $\Sigma_1(\Sigma_2)$ is much lighter than $\Sigma_2(\Sigma_1)$, the final $B-L$ asymmetry should come from the decays of $\Sigma_1(\Sigma_2)$. Alternatively, if $\Sigma_1$ and $\Sigma_2$ have a small mass split, both of them will significantly contribute to the final $B-L$ asymmetry. In this case, the CP asymmetry could be resonantly enhanced [11].

Since the leptoquarks decays into the leptons and the quarks, their $B-L$ asymmetries can be transferred to a baryon asymmetry and a lepton asymmetry through the sphaleron processes. The final baryon asymmetry in the universe should be [2]

$$\frac{n_B}{s} = \frac{28 n_{B-L}}{79 s}.$$ (30)

![FIG. 2: The decays of the Higgs triplets. The CP conjugation is not shown for simplicity.](image)

V. PROTON DECAY

Due to the VEVs of the Higgs triplets $\Sigma_a$, the $\omega^{-2/3}$ component of the leptoquark triplet $\Omega$ will have a trilinear coupling with the leptoquark singlets $\delta_{1,2}$, i.e.

$$\mathcal{L} \supset -\rho \delta_{1}^{1/3} \delta_{2}^{2/3} \omega^{-2/3} + \text{H.c.} \text{ with }$$

$$\rho = \kappa_1 \langle \sigma_1^{0*} \rangle + \kappa_2 \langle \sigma_2^{0*} \rangle.$$ (31)
By integrating out the leptoquark scalars, we can obtain a low-scale effective Lagrangian as below,

\[ L^{\text{eff}} = \sum_{a \neq b} \sum_{ij} \frac{\rho^* f_{ij}^a f_{ij}^b h^a_{ij} h^b_{ij}}{m_{aij}^2 m_{bij}^2} (\bar{v}_{L_i}^a u_{L_j}^b)(\bar{v}_{L_j}^b d_{L_i}^a)(\bar{v}_{R_i}^a u_{R_j}^b) + \text{H.c.}. \]  

(32)

The dominant proton decay thus should be

\[ p \rightarrow e_R^+ (\mu_R^+ + \nu_L^+ + \bar{v}_L^+ + v_L^+), \]  

(33)
as shown in Fig. 3. Clearly, the proton decay violates the $B-L$ number by two units. We can roughly estimate the proton decay width by

\[ \Gamma_{p \rightarrow e^+ \nu} = \sum_{ij} \Gamma_{p \rightarrow e_R^+ + \nu_L^+ + \bar{v}_L^+ + v_L^+} \propto \sum_{a \neq b} \sum_{ij} \frac{|f_{ij}^a|^2 |f_{ij}^b|^2 |h_{ij}^a|^2 |h_{ij}^b|^2 |\rho|^2}{m_{aij}^2 m_{bij}^2 m_{aij}^2 m_{bij}^2}, \]

\[ \Gamma_{p \rightarrow \mu^+ \nu} = \sum_{ij} \Gamma_{p \rightarrow \mu_R^+ + \nu_L^+ + \bar{v}_L^+ + v_L^+} \propto \sum_{a \neq b} \sum_{ij} \frac{|f_{ij}^a|^2 |f_{ij}^b|^2 |h_{ij}^a|^2 |h_{ij}^b|^2 |\rho|^2}{m_{aij}^2 m_{bij}^2 m_{aij}^2 m_{bij}^2}. \]  

(34)

VI. PARAMETER CHOICE

We now give an example of the parameter choice to show that our model can simultaneously generate a desired baryon asymmetry and an observable proton decay. We take

\[ M_{\Sigma_1} = 0.2 M_{\Sigma_2} = 10^{12} \text{ GeV}, \]

\[ |\mu_1| = 0.2 |\mu_2| = 3 \times 10^9 \text{ GeV}, \]

\[ |\kappa_1| = |\kappa_2| = 0.1, \]

\[ \sin\left(\frac{\kappa_1^2 \mu_1^2 H_2}{\kappa_1^2 \mu_2^2 H_2}\right) = -0.32, \]  

(35)
to derive the out-of-equilibrium quantity

\[ K_1 \simeq 0.62, \]  

(36)
and the CP asymmetry

\[ \varepsilon_1 \simeq \varepsilon_1^\Omega \simeq 1.2 \times 10^{-8} \gg \varepsilon_1^\mu. \]  

(37)
The final baryon asymmetry then would be

\[ \eta_B = 7.04 \times \frac{n_B}{s} \simeq 7.04 \times 3 \times \frac{28 \varepsilon_1}{79 g_*} \simeq 6.57 \times 10^{-10} \]  

(38)
which is consistent with the cosmological observations.

From the above parameter choice, we can also read the trilinear coupling among the leptoquarks,

\[ |\rho| \simeq 1.1 \text{ eV}. \]  

(39)
Such a tiny parameter means the proton decay can naturally have a life time close to the experimental limits.

\[ \tau_{p \rightarrow e^+ \nu} > 1.7 \times 10^{31} \text{ yr} \]  

and \[ \tau_{p \rightarrow \mu^+ \nu} > 2.1 \times 10^{31} \text{ yr} \]  

even if the leptoquarks are at the TeV scale.

VII. SUMMARY

In this paper, we have shown that the baryon asymmetry and the proton decay can have a common origin. In our model, the decays of the heavy Higgs triplets can produce a $B-L$ asymmetry in the TeV-scale leptoquarks. Due to the sphalerons, we eventually can obtain a baryon asymmetry to explain the baryon asymmetry in the universe. Benefited from the seesaw-suppressed VEVs of the Higgs triplets, the leptoquarks can have a trilinear coupling to mediate an observable proton decay.

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