Annihilating Leptogenesis

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Leptogenesis is usually realized through decays of heavy particles. In this article we consider another possibility of generating a lepton asymmetry through annihilations of heavy particles. We demonstrate our idea with a realistic extension of the standard model containing a heavy doublet and a light singlet scalars in addition to right-handed neutrinos and Higgs triplets required for type-I+II seesaw of neutrino masses. We also clarify that this annihilating leptogenesis scenario can be naturally embedded in more fundamental theories, like left-right symmetric models or grand unified theories.

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Introduction: It is well known that any CPT-conserved baryogenesis theories should satisfy Sakharov conditions [1]: (1) baryon number violation, (2) C and CP nonconservation, (3) thermodynamic nonequilibrium. In the standard model (SM), there is a $\mathrm{SU}(2)_L$ global anomaly [2], which causes baryon number (B) and lepton number (L) violation, although their difference $B-L$ is still conserved. This anomaly induced $B+L$ violating processes will be suppressed by quantum tunneling probability at zero temperature, however, at finite temperature it will become fast in presence of an instanton-like solution, the sphaleron [3]. The sphaleron action can partially convert an existing $B-L$ asymmetry to a baryon asymmetry and then we can understand the matter-antimatter asymmetry of the present Universe. With this essence, Fukugita and Yanagida proposed the leptogenesis [4] scenario, where a lepton asymmetry (without baryon asymmetry) is generated before the sphaleron processes become very slow around the time of the electroweak phase transition. In the conventional leptogenesis scenario, the lepton asymmetry is produced by decays of heavy particles [4, 5, 6]. We argue here that it is unnecessary to constrain the leptogenesis mechanism in the decaying scenario, since the required conditions: lepton number violation, C and CP violation, and departure from equilibrium, can also be reached in annihilating processes. In the following, we demonstrate the possibility of "annihilating leptogenesis" in a realistic model.

The model: For simplicity, we only write down the following mass terms and interactions that are relevant for the rest of our discussions,

$$\begin{aligned}\mathcal{L} \supset & \left[-\frac{1}{2}M_N\overline{N_R^c}N_R - y\overline{\psi_L}\phi N_R + \text{H.c.}\right] - M_\xi^2 \mathrm{Tr}\left(\xi^\dagger\xi\right) - \left[\frac{1}{2}f\overline{\psi_L^c}i\tau_2\xi\psi_L + \mu\phi^T i\tau_2\xi\phi + \text{H.c.}\right]\\ & - M_\eta^2\eta^\dagger\eta - \left[\mu'\eta^T i\tau_2\xi\eta + \lambda(\phi^\dagger\eta)^2 + \text{H.c.}\right] - \left(\rho\chi\eta^\dagger\phi - \kappa\chi\eta^T i\tau_2\xi\phi + \text{H.c.}\right)\\ & - \alpha_1\left(\eta^\dagger\eta\right)\left(\phi^\dagger\phi\right) - \alpha_2\left(\eta^\dagger\phi\right)\left(\phi^\dagger\eta\right) - \alpha_3\chi^2\left(\eta^\dagger\eta\right) - \alpha_4\left(\eta^\dagger\eta\right)\mathrm{Tr}\left(\xi^\dagger\xi\right) \,. \end{aligned} \tag{1}$$

Here ψ_L and ϕ, respectively, are the SM lepton and Higgs doublets, N_R denotes the right-handed neutrinos, ξ stands for the Higgs triplets, η is a heavy doublet scalar carrying the same quantum number with ϕ, and χ is a light singlet scalar. We impose a Z_2 discrete symmetry, under which only η and χ are odd-parity fields and hence are protected from nonzero vacuum expectation value (VEV).

Corresponding to $L=+1$ for the SM leptons and $L=0$ for the SM Higgs doublet, we assign $L=+1$ for the right-handed neutrinos and $L=-2$ for the Higgs triplets. Therefore, the lepton number is explicitly violated by the Majorana masses of the right-handed neutrinos, the trilinear interactions between the triplet and doublet scalars and the quartic interactions among the triplet, doublet and singlet scalars. We consider this as an effective theory from a more fundamental theory, where the lepton number is spontaneously broken locally or globally. As a result of the lepton number violation, the type-I and II seesaw mechanisms [7, 8] can be realized phenomenologically. The resulting neutrino masses would be

$$\mathcal{L}^{\nu}_{mass} = \frac{1}{2} m_\nu \overline{\nu^c_L} \nu_L + \text{h.c.}\,, \quad (2)$$

where the mass matrix m_ν contains two parts,

$$m_\nu = m_\nu^{\text{I}} + m_\nu^{\text{II}}\,, \quad (3)$$

with the type-I seesaw,

$$m_\nu^{\text{I}} = -y^* \frac{v^2}{M_N} y^\dagger\,, \quad (4)$$

and the type-II seesaw,

$$m_\nu^{\text{II}} = -f \frac{\mu^* v^2}{M_\xi^2}\,. \quad (5)$$

Here $v \equiv \langle \phi \rangle \simeq 174\,\text{GeV}$ is the VEV of the SM Higgs doublet.

CP-asymmetry: The heavy doublet scalar can annihilate into two SM Higgs or lepton doublets as shown in Figs. 1 and 2. At the tree level, the cross sections for the CP-conjugate channels, $(\eta\eta \to \phi\phi,\ \eta^*\eta^* \to \phi^*\phi^*)$ and $(\eta\eta \to \psi_L\psi_L,\ \eta^*\eta^* \to \psi^c_L\psi^c_L)$ are given by

$$\begin{aligned} &\sigma_{\eta\eta\to\phi\phi}|\vec{v}| = \sigma_{\eta^*\eta^*\to\phi^*\phi^*}|\vec{v}| \\ &= \frac{1}{4\pi}\left|\lambda - \frac{\mu'\mu^*}{M_\xi^2}\right|^2 \frac{1}{s}\,, \quad (6a) \\ &\sigma_{\eta\eta\to\psi_L\psi_L}|\vec{v}| = \sigma_{\eta^*\eta^*\to\psi^c_L\psi^c_L}|\vec{v}| \\ &= \frac{1}{4\pi}\frac{|\mu'|^2}{M_\xi^4}\text{Tr}\left(f^\dagger f\right)\,. \quad (6b) \end{aligned}$$

Here $s \geq 4M_\chi^2$ is the squared center of mass energy and $|\vec{v}| = 2\left(1 - 4M_\chi^2/s\right)^{\frac{1}{2}}$ is the relative velocity between the two heavy doublets. Note in the above and following calculations the Higgs triplets are assumed to be much heavier than the heavy doublet.

At the one-loop order, the vertex correction induced by the right-handed neutrinos and/or the self-energy correction induced by the Higgs triplets (if there are more than two Higgs triplets), will result in a difference between the cross sections of the CP-conjugate channels, as long as the CP is not conserved. For example, we consider the case only with one Higgs triplet and then derive the CP-asymmetry,

$$\begin{aligned} \varepsilon &\equiv 2\frac{\sigma_{\eta\eta\to\psi_L\psi_L} - \sigma_{\eta^*\eta^*\to\psi^c_L\psi^c_L}}{\sigma_{\eta\eta\to\psi_L\psi_L} + \sigma_{\eta\eta\to\phi\phi}} \\ &\equiv 2\frac{\sigma_{\eta\eta\to\psi_L\psi_L} - \sigma_{\eta^*\eta^*\to\psi^c_L\psi^c_L}}{\sigma_{\eta^*\eta^*\to\psi^c_L\psi^c_L} + \sigma_{\eta^*\eta^*\to\phi^*\phi^*}} \\ &\simeq \frac{1}{4\pi}\frac{\text{Im}\left[\text{Tr}\left(m_\nu^{\text{I}\dagger} m_\nu^{\text{II}}\right)\right]}{\text{Tr}\left(m_\nu^{\text{II}\dagger} m_\nu^{\text{II}}\right)}\frac{|\mu|^2}{M_\xi^2}\text{Br}\,, \end{aligned} \quad (7)$$

where the branch ratio is defined as

$$\begin{aligned} \text{Br} &= \frac{\sigma_{\eta\eta\to\psi_L\psi_L}}{\sigma_{\eta\eta\to\psi_L\psi_L} + \sigma_{\eta\eta\to\phi\phi}} \\ &= \frac{\text{Tr}\left(f^\dagger f\right)}{\text{Tr}\left(f^\dagger f\right) + \left|\lambda M_\xi^2/\mu' - \mu^*\right|^2/s}\,. \end{aligned} \quad (8)$$

Frozen Temperature: The heavy doublet scalar have four types of interactions, including (1) the gauge couplings; (2) the quartic couplings with other scalars; (3) the trilinear couplings with the triplet Higgs scalar; (4) the trilinear couplings with the light singlet scalar and the doublet Higgs scalar. The induced annihilating and decaying processes will determine the frozen temperature T_F, below which the heavy doublet will deviate from its equilibrium distribution. We now analyze these processes. Firstly, the gauge interactions can be safely ignored when the heavy doublet is very heavy (roughly $\gtrsim \mathcal{O}(10^{10}\,\text{GeV})$). Secondly, we assume the decays of the heavy doublet has been decoupled before it became non-relativistic. This yields

$$\Gamma_D \ll H(T)\Big|_{T=M_\eta}\,, \quad (9)$$

where

$$\begin{aligned} \Gamma_D &= \Gamma(\eta \to \chi\phi) = \Gamma(\eta^* \to \chi\phi^*) \\ &= \frac{1}{16\pi}\frac{|\rho|^2}{M_\eta}\,, \end{aligned} \quad (10)$$

is the decay width [1] and

$$H(T) = \left(\frac{8\pi^3 g_*}{90}\right)^{\frac{1}{2}}\frac{T^2}{M_{\text{Pl}}} \quad (11)$$

is the Hubble constant with $M_{\text{Pl}} \simeq 10^{19}\,\text{GeV}$ and $g_* = \mathcal{O}(100)$. Here the four-body decays mediated by the imaginary Higgs triplet are greatly suppressed and hence have been ignored in the decay width. The condition (9) is easy to realize. For example, we input $M_\eta = 10^{12}\,\text{GeV}$ and $|\rho| = 10^9\,\text{GeV}$. Thirdly, we consider the annihilating processes shown in Figs. 1 and 2. Their frozen temperature can be solved through the following out-of-equilibrium condition,

$$\Gamma_A \simeq H(T)\,, \quad (12)$$

[1] The light singlet scalar χ is stable and will contribute a relic density to the Universe. In the presence of its quartic coupling to the SM Higgs doublet ϕ, i.e. $\mathcal{L} \supset \epsilon\chi^2\left(\phi^\dagger\phi\right) + \text{H.c.}$, its frozen temperature and then its relic density can be determined by its annihilations into the SM fields, including the quarks, the leptons, the gauge bosons, and the Higgs boson. For appropriate choice of the coefficient ϵ, this singlet scalar χ with a mass of the order of $\mathcal{O}(\text{GeV} - \text{TeV})$ can leave a desired relic density to serve as the dark matter [9].

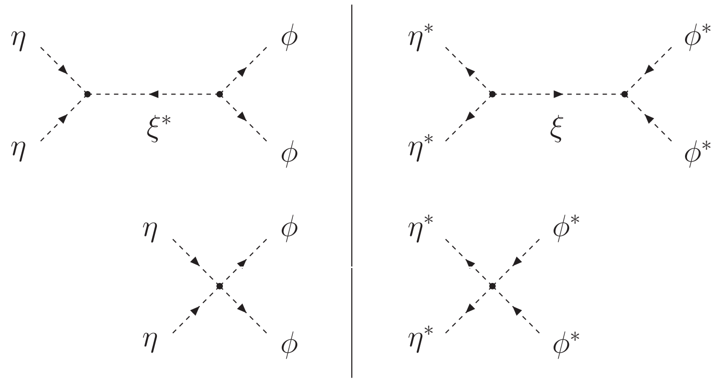

FIG. 1: The heavy doublet scalar annihilates into the SM Higgs doublet at tree level.

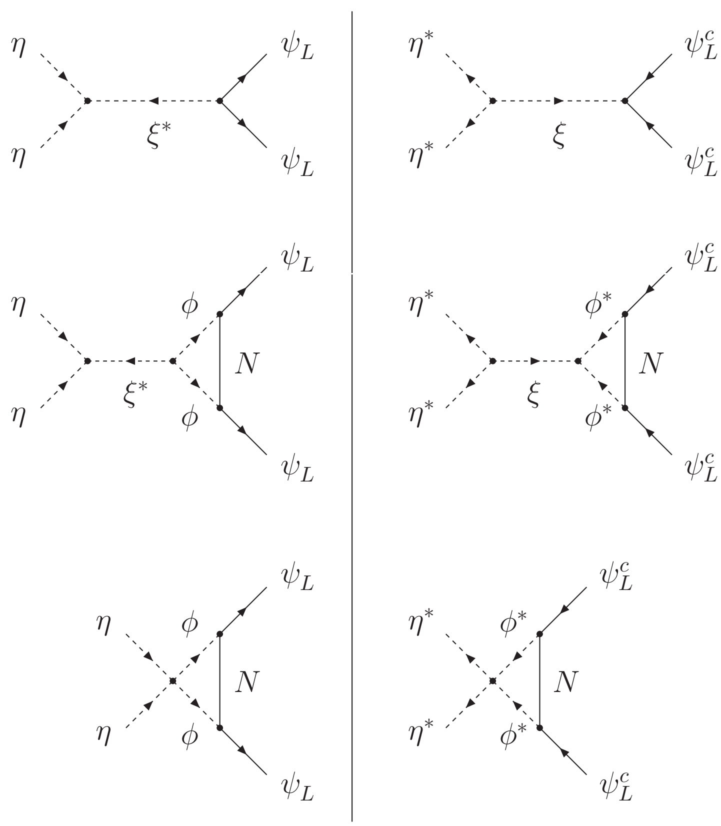

FIG. 2: The heavy doublet scalar annihilates into the SM lepton doublet at tree level and one-loop order. Here we don't consider the cases with more than two Higgs triplets, which can result in self-energy correction even if the right-handed neutrinos are absent.

where

$$\Gamma_A = n_\eta^{\mathrm{eq}} \left\langle \left(\sigma_{\eta\eta\to\psi_L\psi_L} + \sigma_{\eta\eta\to\phi\phi} \right) |\vec{v}| \right\rangle , \qquad (13)$$

is the rate with

$$n_\eta^{\mathrm{eq}} = \frac{2}{\pi^2} T^3 \frac{M_\eta^2}{T^2} K_2 \left(\frac{M_\eta}{T} \right) \qquad (14)$$

being the equilibrium distribution of number density. Finally, we study other annihilating processes. For $M_\eta \ll M_\xi$, only the $2 \to 2$ processes $(\eta\eta^* \to \phi\phi^*, \chi\chi)$ are not suppressed. We can replace $|\lambda - \mu'\mu^*/M_\xi^2|^2$ by $\alpha_1^2 + \alpha_2^2 + \alpha_1\alpha_2 + 2\alpha_3^2$ in Eq. (6a) and then get the cross section. In the following section, we will take $\alpha_1^2 + \alpha_2^2 + \alpha_1\alpha_2 + 2\alpha_3^2 \ll |\lambda - \mu'\mu^*/M_\xi^2|^2$ to simply give a frozen temperature for discussing the final baryon asymmetry.

Final Baryon Asymmetry: The right-handed neutrinos and/or Higgs triplets in the seesaw context will mediate some lepton number violating processes, including

$$\phi\phi \leftrightarrow \psi_L\psi_L , \ \phi^*\phi^* \leftrightarrow \psi_L^c\psi_L^c , \text{ and } \psi_L^c\phi \leftrightarrow \psi_L\phi^* . \qquad (15)$$

These processes will erase any lepton asymmetry produced before their departure from equilibrium. At low temperatures (compared with the masses of the right-handed neutrinos and/or Higgs triplets), the processes (15) will take place with the rate [10],

$$\Gamma_{\Delta L=2} = \frac{1}{\pi^3} \frac{T^3}{v^4} \mathrm{Tr} \left(m_\nu^\dagger m_\nu \right) . \qquad (16)$$

Requiring the above rate to be smaller than the Hubble constant, one can yield a decoupled temperature,

$$T_D = 10^{12}\,\mathrm{GeV} \left[\frac{(0.2\,\mathrm{eV})^2}{\mathrm{Tr}\left(m_\nu^\dagger m_\nu \right)} \right] , \qquad (17)$$

above which any existing lepton asymmetry will be washed out. By inputting the neutrino masses from the neutrino oscillation experiments and cosmological observations, it is straightforward to see that $T_D = \mathcal{O}(10^{12}\,\mathrm{GeV})$. This also means that for a typically seesaw scale $\sim \mathcal{O}(10^{14}\,\mathrm{GeV})$, the decays of the right-handed neutrinos and/or Higgs triplets will fail in generating a desired lepton asymmetry.

We now demonstrate how the annihilating leptogenesis can be realized in the present model. Here we do not attempt to solve the completed Boltzmann equations, which will not give any better insight to the problem and will be studied elsewhere. For simplicity, we consider the case where $T_D > T_F$ with T_F being determined by Eq. (12) and hence the final baryon asymmetry can be well described by

$$\frac{n_B}{s} = \frac{28}{79} \frac{n_{B-L}}{s} = -\frac{28}{79} \frac{n_L}{s} \simeq -\frac{28}{79} \left[\langle \varepsilon \rangle \frac{n_\eta^{\mathrm{eq}}}{s} \right] \Bigg|_{T_F} . \qquad (18)$$

Here s is the entropy density given by a very good approximation,

$$s = \frac{2\pi^2}{45} g_{*s} T^3 \qquad (19)$$

with $g_{*s} \simeq g_* = \mathcal{O}(100)$. We consider here a representative choice of parameters $f = \mathcal{O}(1)$, $y = \mathcal{O}(1)$ and $|\mu| \lesssim M_\xi \sim M_N = \mathcal{O}(10^{14}\,\mathrm{GeV})$, we obtain the desired neutrino masses, $m_\nu^{\mathrm{I}} \sim m_\nu^{\mathrm{II}} \sim m_\nu = \mathcal{O}(0.01 - 1\,\mathrm{eV})$. We further consider $M_\eta = \mathcal{O}(10^{12}\,\mathrm{GeV})$, $\mu' = \mathcal{O}(10^{13}\,\mathrm{GeV})$, $\rho = \mathcal{O}(10^9\,\mathrm{GeV})$, $\lambda \sim \mu'\mu^*/M_\xi^2 \sim \lambda - \mu'\mu^*/M_\xi^2 = \mathcal{O}(0.1)$, $\kappa < \mathcal{O}(1)$, $\alpha_{1,2,3,4} = \mathcal{O}(0.01)$ and hence obtain $T_F = \mathcal{O}(10^{11-12}\,\mathrm{GeV})$ and $n_\eta^{\mathrm{eq}}/s = \mathcal{O}(10^{-(3-4)})$. The thermal averaged CP-asymmetry then comes out to be $|\langle\varepsilon\rangle| \lesssim 10^{-5}$, so that we are flexible enough to get the desired baryon asymmetry

$$\frac{n_B}{s} = \mathcal{O}(10^{-10}) . \qquad (20)$$

Left-Right Symmetric Extension: This model can be naturally embedded in a left-right symmetric model or any grand unified theory. In a left-right symmetric model, besides the usual bi-doublet Higgs scalar $\Phi \equiv (1,2,2,0)$ [under the left-right symmetric gauge group $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$], we introduce a second bi-doublet Higgs scalar $\Psi \equiv (1,2,2,0)$ and a singlet scalar $\chi \equiv (1,1,1,0)$, which are odd under the Z_2 symmetry. The discrete symmetry protects Ψ and χ from any VEV and also restricts its couplings. We also introduce the triplet Higgs scalar $\Delta_R \equiv (1,1,3,-2)$ (to break the left-right symmetry) and its counterpart $\Delta_L \equiv (1,3,1,-2)$. Then the lepton number violating interactions for the type-I+II seesaw and the annihilating leptogenesis will emerge when Δ_R acquires a VEV $\langle\Delta_R\rangle$ to break the left-right symmetry. If we embed this left-symmetric model in any grand unified theory, the scale of left-right symmetry breaking comes out to be $\langle\Delta_R\rangle > 10^{13}\,\mathrm{GeV}$, so that our choice of the seesaw scale $\sim \langle\Delta_R\rangle = \mathcal{O}(10^{14}\,\mathrm{GeV})$ is a very natural one.

Conclusion: In this paper, we proposed and demonstrated that the leptogenesis could be realized in the annihilating scenario with the necessary conditions: lepton number violation, C and CP violation, and departure from equilibrium. We gave a realistic model where (1) the right-handed neutrinos and Higgs triplets required for the seesaw failed in realizing the decaying leptogenesis; (2) but the heavy doublet scalar succeeded in generating a lepton asymmetry through its annihilating to the SM lepton or Higgs doublet. The "annihilating leptogenesis" can be realized in more fundamental theories, like left-right symmetric theories or grand unified theories, where the seesaw scale considered in the present model comes out from an analysis of the gauge coupling unification.

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