Baryogenesis and degenerate neutrinos

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We bring the theoretical issue of whether two important cosmological demands, baryon asymmetry and degenerate neutrinos as hot dark matter, can be compatible in the context of the seesaw mechanism. While the canonical seesaw model with right-handed neutrinos is disregarded in this aspect, the triplet seesaw model is able to reconcile leptogenesis with almost degenerate Majorana neutrinos but with some unnatural arrangements of parameters. To remedy this, we propose a hybrid seesaw model with a heavy Higgs triplet and right-handed neutrinos.

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Current data from atmospheric [1] and solar [2] neutrino observations provide strong evidence for massive neutrinos. The atmospheric neutrino oscillation indicates the near maximal mixing between ν_μ and ν_τ with a mass squared difference $\Delta m^2_{\rm atm} \approx 3\times 10^{-3}\,{\rm eV}^2$ [3]. The solar neutrino anomaly can be explained through ν_e-ν_x oscillation with small mixing for $\Delta m^2_{\rm sol}\sim 5\times 10^{-6}\,{\rm eV}^2$ [small mixing angle (SMA)], or with large mixing for $\Delta m^2_{\rm sol}\sim 5\times 10^{-5}\,{\rm eV}^2$ [large mixing angle (LMA)], $\Delta m^2_{\rm sol}\sim 10^{-7}\,{\rm eV}^2$ [low mass, low probability (LOW)], or $\Delta m^2_{\rm sol}\sim 10^{-10}\,{\rm eV}^2$ [vacuum oscillation (VO)] [4]. On the other hand, the reactor experiments [5] constrain ν_e-ν_x oscillation with $\Delta m^2_{13}\gtrsim 10^{-3}\,{\rm eV}^2$ giving the restriction $\sin^2 2\theta \lesssim 0.2$. If we take into account the cosmological demand for hot dark matter consisting of neutrinos [6], the above neutrino data combined with the result from neutrinoless double-beta decay [7] experiments lead us to a unique pattern of Majorana neutrino mass matrix in leading order [8]:

$$m_\nu \sim m_0 \begin{pmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{2} & -\frac{1}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{1}{2} \end{pmatrix}, \qquad (1)$$

which has three almost degenerate mass eigenvalues, $m_0 \sim 1$ eV, and bimaximal mixing for the atmospheric and solar neutrino oscillations. Interestingly, such a degenerate mass pattern may also explain the recent Liquid Scintillation Neutrino Detector (LSND) result [9] if a sterile neutrino is introduced. With the allowed region shifted a bit below in the new analysis of the LSND data, four neutrino oscillation schemes with the fourth (sterile) neutrino separated from the group of three active neutrinos by the LSND mass gap $m_{\rm LSND}\sim 1$ eV [10] become viable. It is then allowed to have a sterile neutrino lighter than active neutrinos, which implies the active three neutrinos should be almost degenerate at the mass ~ 1 eV and participate dominantly in the atmospheric and solar neutrino oscillations. The Majorana neutrino mass matrix (1) is to be completed with the next leading terms which lift the degeneracy by small amounts so as to accommodate the atmospheric and solar neutrino observations, simultaneously. Defining the quantities $\epsilon_a \equiv (m_{\nu_3}-m_{\nu_2})/m_0$ and $\epsilon_s \equiv (m_{\nu_2}-m_{\nu_1})/m_0$ the observed mass-squared differences $\Delta m^2_{\rm atm}$ and $\Delta m^2_{\rm sol}$, fix their values as

$$\epsilon_a = \frac{\Delta m^2_{\rm atm}}{2m_0^2} \quad \text{and} \quad \epsilon_s = \frac{\Delta m^2_{\rm sol}}{2m_0^2}. \qquad (2)$$

Therefore, we have $\epsilon_a \sim 10^{-3}$ for the atmospheric neutrino oscillation and $\epsilon_s \sim 10^{-5}$, 10^{-7}, or 10^{-10} for the LMA, LOW, and VO solution to the solar neutrino problem, respectively.

The most popular way of generating light active neutrinos is the seesaw mechanism [11] which introduces heavy fields and lepton number violation at an intermediate scale. Then, the most attractive scenario for explaining the cosmological baryon asymmetry would be the leptogenesis mechanism [12] in which decays of the heavy fields generate a lepton asymmetry and it is then converted to the observed baryon asymmetry by the sphaleron processes. These heavy fields can be either right-handed neutrinos [11] or Higgs triplets [13], both of which are known to yield a successful baryogenesis without fine-tuning of parameters [14,15]. In this scenario, it is worthwhile to note that the requirement for generating the right amount of baryon asymmetry puts meaningful constraints on the patterns of neutrino masses and mixing [16,17].

An interesting issue in this regard is whether the leptogenesis mechanism can be consistent with degenerate neutrino mass pattern (1) which can also provide hot dark matter of the universe. The purpose of this article is to address such a question in the context of various seesaw models. To do so,

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it will be important to check whether the small mass splittings accounting for the atmospheric and solar neutrino oscillations (2) can also be obtained consistently with the leptogenesis mechanism. As will be shown later, the leptogenesis cannot be compatible with degenerate neutrinos in a natural way in the canonical and triplet seesaw models. We will then suggest a ''hybrid seesaw model'' consisting of right-handed neutrinos and a Higgs triplet, in which the required lepton asymmetry is generated by the decay of heavy right-handed neutrinos.

Our consideration will be based on the two basic requirements for the successful leptogenesis. First, the lepton number and CP violating decay of a heavy right-handed neutrino N or triplet Δ should be out-of-equilibrium:

$$\Gamma_{N,\Delta} < H \approx 1.7\sqrt{g_*}\,\frac{T^2}{M_{\rm Pl}} \tag{3}$$

at the temperature $T = M_{N,\Delta}$ where g_* is the number of relativistic degree of freedom at the temperature T and $M_{\rm Pl}$ is the Planck mass. Second, the effective operator $(m_{\nu\alpha\beta}/2v^2)L_\alpha L_\beta \overline{HH}$ generated below the seesaw scale should also be out-of-equilibrium in order not to erase the lepton asymmetry generated at the temperature T_{B-L}. This gives rise to [17]

$$T_{B-L} \lesssim 10^{11}\left(\frac{m_{\nu\alpha\beta}}{1\ \ {\rm eV}}\right)^{-2}\ \ {\rm GeV}, \tag{4}$$

where $T_{B-L} = M_{N,\Delta}$ in our case under the consideration.

Let us first note that the canonical seesaw mechanism with heavy right-handed neutrinos cannot provide three degenerate masses of the order 1 eV together with the successful leptogenesis. Given the Lagrangian with right-handed neutrinos N_i,

$$-\mathcal{L} = f_{ij}L_i N_j \overline{H} + \frac{1}{2}M_i N_i^2 + {\rm H.c.}, \tag{5}$$

the out-of-equilibrium condition (3) for the decay of a right-handed neutrino N_1 gives

$$\sum_i \frac{|f_{i1}|^2 v^2}{M_1} \lesssim 4\times 10^{-3}\ \ {\rm eV}. \tag{6}$$

Therefore, the right-handed neutrino N_1 decouples from generating an effective neutrino mass of order 1 eV and thus there must be a lightest neutrino ν_1 with a mass $m_{\nu_1} \lesssim 4 \times 10^{-3}$ eV [16].

We turn to the consideration of other types of seesaw models. [18]. Next candidate for the leptogenesis is the seesaw mechanism with heavy Higgs triplets where one needs at least two Higgs triplets in order to have proper CP violation [15]. In this model, the couplings of the heavy Higgs triplets Δ_i with the lepton doublets L_α and Higgs doublet H are given by

$$-\mathcal{L} = \frac{1}{2}h_{i\alpha\beta}L_\alpha L_\beta \Delta_i + \mu_i HH\Delta_i + \cdots. \tag{7}$$

Here we take $\mu_i \sim M_i$ where M_i is the mass of the Higgs triplet Δ_i. Neutrino masses, then, come from the nonvanishing vacuum expectation values of the neutral components of the Higgs triplets and the resulting neutrino mass matrix is

$$m_{\nu\alpha\beta} = m_{1\alpha\beta} + m_{2\alpha\beta} \equiv h_{1\alpha\beta}\frac{\mu_1 v^2}{M_1^2} + h_{2\alpha\beta}\frac{\mu_2 v^2}{M_2^2}, \tag{8}$$

where $v \equiv \langle H\rangle$ and the mass mixing between Δ_1 and Δ_2 is neglected. A key ingredient for the lepton asymmetry is the one-loop CP-violating mass correction in the decay of the lighter Higgs triplet, say, Δ_1, and it can be written as

$$\varepsilon_L \approx \frac{1}{8\pi}\sum_{\alpha\beta}\frac{m_{1\alpha\beta}m_{2\alpha\beta}}{m_{\nu\alpha\beta}^2}\frac{m_{\nu\alpha\beta}^2 M_1^2 M_2^2}{v^4(M_1^2 - M_2^2)}\frac{1}{\sum_{\gamma\delta}|h_{1\gamma\delta}|^2}, \tag{9}$$

where we take the CP phase of order 1 from the result of Ref. [15]. Since the baryon asymmetry is related to the lepton asymmetry through $n_B/s \approx \kappa\varepsilon_L/g_* \approx 10^{-10}$, we need $\varepsilon_L \approx 10^{-5} - 10^{-7}$ for $\kappa \approx 10^{-1} - 10^{-3}$ and $g_* \sim 100$.

Let us now discuss how the lepton asymmetry (9) is constrained by the out-of-equilibrium conditions (3),(4). Equation (4) restricts M_1 to be less than 10^{11} GeV and Eq. (3) concerned with the decay of Δ_1 leads to

$$\sum_{\gamma\delta}|h_{1\gamma\delta}|^2 < 10^{-6}\left(\frac{M_1}{10^{11}\ \ {\rm GeV}}\right). \tag{10}$$

This tells us that

$$\varepsilon_L \gtrsim 0.4\frac{m_{1\alpha\beta}m_{2\alpha\beta}}{m_{\nu\alpha\beta}^2}\left(\frac{M_1}{10^{11}\ \ {\rm GeV}}\right) \tag{11}$$

assuming no fine cancellation among various components $m_{\alpha\beta}$ and no fine degeneracy between M_1 and M_2. If $m_{1\alpha\beta} \sim m_{2\alpha\beta} \sim 1$ eV and the small splitting ϵ_a (2) is arranged within each component m_1 or m_2, the condition (11) indicates a low seesaw scale; $M_1 \lesssim 10^6$ GeV, and then Eq. (10) shows that the coupling h_1 has to be unnaturally small. Thus, it would be desirable to allow a hierarchy between m_1 and m_2, from which the small value ϵ_a naturally arises, that is, $\epsilon_a \sim m_1/m_2$ or m_2/m_1. In either case, from Eqs. (10),(11), we obtain $M_1 \lesssim 10^9$ GeV and $h_1 \lesssim 10^{-4}$. Now, let us briefly demonstrate how naturally such a hierarchy can be achieved in triplet seesaw models. Taking, as an example, the allowed values $M_1 \simeq 10^9$ GeV, $h_1 \simeq 10^{-4}$, and $\mu_2^2 \simeq M_1^2/10$, we can obtain $m_1 \simeq 1$ eV [see Eq. (8)]. But, in order to get $m_2/m_1 = (h_2/h_1)(\mu_2/\mu_1)(M_1^2/M_2^2) \simeq 10^{-3}$, we should require an unnatural hierarchy between h_1 and h_2 for the same order of mass parameters, i.e., $M_i \sim \mu_i (i=1,2)$, or otherwise, it can also be achieved without any large hierarchies among the parameters by arranging the various parameters such as $h_2 = 0.1h_1$, $M_2^2 = 10^2 M_1^2$, and $\mu_2 = 0.1M_2$. However, it would be very difficult to explain the origin of those relations between the parameters associated with the triplets Δ_i. Thus, although degenerate neutrinos can be compatible with lepto-

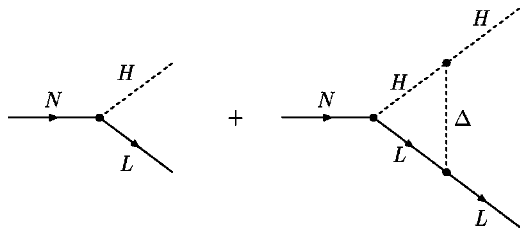

FIG. 1. The tree and one-loop diagrams generating the lepton asymmetry.

genesis in triplet seesaw model by arranging some parameters appropriately, it is not natural.

To remedy this, we would like to suggest a ''hybrid seesaw model'' in which the leptogenesis and degenerate neutrino mass can be reconciled in a more natural way. In the hybrid seesaw model, we introduce a heavy Higgs triplet Δ on top of three right-handed neutrinos N_α which have the following Yukawa and Higgs couplings:

$$-\mathcal{L}=\frac{1}{2}h_{\alpha\beta}L_\alpha L_\beta\Delta+f_{\alpha\beta}L_\alpha N_\beta\bar{H}+\mu HH\Delta. \tag{12}$$

Let M_Δ and M_N are the masses of the Higgs triplet and the right-handed neutrinos, respectively, and take all the mass parameters M_Δ, M_N, μ at the intermediate seesaw scale which will be determined from our consideration. We will further assume that $M_\Delta \gtrsim M_N$ so that the lepton asymmetry can arise from the decay of the heavy right-handed neutrinos. If we take the decay of the heavy Higgs triplet as the origin of the lepton asymmetry which may arise when $M_\Delta \lesssim M_N$, we encounter the similar situation as in the triplet seesaw model. Thus, we are not much interested in the possibility of the decay of the heavy Higgs triplet in the hybrid seesaw model. In the hybrid model, there are also two contributions to the neutrino mass given by

$$m_\nu = m_1 + m_2 \equiv \frac{f^2 v^2}{M_N} + h\frac{\mu v^2}{M_\Delta^2}, \tag{13}$$

where we abbreviated the flavor indices of the parameters f, h, and M_N. Now, the out-of-equilibrium conditions (3),(4) are satisfied when

$$m_1 \lesssim 4\times 10^{-3} \text{ eV}, \tag{14}$$

$$M_N \lesssim 10^{11}\left(\frac{m_{\nu\alpha\beta}}{1 \text{ eV}}\right)^2 \text{ GeV}. \tag{15}$$

Equation (14) implies that the mass m_1 can provide a right value for the tiny mass splitting of the atmospheric neutrino while the mass m_2 produces almost degenerate three neutrinos with $m_\nu \sim 1$ eV, that is $\epsilon_a \approx m_1/m_2 \sim 10^{-3}$. The CP nonconservation in our model is generated by the interference between the tree and one-loop diagram mediated by the Higgs triplet as shown in Fig. 1, and the resulting lepton asymmetry is given by

$$\varepsilon_L \approx \frac{1}{8\pi}\frac{\mathrm{Im}(f^2 h^* \mu)}{M_N |f|^2} F\left(\frac{M_\Delta^2}{M_N^2}\right), \tag{16}$$

where $F(x)=\sqrt{x}[1-(1-x)\ln(1+x)/x]$. Taking the CP phase of order 1, we thus have

$$\varepsilon_L \approx 10^{-5}\left(\frac{m_2}{1 \text{ eV}}\right)\left(\frac{M_\Delta}{10^{10} \text{ GeV}}\right)\left(\frac{M_\Delta}{M_N}\right), \tag{17}$$

which provides the right amount of the lepton asymmetry for $M_N \sim M_\Delta \sim (10^8 - 10^{10})$ GeV while satisfying the out-of-equilibrium condition (14). As alluded above, it is natural to have the splitting ϵ_a in terms of the ratio m_1/m_2 which fixes the values of the couplings f and h. To get $m_1 = 10^{-3}$ eV and $m_2 = 1$ eV, we need

$$f \approx 6\times 10^{-4}\left(\frac{M_N}{10^{10} \text{ GeV}}\right)^{1/2},$$

$$h \approx 3\times 10^{-4}\left(\frac{M_\Delta}{\mu}\right)\left(\frac{M_\Delta}{10^{10} \text{ GeV}}\right). \tag{18}$$

Therefore, we can accomplish leptogenesis in the hybrid model with three almost degenerate light neutrinos without assuming any hierarchies among various mass parameters and couplings. But, as in the triplet models, it still remains to be understood the origin of the smallness of the couplings $f \sim h \sim 10^{-4}$. Our requirement demands also the mass scales $\mu \sim M_N \sim M_\Delta$ to be less than $\sim 10^{10}$ GeV, which lies in the low end of the Peccei-Quinn symmetry breaking scale introduced to solve the strong CP problem [19]. Such a scale may be relevant to provide enough axionic cold dark matter if axionic strings play a role [20].

Let us finally make a remark on the hybrid seesaw models. Since the degenerate mass $m_\nu \sim 1$ eV should come from the triplet seesaw sector, it suffices to introduce only one right-handed neutrino and one triplet in its minimal scheme. The degenerate mass m_2 may be a consequence of, e.g., SO(3) symmetry in the triplet sector and the small splitting with $m_1 \sim \epsilon_a m_2$ can arise due to the presence of only one right-handed neutrino. The similar constructions have been made in Refs. [21]. We also remark that the much smaller splitting ϵ_s (2) for the solar neutrino oscillation can arise naturally from one-loop radiative corrections to degenerate neutrino mass matrices [22,23]. Most important effect would come from the tau Yukawa coupling h_τ which gives $\epsilon_s \approx \epsilon_\tau^2/4\epsilon_a$ [23,21] where $\epsilon_\tau \equiv h_\tau^2 \tan^2\beta \ln(M_N/M_Z)/32\pi^2 \approx 10^{-5}\tan^2\beta$ and $\tan\beta$ is the ratio between the vacuum expectation values of two Higgs doublets in the two Higgs doublet models or in the supersymmetric standard model. As we have $\epsilon_a \sim 10^{-3}$, we can achieve the LMA or LOW solution, depending on the value of $\tan\beta$.

In conclusion, we have examined whether the almost degenerate mass pattern accounting for hot dark matter and the other neutrino data can be consistent with the leptogenesis mechanism in various types of the seesaw models. While it is impossible to realize this feature in the canonical seesaw mechanism, some unnaturally hierarchical arrangement among the couplings and mass parameters related to each Higgs triplet is needed in the triplet seesaw model. We have then suggested the hybrid seesaw model with a heavy Higgs triplet and right-handed neutrinos. In this model, the out-of-equilibrium conditions required for the baryogenesis can be compatible with the almost degenerate neutrino masses and the small splitting for the atmospheric neutrino oscillation without any hierarchical structure of the couplings and masses in the seesaw sector. An unattractive consequence in either case is to require rather small couplings of order $10^{-4}-10^{-3}$, which will need further explanation.

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