Baryogenesis and Degenerate Neutrinos

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Abstract

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. To realize leptogenesis with almost degenerate Majorana neutrinos without severe fine-tuning of parameters, we propose the hybrid seesaw mechanism with a heavy Higgs triplet and right-handed neutrinos. Constructing a minimal hybrid seesaw model with SO(3) flavor symmetry for the neutrino sector, we show that the mass splittings for the atmospheric and solar neutrino oscillations which are consistent with the requirements for leptogenesis can naturally arise.

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Among various scenarios explaining the cosmological baryon asymmetry, the most attractive one is the leptogenesis mechanism given the experimental indications for nonzero neutrino masses. Current data from atmospheric [1] and solar [2] neutrino observations provide evidence for massive neutrinos, and terrestrial neutrino experiments [3–5] lead to meaningful constraints on neutrino masses and mixing. The atmospheric neutrino oscillation indicates the near maximal mixing between $\nu_\mu$ and $\nu_\tau$, $\sin^2 2\theta_{atm} \geq 0.85$, with a mass squared difference $\Delta m^2_{atm} \simeq 3 \times 10^{-3} \text{eV}^2$ [6]. The solar neutrino anomaly can be explained through matter enhanced neutrino oscillation if $3 \times 10^{-6} \leq \Delta m^2_{sol} \leq 10^{-5} \text{eV}^2$ and $2 \times 10^{-3} \leq \sin^2 2\theta_{sol} \leq 2 \times 10^{-2}$ (small angle MSW), or $10^{-5} \leq \Delta m^2_{sol} \leq 10^{-4} \text{eV}^2$, $\sin^2 2\theta_{sol} \geq 0.5$ (large angle MSW), $\Delta m^2_{sol} \sim 10^{-7} \text{eV}^2, \sin^2 2\theta_{sol} \sim 1.0$ (LOW solution) [7] and through long-distance vacuum oscillation if $5 \times 10^{-11} \leq \Delta m^2_{sol} \leq 10^{-9} \text{eV}^2$, $\sin^2 2\theta_{sol} \geq 0.6$. On the other hand, the CHOOZ experiment can constrain $\nu_e - \nu_x$ oscillation with $\Delta m^2_{13} \geq 10^{-3} \text{eV}^2$ [4], and the recent Palo Verde reactor experiment also indicates no observation of atmospheric $\nu_e - \nu_x$ oscillation for $\Delta m^2 \geq 1.12 \times 10^{-3}$ and for $\sin^2 2\theta \geq 0.21$ (for large $\Delta m^2$) [5].

The lightness of three active neutrinos could be a consequence of the existence of heavy fields and lepton number violation at a high scale through the seesaw mechanism [8]. This lepton number violation can erase the pre-existing baryon asymmetry of the universe, but can also lead to baryogenesis above the electroweak scale. The latter is called the leptogenesis mechanism in which the decays of the heavy fields can generate a lepton asymmetry which converts into the observed baryon asymmetry due to the sphaleron processes [9]. The heavy fields in the seesaw mechanism can be either the right-handed neutrinos [8] or Higgs triplets [10] both of which are known to yield a successful baryogenesis without fine-tuning of parameters [11,12]. In this scenario, the requirement for generating the right amount of baryon asymmetry puts meaningful constraints on the pattern of neutrino masses and mixing [13,14].

An interesting question in this regard is whether the leptogenesis mechanism can be consistent with degenerate neutrino scenarios which may come from another cosmological
demand for hot dark matter consisting of neutrinos \[15\]. Taking this cosmological indication together with the current neutrino data coming from the atmospheric \[1\], solar neutrino \[2\], the reactor \[4,5\], and neutrinoless double-beta decay \[16\] experiments, one is led to a specific pattern of Majorana neutrino mass matrix in the leading order terms as follows \[17\];

\[
m_\nu \sim m_0 \begin{pmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{2} & -\frac{1}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{1}{2} \end{pmatrix},
\]

which gives rise to three degenerate mass eigenvalues and bimaximal mixing for the atmospheric and solar neutrino oscillations. Here the three neutrinos with \(m_0 \approx 2\) eV can provide the right amount of hot dark matter to explain the structure formation of the universe \[13\].

Let us first recall that the degenerate mass pattern (1) with \(m_0 = \mathcal{O}(1)\) eV cannot yield a successful leptogenesis in the canonical seesaw mechanism with heavy right-handed neutrinos. This is because the condition for the out-of-equilibrium decay of a right-handed neutrino \(N_1\), \(\Gamma_{N_1} < H\), is satisfied only when

\[
m_{\nu_1} \lesssim 4 \times 10^{-3}\text{eV}
\]

for the lightest neutrino \(\nu_1\) \[13\].

In this letter, we investigate the possibility of realizing both the almost degenerate neutrino mass pattern (1) and a successful leptogenesis in the context of the seesaw mechanism. To find a natural model of this kind, it will be important to check whether the small mass splittings accounting for the atmospheric and solar neutrino oscillations are consistent with the out-of-equilibrium conditions of the leptogenesis mechanism. First of all, we will examine the leptogenesis in the triplet seesaw model recently proposed in Ref. \[12\], and show that the reconciliation of leptogenesis with degenerate neutrinos can be made with the price of fine tuning of parameters. Then, we will suggest the hybrid seesaw model consisting of right-handed neutrinos and a Higgs triplet \[18\], in which the required lepton asymmetry is generated by the decay of heavy right-handed neutrinos, and almost degenerate neutrinos with the desired tiny mass splittings arise in a natural manner.
In order to realize leptogenesis in the seesaw mechanism with heavy Higgs triplets, one needs at least two Higgs triplets \[\Delta_i\]. In this model, the couplings of the heavy Higgs triplets \[\Delta_i\] with the lepton doublets \[L_\alpha\] and Higgs doublet \[H\] are given by

\[
\mathcal{L} = \frac{1}{2} h_{i\alpha\beta} L_\alpha L_\beta \Delta_i + \mu_i H H \Delta_i + \cdots .
\] (3)

Here we take \[\mu_i \sim M_i\] where \[M_i\] is the mass of the Higgs triplet \[\Delta_i\]. 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

\[
m_{\nu\alpha\beta} = m_{1\alpha\beta} + m_{2\alpha\beta} \equiv h_{1\alpha\beta} \frac{\mu_1 v^2}{M_1^2} + h_{2\alpha\beta} \frac{\mu_2 v^2}{M_2^2}
\] (4)

where \[v \equiv \langle H \rangle\] and the mass mixing between \[\Delta_1\] and \[\Delta_2\] 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, \[\Delta_1\], and it can be written as

\[
\varepsilon_L \approx \frac{1}{8\pi} \sum_{\alpha\beta} \frac{m_{1\alpha\beta} m_{2\alpha\beta}}{m_{\nu\alpha\beta}^2 v^4 (M_1^2 - M_2^2)} \frac{1}{\sum_{\gamma\delta} |h_{1\gamma\delta}|^2}
\] (5)

where we take the CP phase of order 1 from the result of Ref. [12].

The quantity (5) is constrained by the out-of-equilibrium conditions for the baryogenesis. First, let us recall that the effective operator \[(m_{\nu\alpha\beta}/v^2)L_\alpha L_\beta \bar{H} \bar{H}\] generated below the scale \[M_1\] or \[M_2\] should be out-of-equilibrium in order not to erase the lepton asymmetry generated at the temperature \[T_{B-L}\]. This gives rise to [14]

\[
T_{B-L} \lesssim 10^{11} \left( \frac{m_{\nu\alpha\beta}}{1\text{eV}} \right)^2 \text{GeV},
\] (6)

where \[T_{B-L} = M_1\] in our scenario under the consideration. Second, the decay of \[\Delta_1\] should also be out-of-equilibrium, \[\Gamma_{\Delta_1} < H\], leading to \[\sum_{\gamma\delta} |h_{1\gamma\delta}|^2 M_1/8\pi < 1.7 \sqrt{g_* T}^2 / M_{Pl}\] at the temperature \[T = M_1\]. With \[g_* \sim 100\], we then have

\[
\sum_{\gamma\delta} |h_{1\gamma\delta}|^2 < 10^{-6} \left( \frac{M_1}{10^{11}\text{GeV}} \right).
\] (7)

Since the baryon asymmetry is related to the lepton asymmetry by \[n_B/s \approx \kappa \varepsilon_L / g_* \approx 10^{-10}\], we can estimate \[\varepsilon_L \approx 10^{-5} - 10^{-7}\] for \[\kappa \approx 10^{-1} - 10^{-3}\] and \[g_* \sim 100\]. Combining this with
the out-of-equilibrium conditions (8, 7) and assuming that there are no fine cancellations in Eq. (5), we get

$$m_{1\alpha\beta}m_{2\alpha\beta}\left(\frac{m_{\nu\alpha\beta}}{1\text{eV}}\right) \lesssim 10^{-6}.$$  

This result implies a large hierarchy between \(m_{1\alpha\beta}\) and \(m_{2\alpha\beta}\), in other words, \(m_{1\alpha\beta} \ll m_{2\alpha\beta} \sim m_{\nu\alpha\beta}\) with \(m_{1\alpha\beta}/m_{2\alpha\beta} \lesssim 10^{-6}\). To achieve such a large hierarchy, an unpleasant fine tuning between parameters related to two Higgs triplets is needed;

$$\frac{h_{1\alpha\beta} \mu_1}{h_{2\alpha\beta} \mu_2} \lesssim 10^{-6} \left(\frac{M_1}{M_2}\right)^2.$$  

Note that we have the condition \(M_1 < M_2\).

At this point, we pay attention to another important theoretical issue concerned with degenerate neutrinos. For the Majorana neutrino mass matrix (1) to be realistic, it has to be completed with the next leading terms which lift the degeneracy by the 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 \(\epsilon_s \equiv (m_{\nu_2} - m_{\nu_1})/m_0\) with the mass eigenvalues, \(m_{\nu_3} \gtrsim m_{\nu_2} \gtrsim m_{\nu_1}\), the observed mass-squared differences, \(\Delta m^2_{\text{atm}}\) and \(\Delta m^2_{\text{sol}}\), respectively for the atmospheric and solar neutrino oscillations fix their values as

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

Therefore, we have \(\epsilon_a \sim 10^{-3}\) for the atmospheric oscillation (3) and \(\epsilon_s \sim 10^{-5}, 10^{-7} \text{ or } 10^{-10}\) for the large mixing angle MSW solution (LMA), the low \(\Delta m^2\) MSW solution (LOW) or the vacuum oscillation solution (VO) to the solar neutrino problem, respectively (7).

Given the two contributions to the neutrino mass matrix (1), an interesting question one can address is whether one contribution corresponds to a large mass of order of \(m_0\) and the other to the tiny splitting \(\epsilon_a\) or \(\epsilon_s\). The required hierarchy (8) shows that the ratio \(m_{1\alpha\beta}/m_{2\alpha\beta}\) cannot give rise to \(\epsilon_a\), but it can be used to generate \(\epsilon_s\) for the case of the LOW or VO solution. That is, the splitting \(\epsilon_a\) and \(\epsilon_s\) for the LMA solution have to be arranged within the mass matrix \(m_2\) in the triplet seesaw model.
To remedy the fine-tuning problem in realizing both the leptogenesis mechanism and three degenerate neutrinos in the triplet seesaw mechanism, let us suggest a simple hybrid model with a Higgs triplet and three heavy right-handed neutrinos which allows for the Yukawa and Higgs couplings

\[ \mathcal{L} = \frac{1}{2} h_{\alpha\beta} L_\alpha L_\beta \Delta + f_{\alpha\beta} L_\alpha N_\beta \bar{H} + \mu HH \Delta + \cdots. \]  

(11)

Let \( M_\Delta \) and \( M_N \) are the masses of the Higgs triplet and the right-handed neutrinos, respectively, and \( \mu \) parameter is taken to be of order \( M_\Delta \). We will further assume that \( M_\Delta \gtrsim M_N \) and the lepton asymmetry arises 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, we encounter the similar fine-tuning problem as in Eq. (9). There are again two contributions to the neutrino mass matrix given by

\[ m_\nu = m_1 + m_2 \equiv \frac{f^2 v^2}{M_N} + \frac{\mu v^2}{M_\Delta^2}, \]  

(12)

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

\[ m_1 \lesssim 4 \times 10^{-3} \text{eV}, \]  

(13)

\[ M_N \lesssim 10^{11} \left( \frac{m_{\nu e}}{1 \text{eV}} \right)^2 \text{GeV}, \]  

(14)

which are the counterparts of the previous Eqs. (2) and (6), respectively. The condition (13) implies the hierarchy \( m_1 \ll m_2 \sim 1 \text{eV} \) with \( m_1/m_2 \lesssim 10^{-3} \), which would be relevant for the required splitting \( \epsilon_a \) for the atmospheric neutrino oscillation. The CP-nonconservation in our hybrid 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

\[ \varepsilon_L \approx \frac{1}{8\pi} \frac{\text{Im}(f^2 h^* \mu)}{M_N |f|^2} F(\frac{M_\Delta^2}{M_N^2}) \]  

(15)

where \( F(x) = \sqrt{x}[1 - (1 - x) \ln(1 + x)/x] \). Taking the CP phase of order 1, we thus have
\[ \varepsilon_L \approx 10^{-5} \left( \frac{m_2}{\text{1eV}} \right) \left( \frac{M_\Delta}{10^{10}\text{GeV}} \right) \left( \frac{M_\Delta}{M_N} \right), \]

which provides the right amount of the lepton asymmetry for \( M_N \sim M_\Delta \sim (10^8 - 10^{10}) \text{ GeV} \) while satisfying the out-of-equilibrium condition (14).

As alluded above, it is amusing to observe that the splitting \( \epsilon_a \) can be provided by the ratio \( m_1/m_2 \) satisfying the leptogenesis requirements, contrary to the triplet seesaw model. Requiring \( m_1 \sim 10^{-3} \text{ eV} \) and \( m_2 \sim 1 \text{ eV} \), therefore, we find

\[ f \sim 4 \times 10^{-4} \left( \frac{M_N}{10^{10}\text{GeV}} \right)^{1/2}, \]
\[ h \sim 10^{-4} \left( \frac{M_\Delta}{\mu} \right) \left( \frac{M_\Delta}{10^{10}\text{GeV}} \right). \]

Thus, we can accomplish leptogenesis in the hybrid model with three almost degenerate light neutrinos when both Yukawa couplings \( f \) and \( h \) are of order \( 10^{-4} \). Therefore, we one can avoid a big hierarchy between the parameters of the theory. Still, it remains to be understood the overall smallness of our parameters; \( f \sim h \sim 10^{-4} \) and \( \mu \sim M_N \sim M_\Delta \sim 10^{-10} \text{ GeV} \), which would be resolved with the question of an intermediate scale. Having \( \epsilon_a \sim m_1/m_2 \), let us remark that the splitting \( \epsilon_s \) can come from the \( \tau \) Yukawa coupling effect through the renormalization group evolution [19,20]. It is then enough to introduce only two Yukawa couplings for our purpose: one \( h \) for generating \( m_0 \) and one \( f \) for \( \epsilon_a \).

From now on, we construct the minimal hybrid seesaw model accommodating all the features under consideration. For this, we rely on the symmetry principle from which the degenerate mass \( m_0 \) and the relevant splittings \( \epsilon_a \) and \( \epsilon_s \) are obtained in a systematic way. Let us consider the SO(3) flavor symmetry under which the lepton doublets form a triplet with the \((+, -, 0)\) components. The SO(3) symmetry has to be badly broken by the charged-lepton Yukawa couplings, and the working hypothesis is that the SO(3) flavor basis is related to the charged-lepton flavor basis as follows [21];

\[ L_+ = L_e, \quad L_- = c_1 L_\mu - s_1 L_\tau, \quad L_0 = s_1 L_\mu + c_1 L_\tau \]

where \( c_1 = \cos \theta_1 \), etc. Recall that the angle \( \theta_1 \) is determined by the atmospheric neutrino mixing, that is, \( c_1^2 = s_1^2 = 1/2 \). We further assume that the lepton doublet couplings with
the Higgs triplet $\Delta$ and a right-handed neutrino preserve the SO(3) symmetry and its U(1)
subgroup, respectively as follows;

$$\mathcal{L} = h(L_+ L_- + \frac{1}{2} L_0 L_0)\Delta + fL_0N_0\bar{H} + \mu HH\Delta + \cdots$$  \hspace{1cm} (19)

where we introduced only one right-handed neutrino $N_0$ with the U(1) charge 0 as a minimal
choice. Our conclusion is not altered by introducing three right-handed neutrinos as long
as their couplings and mass terms preserve the U(1) subgroup [22]. The full neutrino mass
matrix gets important contributions not only from the Lagrangian (19) at tree level but
also from the one-loop correction due to the tau Yukawa coupling $h_\tau$ [19,20]. The latter
contribution breaks the U(1) subgroup of the SO(3) flavor symmetry and is controlled by
the quantity $\epsilon_\tau \equiv h_\tau^2 \ln(M_N/M_Z)/32\pi^2 \approx 10^{-5}$. Including all these contributions, we get the
neutrino mass matrix in the SO(3) basis;

$$m_\nu = m_0\begin{pmatrix} 0 & (1 + \frac{1}{2}s_1^2\epsilon_\tau) & -\frac{1}{2}c_1s_1\epsilon_\tau \\ (1 + \frac{1}{2}s_1^2\epsilon_\tau) & 0 & -\frac{1}{2}c_1s_1\epsilon_\tau \\ -\frac{1}{2}c_1s_1\epsilon_\tau & -\frac{1}{2}c_1s_1\epsilon_\tau & (1 + c_1^2\epsilon_\tau_0 + \frac{\delta m_0}{m_0}) \end{pmatrix}$$ \hspace{1cm} (20)

where $m_0 \equiv h\mu v^2/M_\Delta^2$ and $\delta m_0 \equiv f^2v^2/M_N$ as in Eq. (12). Transformed into the charged-lepton flavor basis by Eq. (18), the leading terms of the matrix (20) reproduce the desired
form of mass matrix (1). From Eq. (20), the quantities $\epsilon_a$ and $\epsilon_s$ can be calculated as

$$\epsilon_a \approx \frac{\delta m_0}{m_0}, \quad \epsilon_s \approx \frac{1}{4} \sin^2 2\beta_1 \frac{\epsilon_\tau^2}{\epsilon_a}.$$ \hspace{1cm} (21)

With $\epsilon_a \sim 10^{-3}$ required by the atmospheric neutrino oscillation, we have $\epsilon_s \sim 10^{-7}$ which is
in the right range for the LOW solution. As noted in Ref. [22], the LMA solution (requiring
$\epsilon_s \sim 10^{-5}$) can be realized in the two Higgs doublet model where $\epsilon_s$ contains the additional
factor $\tan^4 \beta$. For the successive SO(3) breaking to be realistic, the hierarchy between the
Yukawa couplings, $f \ll h$, would have to be imposed as the latter conserves the SO(3) flavor
symmetry and the former breaks it. This would require $\mu/M_\Delta \approx 0.1 - 0.01$ as can be seen
from Eq. (17).

In conclusion, we have brought the theoretical issue of reconciling two important cosmo-
logical demands, baryon asymmetry and neutrino as hot dark matter, in the context of the
seesaw mechanism. For this purpose, 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. As was pointed out, this feature cannot be realized in the canonical seesaw mechanism. On the other hand, we have shown that some fine-tuning between the couplings related to each Higgs triplet is needed to achieve leptogenesis with almost degenerate neutrinos in the triplet seesaw model. To resolve this problem, we have suggested the hybrid seesaw mechanism with a heavy Higgs triplet and right-handed neutrinos. In this type of models, the out-of-equilibrium conditions required for the successful baryogenesis can be naturally satisfied with the almost degenerate neutrino masses and the small mass splitting for the atmospheric neutrino oscillation. Furthermore, the mass splitting for the solar neutrino can come from the renormalization group effect due to the tau Yukawa coupling. Finally, we have presented a simple model realizing all these features. In the minimal case, the model consists of a Higgs triplet and a right-handed neutrino with two additional leptonic Yukawa couplings. These two parameters are responsible for generating the degenerate neutrino mass in the leading order and the splitting for the atmospheric neutrino mass-squared difference, which respect the SO(3) flavor symmetry and its U(1) subgroup, respectively.
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Figure 1. The tree and one-loop diagrams generating the lepton asymmetry.