Left-Right Symmetric Model of Neutrino Dark Energy

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We implemented the neutrino dark energy (νDE) proposal in a left-right symmetric model. Unlike earlier models of mass varying neutrinos, in the present model the mass parameter that depends on the scalar field (acceleron) remains very light *naturally*. The required neutrino masses then predicts the $U(1)_R$ breaking scale to be in the TeV range, providing new signals for LHC. Compared to all other νDE proposals, this model has the added advantage that it can also be embedded into a grand unified theory. In this scenario leptogenesis occurs through decays of scalars at very high energy.

Present observations reveal that the dark energy $\sim (3\times 10^{-3}\,\text{eV})^4$[1] contributes about 70% to the total density of our universe. Since the only known physics around this scale is the neutrino mass, there are now attempts to relate the origin of the dark energy with the neutrino masses [2, 3, 4]. This connection is based on the idea of quintessence [5], and have several interesting consequences [6, 7].

In the original model of neutrino dark energy (νDE) or the mass varying neutrinos (mavans) [2, 3, 4], the standard model is extended by including singlet right-handed neutrinos $N_i, i = 1, 2, 3$, and giving a Majorana mass to the neutrinos which varies with a scalar field, the acceleron. This model was not complete and several problems were pointed out [3, 8]. Some of the problems have been solved in subsequent works [9, 10], but more studies are required to make this model fully consistent. The main motivation of the present article is to justify the very low scale entering in this model naturally, embed this idea into a left-right symmetric model and also in grand unified theories. Since the right-handed neutrinos are not very heavy, leptogenesis occurs through scalar decays.

In the νDE models, the Majorana masses of the right-handed neutrinos varies with the acceleron field and that relates the scale of dark energy with the light neutrino masses. Naturalness requires the Majorana masses of the right-handed neutrinos also to be in the range of eV, so the main motivation of the seesaw mechanism is lost. The smallness of the light neutrino masses cannot be attributed to a large lepton number violating mass scale in the theory. In this νDE model, the neutrino Dirac masses cannot be made to vary with the acceleron field, since that will then allow coupling of the acceleron field with the charged leptons and a natural scale for the dark energy will then be the mass of the heaviest charged lepton. For the same reason, this mechanism cannot be embedded into a left-right symmetric model, in which the $SU(2)_R$ group relates the right-handed neutrinos to the right-handed charged leptons.

The problem with the smallness of the mass parameter that depends on the acceleron field can be softened in the νDE models with triplet Higgs scalars [10]. In these models the standard model is extended to include triplet Higgs scalars. In any phenomenologically consistent triplet Higgs scalar model, lepton number is violated explicitly by a trilinear scalar couplings of the triplet Higgs scalar with the standard model Higgs doublet. In the νDE model with the triplet Higgs scalars, the coefficient of this trilinear scalar coupling with mass dimension varies with the acceleron field, and naturalness allows this parameter to be as large as a few hundred GeV. Although the scale of this mass parameter predicts new signals in the TeV range, there is no symmetry that makes this scale natural.

We propose a left-right symmetric model, in which the mass parameter that varies with the acceleron field remains small naturally and the scale of dark energy is related to the neutrino masses. This is the only νDE model that can be embedded into a grand unified theory, without relating the scale of dark energy to the charged fermion masses. We then discuss the question of leptogenesis in this model.

We start with the left-right symmetric extension of the standard model [11] with the gauge group $G_{LR} \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, and the electric charge is related to the generators of the group as:

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2} = T_{3L} + Y\,. \qquad (1)$$

The quarks and leptons transform under the left-right symmetric group as:

$$\begin{aligned} Q_L &= \begin{pmatrix} u_L \\ d_L \end{pmatrix} \equiv [3,2,1,\tfrac{1}{3}] \quad Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \equiv [3,1,2,\tfrac{1}{3}] \\ \ell_L &= \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \equiv [1,2,1,-1] \quad \ell_R = \begin{pmatrix} N_R \\ e_R \end{pmatrix} \equiv [1,1,2,-1] \\ & S_R \equiv [1,1,1,0]\,. \end{aligned} \qquad (2)$$

In addition to the standard model fermions, the right-handed neutrinos N_R and a right-handed singlet fermion S_R have been introduced. Under left-right parity this field transform to its CP conjugate state as: $S_R \leftrightarrow {S^c}_L$, and the Majorana mass term is invariant under the parity transformation. So, although we do not include another field S_L, the theory is left-right symmetric. This is possible because this field transform to itself $S_R \equiv (1,1,1,0) \leftrightarrow (1,1,1,0)$ under the transformation $SU(2)_L \leftrightarrow SU(2)_R$.

We consider the symmetry breaking pattern [12, 13]:

$$\begin{aligned} & SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{(B-L)} \; [G_{LR}] \\ \stackrel{M_R}{\rightarrow} \; & SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{(B-L)} \quad [G_{1R}] \\ \stackrel{m_r}{\rightarrow} \; & SU(3)_c \times SU(2)_L \times U(1)_Y \qquad [G_{std}] \\ \stackrel{m_W}{\rightarrow} \; & SU(3)_c \times U(1)_Q \qquad [G_{em}] \,. \end{aligned}$$

The Higgs scalars required to break the left-right symmetric group to G_{1R} transform as $\xi_R \equiv (1,1,3,0)$. This Higgs scalar does not couple to the fermions and cannot give Majorana masses to the neutrinos, since it does not carry any $B-L$ quantum number. The group G_{1R} and the B_L symmetry is broken by the vacuum expectation value (*vev*) of the field $\chi_R \equiv (1,1,2,1)$ [14, 15]. If $SU(2)_R$ is not broken to its subgroup $U(1)_R$ at some high scale, the field χ_R can break the left-right symmetry group directly to the standard model. For consistency with the left-right symmetry, or the existence of the left-right parity would then require the fields $\xi_L \equiv (1,3,1,0)$ and $\chi_L \equiv (1,2,1,1)$. We break the standard model gauge symmetry by a bi-doublet $\Phi \equiv (1,2,2,0)$, whose *vev* can give masses to the charged fermions. In addition, we introduce another bi-doublet $\Psi \equiv (1,2,2,0)$, which does not contribute to the fermion masses but has similar *vev* and a singlet scalar field $\eta \equiv (1,1,1,0)$, which acquires a tiny *vev* and generate the mass scale for the dark energy.

We start with the interactions of the Higgs scalar fields. There are quadratic and quartic self interactions of all the fields, which determines their masses and vacuum expectation values (*vev*). However, some of the fields would acquire induced *vev*s due to their linear interactions. We shall first write down these terms which will allow us to determine the *vev*s of the different fields. In principle, one should write down all the scalar interactions and then minimize the potential to find the consistent solution for the *vev*s of the different fields. These details will be presented elsewhere. Here we shall present the essential part of the scalar interactions and an estimate of the *vev*s. In addition to the usual quadratic and quartic interactions of the different fields, for the working of the present mechanism the Lagrangian contains the terms:

$$\begin{aligned} \mathcal{L}_s &= h_\Phi \eta (\Psi \xi_L \Phi + \Psi^\dagger \xi_R \Phi) + h_\chi \eta \chi_L^\dagger \chi_R \Phi \\ &+ h_\xi \xi_L \xi_R (\Phi^\dagger \Phi + \Psi^\dagger \Psi) \end{aligned} \tag{3}$$

This Lagrangian results from a Z_4 discrete symmetry, under which the different fields transform as:

$$\begin{array}{ccc} \chi_L \to i\chi_L & \chi_R \to -i\chi_R & S_R \to iS_R \\ \xi_L \to i\xi_L & \xi_R \to -i\xi_R & \eta \to -\eta \\ & \Psi \to i\Psi & \end{array}$$

Denoting the *vev*s of the different fields by:

$$\begin{array}{ll} \langle \xi_L \rangle = u_L & \langle \xi_R \rangle = u_R \\ \langle \chi_L \rangle = v_L & \langle \chi_R \rangle = v_R \\ \langle \Phi \rangle = v & \langle \eta \rangle = u \\ \langle \Psi \rangle = w & \end{array}$$

we can minimize the complete scalar potential and find a consistent solution with (the details will be presented elsewhere):

$$\begin{aligned} u \approx \frac{vw(u_L+u_R)}{m_\eta^2} \quad u_L \approx \frac{(v^2+w^2)u_R}{m_\xi^2} \quad v_L \approx \frac{v v_R u}{m_\chi^2} \\ u_R \gg v_R > v > w \gg u \gg v_L \,. \end{aligned} \tag{4}$$

In grand unified theories the consistency of the gauge coupling unification requires the scale of left-right symmetry breaking to be above 10^{11} GeV, so we shall assume $u_R \sim 10^{11}$ GeV. We also assume $m_\eta \sim m_\xi \sim u_R$. However, the G_{1R} symmetry breaking scale could be very low, so we shall assume $m_\chi \sim v_R \sim$ TeV. The other mass scales are then $v \sim m_w \sim 100$ GeV, $u \sim u_L \sim$ eV and $v_L \sim 10^{-2}$ eV. Since the $B-L$ symmetry is broken around the TeV scale, there will be new phenomenological consequences that may be observed at LHC.

The neutrino masses come from the Yukawa interactions of the leptons and the singlet fermion S, which are given by:

$$\begin{aligned} \mathcal{L}_Y &= f \overline{\ell_L} \, \ell_R \Phi + f_L \overline{S_R} \, \ell_L \chi_L + f_R \overline{S^c{}_L} \ell_R \, \chi_R \\ &+ \frac{1}{2} f_s \eta \overline{S^c{}_L} \, S_R + H.c. \,. \end{aligned} \tag{5}$$

The Yukawa couplings f are 3×3 matrix, while f_L and f_R are $3 \times n$ matrices, if we assume that there are n singlet fermions S and f_s is a $n \times n$ matrix. The neutrino mass matrix can now be written in the basis ($\nu_L \quad N^c{}_L \quad S^c{}_L$) as:

$$M_\nu = \begin{pmatrix} 0 & fv & f_L v_L \\ fv & 0 & f_R v_R \\ f_L v_L & f_R v_R & f_s u \end{pmatrix} . \tag{6}$$

This matrix can be block diagonalised, which gives the masses of the right-handed neutrinos and the singlet fermions S to be of the order of the largest entry in the mass matrix v_R. The left-handed neutrinos remains light with small admixture with heavier states and the light eigenvalue comes out to be

$$m_\nu = -2 \frac{f f_L}{f_R} \frac{v v_L}{v_R} + \frac{f_s f^2}{f_R^2} \frac{u v^2}{v_R^2} \,. \tag{7}$$

The first term is the type-III seesaw [16] contribution and the second term is the double seesaw contribution. With the choice of the *vev*s discussed earlier, both these terms become comparable, although the second term dominates.

We now assume that the mass parameter $M_s = f_s u \sim f_s\langle\eta\rangle$ varies with the acceleron field $\mathcal{A}$. This parameter M_s remains of the order of eV *naturally*, and it does not couple to the charged fermions. Thus the model satisfies both the conditions we wanted to achieve. Embedding this model in a grand unified theory is also straightforward. Consider an $SO(10)$ grand unified theory. The quarks and leptons in this model would belong to a 16-dimensional representation, while S_R will belong to a singlet representation. So, the Majorana mass M_s of the singlet can vary with the acceleron field without affecting the charged fermion masses. The scalars belong to representations: $\xi_{L,R}$ [45], χ_L [16], χ_R $[\overline{16}]$, η [1] and Φ [10]. These fields will then allow the interactions required for the implementation of this model. When this model is embedded in a grand unified theory, the different mass scales for the left-right symmetry breaking and the $U(1)_R$ symmetry breaking come out to be consistent with the gauge coupling unification.

We shall now discuss the implementation of the νDE mechanism in this model. We assume that the singlet mass M_s varies with the acceleron field $\mathcal{A}$, so that the neutrino mass becomes a dynamical quantity since the double seesaw contribution dominates over the type-III seesaw. This gives the coupling between the neutrinos and the acceleron, which stops the dynamical evolution of the acceleron fields when the neutrinos become non-relativistic. The dependence of the mass M_s on the acceleron field governs the dynamics of the dark energy. This details would depend on the nature of the acceleron field. Since we shall not be specifying the origin of the acceleron field, we shall comment only on some generic structures of this solution.

As in the original νDE model, we consider the nonrelativistic limit, when m_ν is a function of dark energy, the potential of dark energy becomes

$$V = m_\nu(\mathcal{A})\, n_\nu + V_0(\mathcal{A})\,. \qquad (8)$$

Here the scalar potential $V_0(\mathcal{A})$ is due to the acceleron field, for example [3],

$$V_0\,(\mathcal{A}) \;=\; \Lambda^4\;\log(1 + |M_s(\mathcal{A})/\mu|)\,. \qquad (9)$$

Due to the back reaction from the neutrinos, the evolution of acceleron field should be described by the effective potential (8) which depends on the total numbers n_ν of thermal background neutrinos and antineutrinos.

The acceleron field will be trapped at the minima of the potential, which ensures that as the neutrino mass varies, the value of the acceleron field will track the varying neutrino mass. One generic feature of this solution is that it leads to a equation of state with $\omega = -1$ at present. The most important feature of this scenario is that the energy scale for the dark energy gets related to the neutrino mass, which is highly desirable. This also explains why the universe enters an accelerating phase now [17].

The effective low-energy Lagrangian will now become

$$-\,\mathcal{L}_{eff} = M_s(\mathcal{A})\frac{f^2}{f_R^2}\frac{v^2}{v_R^2}\;\nu_i\nu_j + H.c. + V_0(\mathcal{A})\,, \qquad (10)$$

where M_s is naturally of the order of fraction of eV and hence can explain the dark energy with the equation of state satisfying $w = -1$. The scale of dark energy $\Lambda \sim 10^{-3}$ eV does not require any unnaturally small Yukawa couplings or symmetry breaking scale in this case. The electroweak symmetry breaking scale v and the $U(1)_R$ breaking scales are comparable and hence the new gauge boson corresponding to the group $U(1)_R$ will have usual mixing with Z and should be accessible at LHC.

Since the minima of the potential relates the neutrino mass to a derivative of the acceleron potential, the value of the acceleron field gets related to the neutrino mass. On the other hand, as the neutrino mass grows, the degeneracy pressure due to the background neutrinos and antineutrinos also starts growing. This causes problem with the stability of this solution [8, 18]. However, this generic problem of this scenario may be explained by considering formation of neutrino lumps in the universe. As the neutrino mass grows, there would be a tendency for the neutrinos to cluster together due to the attractive force originating from the acceleron coupling. These neutrino lumps would then behave as dark matter and will not affect the dynamics of the acceleron field, making the solution stable [19].

In this scenario leptogenesis [20] occurs through decays of the heavy scalars η. Unlike other models of type III seesaw mechanism [15], the right-handed neutrinos and the singlet fermions S_R have masses in the TeV range, and hence, their decays cannot generate any lepton asymmetry. When ξ_R acquires its *vev* at very large scale, the heavy scalars η can decay into $\eta \to \Phi^* + \Psi$ and $\eta \to S_R + S_R$. These decays of η can generate a asymmetry in S_R and $S^c{}_L$ when the tree-level diagrams interfere with self-energy type one loop diagrams [21]. Since S_R does not carry any $B - L$ quantum number, a lepton asymmetry is not generated at this time. Before the electroweak symmetry breaking, when the field χ_R acquires *vev*, the singlet fermions S_R mix with the right-handed neutrinos and at this time the asymmetry in S_R and S_L^c is converted to a lepton asymmetry of the universe. This lepton asymmetry, in turn, generates the required baryon asymmetry of the universe in the presence of the sphalerons [22].

In conclusion, we proposed a left-right symmetric extension of the standard model, where the νDE mechanism could be embedded. The most important advantage of this model over all the existing models is that it allows a naturally small scale for the dark energy. The existence of the large scale that generates this small scale naturally through a seesaw suppression, allows leptogenesis in this model. The model has the added feature that it can be embedded in a grand unified theory.

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