LEPTOGENESIS, NEUTRINOLESS DOUBLE BETA DECAY AND TERRESTRIAL CP VIOLATION*

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Leptogenesis in left–right symmetric theories is studied. The usual see-saw mechanism is modified by the presence of a left-handed Higgs triplet. A simple connection between the properties of the light left-handed and heavy right-handed neutrinos is found. Predictions of this scenario for neutrinoless double beta decay and terrestrial CP violation in long-baseline experiments are given. These observables can in principle distinguish different realizations of the model.

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1. Introduction

One of the problems waiting to be solved in particle physics and cosmology is the explanation of the baryon asymmetry of the Universe. Since Standard Model baryogenesis fails to produce a sufficient baryon asymmetry, other, new physics approaches are being followed. Among them stands out leptogenesis [1] as one of the most popular. Heavy right-handed Majorana neutrinos violate CP and lepton number during their out of equilibrium decay, thereby — when sphalerons [2] convert the lepton asymmetry in a baryon asymmetry — fulfilling all of Sakharov's three conditions [3].

The impressive evidence for non-vanishing neutrino masses opens now the possibility to study this new physics problem on a broader phenomenological basis. Typical models build to explain the neutrino mass and mixing scheme predict also heavy right-handed Majorana neutrinos, mostly due to some see-saw [4] mechanism. It is now a fruitful question to ask if a given

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model for neutrino masses also explains the baryon asymmetry via the leptogenesis mechanism. A number of groups have studied this within their respective approach [5].

As the name already indicates, Left–Right (LR) symmetric theories represent a natural way to connect the light left-handed with the heavy right-handed neutrino sector. In [7] the relationship of both sectors and the impact on leptogenesis was analyzed. An observable effect of the relation between neutrino oscillation and leptogenesis was then proposed in [8]. The three yet unknown phases in the left-handed neutrino mass matrix govern the magnitude of the effective neutrino mass measured in neutrinoless double beta decay and the size of terrestrial CP violating effects in long-baseline experiments. Many models explain the baryon asymmetry as well as the light mass and mixing scheme. Predictions of other observables are then very helpful to rule out or confirm models. The relationship of terrestrial CP violation and leptogenesis was also analyzed in [9].

The paper is organized as follows: In Section 2 the connection of leptogenesis and neutrino oscillation in left–right symmetric theories is given and the results on the baryon asymmetry are presented. The connection to terrestrial CP violation is made in Section 3 and the conclusions are drawn in Section 4.

2. Neutrino oscillation and leptogenesis in left–right symmetric theories

In LR symmetric theories the see-saw formula reads

$$m_\nu = m_{\rm L} - \tilde{m}_{\rm D}\, M_{\rm R}^{-1}\, \tilde{m}_{\rm D}^T\,, \tag{1}$$

where $m_{\rm L}$ and $M_{\rm R}$ are Majorana mass matrices generated by Higgs triplets and $\tilde{m}_{\rm D}$ is a Dirac mass matrix. The matrix m_ν is further diagonalized by

$$U_{\rm L}^T\, m_\nu\, U_{\rm L} = {\rm diag}(m_1, m_2, m_3)\,, \tag{2}$$

where m_i are the light neutrino masses. The symmetric matrix $M_{\rm R}$ also appears in the Lagrangian

$$-\mathcal{L}_Y = \overline{l_{i{\rm L}}}\, \frac{\Phi}{v}\, \tilde{m}_{{\rm D}\,ij}\, N'_{{\rm R}j} + \tfrac{1}{2}\, \overline{N'^{c}_{{\rm R}i}}\, M_{{\rm R}ij}\, N'_{{\rm R}j} + \text{ h.c.} \tag{3}$$

with $l_{i{\rm L}}$ the leptonic doublet and $v \simeq 174$ GeV the vacuum expectation value (vev) of the Higgs doublet Φ. Diagonalizing $M_{\rm R}$ brings us to the physical basis

$$U_{\rm R}^T\, M_{\rm R}\, U_{\rm R} = {\rm diag}(M_1, M_2, M_3)\,. \tag{4}$$

The asymmetry is caused by the interference of tree level with one loop corrections for the decays of the lightest Majorana, $N_1 \to \Phi\, l^c$ and $N_1 \to \Phi^\dagger\, l$:

$$\begin{aligned} \varepsilon &= \frac{\Gamma(N_1 \to \Phi\, l^c) - \Gamma(N_1 \to \Phi^\dagger\, l)}{\Gamma(N_1 \to \Phi\, l^c) + \Gamma(N_1 \to \Phi^\dagger\, l)} \\ &= \frac{1}{8\,\pi\,v^2}\,\frac{1}{(m_{\rm D}^\dagger m_{\rm D})_{11}}\,\sum_{j=2,3}\,{\rm Im}(m_{\rm D}^\dagger m_{\rm D})_{1j}^2\; f\left(\frac{M_j^2}{M_1^2}\right)\,. \end{aligned} \tag{5}$$

The function f includes terms from vertex and self-energy contributions:

$$f(x) = \sqrt{x}\left(1 + \frac{1}{1-x} - (1+x)\,\ln\left(\frac{1+x}{x}\right)\right) \simeq -\frac{3}{2\,\sqrt{x}}\,. \tag{6}$$

The approximation holds for $x \gg 1$.

In our approach, the left–right symmetry [10] plays an important role. It relates the unitary matrices $U_{\rm L}$ and $U_{\rm R}$ to each other since the triplet induced Majorana mass matrices in Eq. (1) have the same coupling matrix f in generation space:

$$m_{\rm L} = f\,v_{\rm L} \quad \text{and} \quad M_{\rm R} = f\,v_{\rm R}\,. \tag{7}$$

The numbers $v_{\rm L,R}$ are the vevs of the left- and right-handed Higgs triplets, whose existence is needed to maintain the left–right symmetry. They receive their vevs at the minimum of the potential, producing at the same time masses for the gauge bosons. In general [10], this results in

$$v_{\rm L}\,v_{\rm R} \simeq \gamma\,v^2\,, \tag{8}$$

where the constant γ is a model dependent parameter of $\mathcal{O}(1)$. Inserting this equation as well as Eq. (7) in (1) yields

$$m_\nu = v_{\rm L}\,\left(f - \tilde{m}_{\rm D}\,\frac{f^{-1}}{\gamma\,v^2}\,\tilde{m}_{\rm D}^T\right)\,. \tag{9}$$

If one compares the relative magnitude of the two contributions in Eq. (1), denoting the largest mass in the Dirac matrix with m, one finds that

$$\frac{|\tilde{m}_{\rm D}\,M_{\rm R}^{-1}\,\tilde{m}_{\rm D}^T|}{|m_{\rm L}|} \simeq \frac{m^2}{v_{\rm R}}\frac{1}{v_{\rm L}} \simeq \frac{m^2}{\gamma\,v^2}\,. \tag{10}$$

Here, we only used Eq. (8) and assumed that the matrix elements of f and f^{-1} are of the same order of magnitude. It is seen that this ratio is of order one only for the top quark mass, *i.e.* if one identifies the Dirac mass matrix with the up quark mass matrix.

We finally specify the order of magnitude of $v_{\rm L,R}$. The scale of $m_\nu = v_{\rm L}\, f$ is $10^{-2} \ldots 10^{-3}$ eV, which, for not too small f, is only compatible with $v_{\rm L}\, v_{\rm R} \simeq \gamma\, v^2$ for $v_{\rm R} \simeq 10^{14} \ldots 10^{15}$ GeV. This means that $v_{\rm R}$ is close to the grand unification scale and $v_{\rm L}$ is of the order of the neutrino masses, which is expected since $m_{\rm L}$ is the dominating contribution to m_ν. In the following, $v_{\rm R} = 10^{15}$ GeV and $\gamma = 1$ is assumed.

From the decay asymmetry ε the baryon asymmetry $Y_{\rm B}$ is obtained by

$$Y_{\rm B} = c\,\kappa \frac{\varepsilon}{g^*}, \tag{11}$$

where $c \simeq -0.55$ is the fraction of the lepton asymmetry converted into a baryon asymmetry via sphaleron processes [11], κ a suppression factor due to lepton-number violating wash-out processes (see [6] for an improved fit) and $g^* \simeq 110$ the number of massless degrees of freedom at the time of the decay. Experimentally, the preferred range for the asymmetry is [12] $Y_{\rm B} \simeq (0.1 \ldots 1) \times 10^{-10}$.

The strategy goes as follows: In Eq. (9) one inserts the solar solution, *i.e.* the small angle (SMA), large angle (LMA) or quasi-vacuum (QVO) solution. The light neutrino masses m_i are obtained by assuming the hierarchical scheme. The Dirac mass matrix $\tilde{m}_{\rm D}$ can be expected to be an up (down) quark or lepton mass matrix, denoted $m_{\rm up}$, $m_{\rm down}$ and $m_{\rm lep}$, respectively. Eq. (9) is then solved for $f = M_{\rm R}/v_{\rm R}$ and $M_{\rm R}$ is diagonalized to obtain the baryon asymmetry via Eqs. (5), (11).

Performing a random scan of the allowed oscillation parameters (see *e.g.* [13]) and the three phases, it is found that if $\tilde{m}_{\rm D}$ is a down quark or lepton mass matrix, m_1 should not be too small, *i.e.* larger than 10^{-6} eV. The LMA solution gives in more cases the correct baryon asymmetry and is thus slightly favored over SMA and QVO. If $\tilde{m}_{\rm D}$ is an up quark mass matrix, fine tuning of the parameters is required. Due to the large hierarchy of the quark and lepton masses, it is sufficient to use a mass matrix which has just the heaviest mass as the (33) entry. Fig. 1 shows $Y_{\rm B}$ in case of $\tilde{m}_{\rm D} = m_{\rm lep}$.

If we identify $\tilde{m}_{\rm D}$ with the down quark or charged lepton mass matrix, then the ratio in Eq. (10) is always much smaller than one, so that the second term in Eq. (9) can be neglected and it follows [8]

$$f \simeq \frac{1}{v_{\rm L}}\, m_\nu\,. \tag{12}$$

Therefore, with the help of Eqs. (2), (4), (7), one arrives at a very simple connection between the left- and right-handed neutrino sectors:

$$U_{\rm R} = U_{\rm L} \quad \text{and} \quad M_i = m_i \frac{v_{\rm R}}{v_{\rm L}}\,. \tag{13}$$

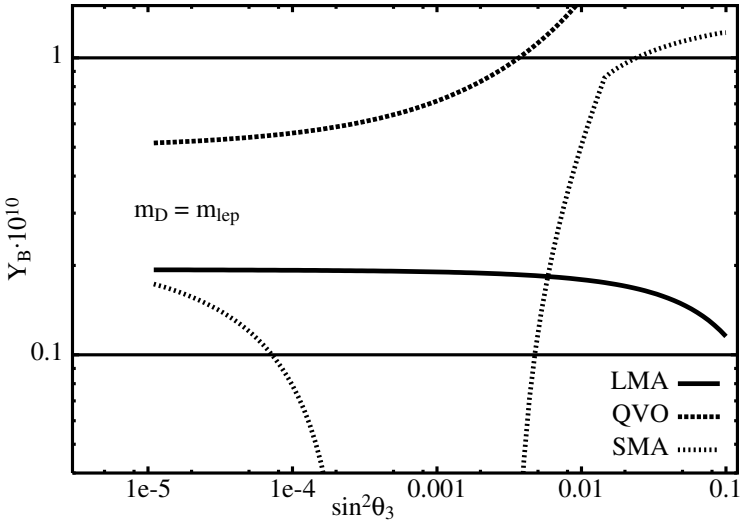

Fig. 1. Baryon asymmetry as a function of s_3 for $\tilde{m}_{\rm D} = m_{\rm lep}$ and all three solar solutions. We chose $3\alpha = 4\beta = 6\delta = \pi$, $\Delta m^2_A = 3.2 \times 10^{-3}$ eV^2 and $\tan^2_2 = 1$. For the solar solutions, we took $\Delta m^2_\odot = 5 \times 10^{-6}$ eV^2 and $\tan^2_1 = 5 \times 10^{-4}$ for SMA, $\Delta m^2_\odot = 5 \times 10^{-5}$ eV^2 and $\tan^2_1 = 1$ for LMA and $\Delta m^2_\odot = 10^{-8}$ eV^2 and $\tan^2_1 = 1$ for QVO. The smallest mass state is $m_1 = 10^{-5}$ eV for QVO and $m_1 = 10^{-4}$ eV for SMA as well as LMA.

The striking property is that the light neutrino masses are proportional to the heavy ones. Analytical estimates for the baryon asymmetry can now be performed. We work with a convenient parametrization of $U_{\rm L}$,

$$U_{\rm L} = U_{\rm CKM} \times P = U_{\rm CKM}\ {\rm diag}(1, {\rm e}^{i\alpha}, {\rm e}^{i(\beta+\delta)})$$

$$= \begin{pmatrix} c_1 c_3 & s_1 c_3 & s_3 {\rm e}^{-i\delta} \\ -s_1 c_2 - c_1 s_2 s_3 {\rm e}^{i\delta} & c_1 c_2 - s_1 s_2 s_3 {\rm e}^{i\delta} & s_2 c_3 \\ s_1 s_2 - c_1 c_2 s_3 {\rm e}^{i\delta} & -c_1 s_2 - s_1 c_2 s_3 {\rm e}^{i\delta} & c_2 c_3 \end{pmatrix} {\rm diag}(1, {\rm e}^{i\alpha}, {\rm e}^{i(\beta+\delta)}), \tag{14}$$

where $c_i = \cos\theta_i$, $s_i = \sin\theta_i$ and the diagonal matrix P contains the additional two Majorana phases α and β. Assuming maximal atmospheric and solar mixing, $c_1^2 = c_2^2 = 1/2$, and taking only the leading order in s_3, one finds for the LMA and QVO solutions [8]

$$Y_{\rm B} \times 10^{10} \lesssim 4.1 \frac{1}{1-2\,s_3\,c_\delta} \left(\frac{m}{\rm GeV}\right)^2$$

$$\times \left\{ \left(s_{2\alpha} + 4\,s_3\,s_\delta\,c_{2\alpha}\right) \frac{m_1}{\sqrt{\Delta m^2_\odot}} + 2\left(s_{2(\beta+\delta)} - 2\,s_3\,s_{2\beta+\delta}\right) \frac{m_1}{\sqrt{\Delta m^2_A}} \right\}, \quad (15)$$

where $c_\delta = \cos\delta$, $s_{2\alpha} = \sin 2\alpha$ and so on. The solar (atmospheric) Δm^2 is denoted $\Delta m^2_\odot$ (Δm^2_A). It is seen explicitly that $Y_{\rm B}$ vanishes if CP conservation holds, *i.e.* if all phases are zero or π. The asymmetry is proportional to the square of the heaviest entry in $\tilde{m}_{\rm D}$, *i.e.* the tau or bottom quark mass. Furthermore, $Y_{\rm B}$ is proportional to the lightest neutrino mass eigenstate m_1, which can be used to set a lower limit on it, it is of the order 10^{-7} to 10^{-8} eV.

3. Terrestrial *CP* violation

If $\tilde{m}_{\rm D} = m_{\rm up}$ then m_ν receives a contribution from the conventional see-saw term $\tilde{m}_{\rm D}\, M_{\rm R}^{-1}\, \tilde{m}_{\rm D}^T$ and the proportionality to m_1 vanishes, see [7] for details.

The remaining unknowns in this approach are the three CP violating phases in the mixing matrix $U_{\rm L}$ and the size of the smallest mass eigenstate m_1. Within the parametrisation Eq. (14) the phases α and β govern the magnitude of neutrinoless double beta decay. The third phase δ is responsible for CP violating effects in oscillation experiments.

The latest SuperKamiokande [14] and first SNO [15] data favor LMA over the other solar solutions. This is good news since leptonic CP violation in long-baseline experiments can only be measured if nature has chosen LMA. Effects of CP violation are proportional to the re-phasing invariant determinant J_{CP} [19], which shows up *e.g.* in the difference between the CP conjugated oscillation probabilities

$$P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu) \propto J_{CP} = \tfrac{1}{8}\,\sin 2\theta_1\,\sin 2\theta_2\,\sin 2\theta_3\,\cos\theta_3\,\sin\delta$$

$$\leq \tfrac{1}{4}\,\sin\theta_3 (1-\sin^2\theta_3)\,. \quad (16)$$

In addition, the higher $\Delta m^2_\odot$ is, the higher are the prospects for detecting the CP violation [16], though the details depend on the experimental facilities. In the hierarchical mass scheme, LMA also provides the highest Majorana mass for the electron neutrino, which can be measured through neutrinoless double beta decay ($0\nu\beta\beta$). It is defined as

$$\langle m \rangle = \sum_i U_{\mathrm{L}\,ei}^2\, m_i \tag{17}$$

and due to the complex matrix elements $U_{\mathrm{L}\,\alpha i}$ there is the possibility of cancellation [17] of terms in Eq. (17).

The quantities $\langle m \rangle$ and J_{CP} are observables, which are depending on the CP violating phases which also govern the lepton asymmetry. It is therefore interesting to ask if the parameters that produce a satisfying Y_{B} also deliver sizable $\langle m \rangle$ and/or J_{CP}. To study this, a random scan of the allowed variables of the LMA solution was performed. The highest fraction of parameter sets providing sufficient Y_{B} occurs for high m_1 and a "low" Dirac mass matrix, *i.e.* $\tilde{m}_{\mathrm{D}}$ should be a lepton (43 %) or down quark (23 %) mass matrix. It is interesting to note that in the most simple realization of LR models $\tilde{m}_{\mathrm{D}}$ is the charged lepton mass matrix. For lower m_1 or $\tilde{m}_{\mathrm{D}} = m_{\mathrm{up}}$ the fraction of parameters producing a correct asymmetry decreases to less than 5%. As mentioned, basically no m_1 dependence exists for $\tilde{m}_{\mathrm{D}} = m_{\mathrm{up}}$. Approximately all the parameter sets providing a correct asymmetry also produce $\langle m \rangle$ bigger than 2×10^{-3} eV, the lowest limit achievable by the GENIUS project [18]. For $m_1 = 10^{-3}$ eV, about 4 % of the parameter sets give $\langle m \rangle$ bigger than 0.01 eV. Fig. 2 shows the distribution of events in the $\langle m \rangle - \sin^2\theta_3$ plane. The difference for different cases is easily seen.

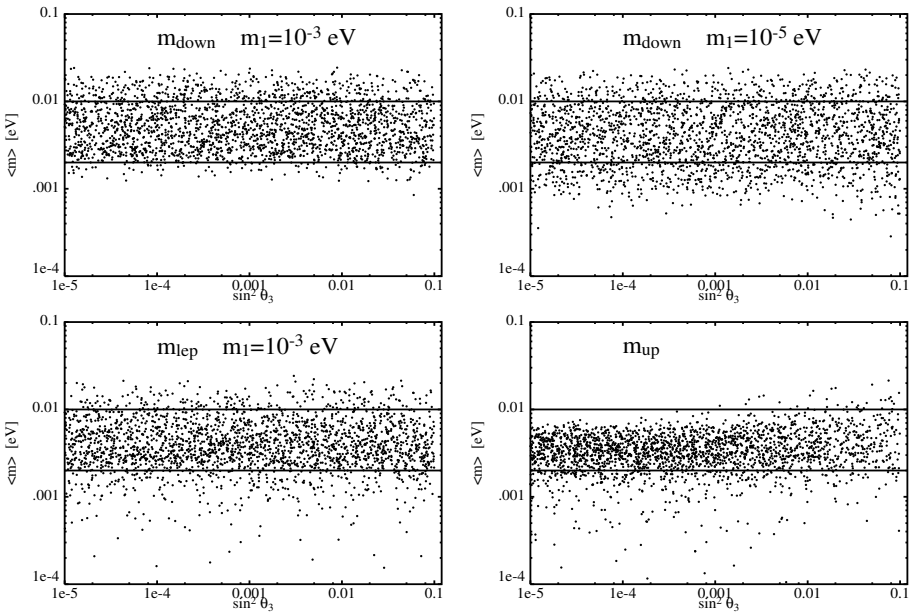

Fig. 2. Distribution of events in the $\langle m \rangle - \sin^2\theta_3$ plane for the LMA solution, different m_1 and $\tilde{m}_{\mathrm{D}}$.

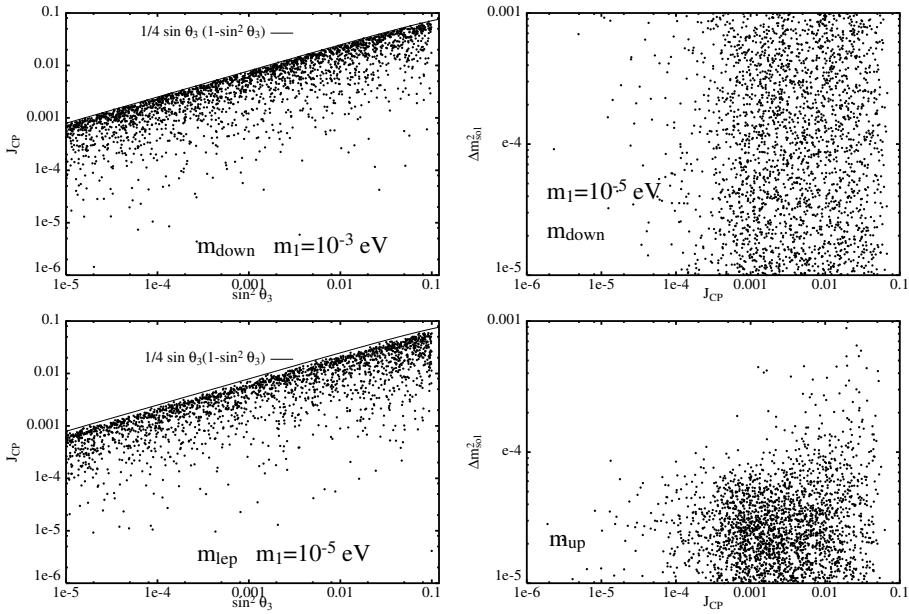

Fig. 3. Distribution of events in the J_{CP}–$\sin^2\theta_3$ (left) and J_{CP}–$\Delta m^2_\odot$ (right) plane for the LMA solution, different m_1 and $\tilde{m}_{\rm D}$.

Regarding CP violation, a criterion for observability might be $J_{CP} \geq 10^{-4}$ and $\Delta m^2_\odot \geq 10^{-4}$ eV^2. Approximately half of the events that give sufficient $Y_{\rm B}$ also fulfill these constraints. Therefore, again high m_1 and $\tilde{m}_{\rm D} = m_{\rm down}$ or $m_{\rm lep}$ are required to expect measurable CP violation. Fig. 3 shows the distribution of J_{CP} against $\sin^2\theta_3$ and $\Delta m^2_\odot$, respectively. Again, the difference is easily seen. The case $\tilde{m}_{\rm D} = m_{\rm up}$ favors low $\Delta m^2_\odot$.

4. Conclusions

Leptogenesis in left–right symmetric models is studied. A simple formula for $Y_{\rm B}$ can be derived, expressing the baryon asymmetry in terms of oscillation parameters and CP violating phases. In many cases a sufficient baryon asymmetry is produced and the LMA solution is favored. Many models in this scenario as well as other approaches fulfill these constraints. In search for an additional criterion we therefore apply our model also to $0\nu\beta\beta$ and terrestrial CP violating effects in long-baseline experiments. In order to expect a sizable signal in $0\nu\beta\beta$ and measurable CP violating effects in long-baseline experiments, m_1 of order 10^{-3} eV is required, and $\tilde{m}_{\rm D}$ should be a lepton or perhaps a down quark mass matrix. The low energy observables J_{CP} and $\langle m \rangle$ can in principle be used to distinguish these possibilities and could also be considered in other leptogenesis models.

Baryon number and CP violation are necessary conditions for the generation of a baryon asymmetry. Since $Y_{\rm B}$ gets converted from a lepton asymmetry, lepton number violation is required. Thus, $0\nu\beta\beta$ and terrestrial CP violation provide a possibility to check two of Sakharov's conditions at low energy. Furthermore, given that in many models the heavy right-handed neutrinos may not be observable at realistic collider energies, $0\nu\beta\beta$ and terrestrial CP violation could be useful to validate leptogenesis.

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