Proc. Natl. Conf. Theor. Phys. **36** (2011), pp. 46-55

S_4 FLAVOR SYMMETRY AND LEPTOGENESIS

NGUYEN THANH PHONG
Department of Physics, College of Natural Science, Can Tho University

Abstract. *We study how leptogenesis can be implemented in a seesaw model with S_4 flavor symmetry, which leads to the neutrino tri-bimaximal mixing matrix. By considering the renormalzation group evolution from high energy scale (GUT scale) to low energy scale (seesaw scale), the off-diagonal terms of the combination of Dirac Yukawa coupling matrix are generated, we show that the flavored leptogenesis can be successfully realized. We also investigate how the effective light neutrino mass $|\langle m_{ee}\rangle|$ associated with neutrinoless double beta decay can be predicted along with the neutrino mass hierarchies by imposing experimental data of low-energy observables. We find a link between leptogenesis and neutrinoless double beta decay characterized by $|\langle m_{ee}\rangle|$ through a high energy CP phase ϕ, which is correlated with low energy Majorana CP phases. It is shown that our predictions of $|\langle m_{ee}\rangle|$ for some fixed parameters of high energy physics can be constrained by the current observation of baryon asymmetry.*

I. INTRODUCTION

Neutrino experimental data provide an important clue for elucidating the origin of the observed hierarchies in mass matrices for quarks and leptons. Recent experiments of the neutrino oscillation have gone into a new phase of precise determination of mixing angles and squared-mass differences [1], which indicate that the tri-bimaximal (TBM) mixing for the three flavors in lepton sector

$$U_{\rm TB} = \begin{pmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}, \tag{1}$$

can be regarded as the PMNS matrix $U_{\rm PMNS} \equiv U_{\rm TB}P_\nu$ [2] where P_ν is a diagonal matrix of CP phases. However, properties related to the leptonic CP violation are not completely known yet. The large mixing angles, which may be suggestive of a flavor symmetry, are completely different from the quark mixing ones. Therefore, it is very important to find a natural model that leads to these mixing patterns of quarks and leptons with good accuracy. In the last years there has been a lot of efforts in searching for models which get the TBM pattern and a fascinating way seems to be the use of some discrete non-Abelian flavor groups added to the gauge groups of the Standard Model. There is a series of models based on the symmetry group A_4 [3], T' [4], and S_4 [5, 6]. The common feature of these models is that they are realized at very high energy scale Λ and the groups are spontaneously broken due by a set of scalar multiplets, the flavons.

In addition to the explanation for the small masses of neutrinos, seesaw mechanism [7] has another appearing feature so-called leptogenesis mechanism for the generation of the observed baryon asymmetry of the Universe (BAU), through the decay of

Table 1. Transformation properties of the matter fields in the lepton sector and all the flavons of the model, ω is the cube root of unity, i.e. $\omega = e^{i2\pi/3}$.

Field	l	e^c	μ^c	τ^c	ν^c	$h_{u,d}$	θ	ψ	η	Δ	φ	ξ'
S_4	3_1	1_2	1_2	1_1	3_1	1_1	1_1	3_1	2	3_1	2	1_2
Z_5	ω^4	1	ω^2	ω^4	ω	1	1	ω^2	ω^2	ω^3	ω^3	1
$U(1)_{FN}$	0	1	0	0	0	0	-1	0	0	0	0	0

heavy right handed (RH) Majorana neutrinos [8]. If this BAU was made via leptogenesis, then CP violation in the leptonic sector is required. For Majorana neutrinos there are one Dirac-type phase and two Majorana-type phases, one (or a combination) of which in principle be measured through neutrinoless double beta ($0\nu2\beta$) decays [9]. The exact TBM mixing pattern forbids at low energy CP violation in neutrino oscillation, due to $U_{e3} = 0$. So any observation of the leptonic CP violation, for instance in $0\nu2\beta$ decay, can strengthen our believe in leptogenesis by demonstrating that CP is not a symmetry of the leptons. It is interesting to explore this existence of CP violation due to the Majorana CP-violating phases by measuring $|\langle m_{ee}\rangle|$ and examine a link between low-energy observable $0\nu2\beta$ decay and the BAU. The authors in Ref. [6] showed that the TBM pattern can be generated naturally in the framework of the seesaw mechanism with $SU(2)_L \times U(1)_Y \times S_4$ symmetry. The textures of mass matrices as given in [6] also could not generate lepton asymmetry which is essential for a baryogenesis. In this work, we investigate the possibility of radiatively leptogenesis when renormalization group (RG) effects are taken into account. And we will show that the leptogenesis can be linked to the $0\nu2\beta$ decay through seesaw mechanism.

This work is organized as follows. In the next section, we present low energy observables of the model based on a supersymmetric seesaw model with the flavor symmetry group S_4. Especially we focus on the effective mass governing the $0\nu2\beta$ decay. In section III, we deal with leptogenesis due to RG effects. Section IV is devoted for our conclusions.

II. LOW ENERGY OBSERVABLES

Although there have been several proposals to construct lepton mass matrices in the framework of seesaw incorporating S_4 symmetry [5, 6], in this paper, we consider the model proposed in [6], which gives rise to TBM mixing pattern of the lepton mixing matrix [2]. The model is supersymmetric and based on the flavor discrete group $G_f = S_4 \times Z_5 \times U(1)_{FN}$. The matter fields and the flavons of the model are given table 1. The superpotential of the model in the lepton sector reads as follows

$$w_l = \sum_{i=1}^{4} \frac{\theta}{\Lambda}\frac{y_{e,i}}{\Lambda^3} e^c (lX_i)_{1_2} h_d + \frac{y_\mu}{\Lambda^2}\mu^c(l\psi\eta)_{1_2}h_d + \frac{y_\tau}{\Lambda}\tau^c(l\psi)_{1_1}h_d + h.c. + ..., \quad (2)$$

$$w_\nu = x(\nu^c l)_{1_1} h_u + x_d(\nu^c\nu^c\varphi)_{1_1} + x_t(\nu^c\nu^c\Delta)_{1_1} + h.c. + ..., \quad (3)$$

where $X_i = \psi\psi\eta, \psi\eta\eta, \Delta\Delta\xi', \Delta\varphi\xi'$ and the dots denote higher order contributions. The alignment of the VEVs of flavons as follows

$$\begin{aligned}\langle\psi\rangle &= \begin{pmatrix} 0 & 1 & 0 \end{pmatrix}^T \upsilon_\psi,\ \langle\Delta\rangle = \begin{pmatrix} 1 & 1 & 1 \end{pmatrix}^T \upsilon_\Delta, \\ \langle\eta\rangle &= \begin{pmatrix} 0 & 1 \end{pmatrix}^T \upsilon_\eta,\ \langle\varphi\rangle = \begin{pmatrix} 1 & 1 \end{pmatrix}^T \upsilon_\varphi,\ \langle\xi'\rangle = \upsilon_{\xi'},\end{aligned} \tag{4}$$

All the VEVs are of the same order of magnitude and for this reason these VEVs are parameterized as VEVs$/\Lambda = u$. The only VEV which originates with a different mechanism with respect to the others is υ_θ and we indicate the ratio $\upsilon_\theta/\Lambda = t$. It is shown in the reference [6] that u and t belong to a well determined range of values $0.01 < u, t < 0.05$.

With this setting the mass matrix for the charged leptons is

$$m_l = \begin{pmatrix} y_e^{(1)}u^2t & y_e^{(2)}u^2t & y_e^{(2)}u^2t \\ 0 & y_\mu u & 0 \\ 0 & 0 & y_\tau \end{pmatrix} u\upsilon_d \tag{5}$$

and the neutrino mass matrices are

$$m_\nu^d = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} x\upsilon_u, \tag{6}$$

$$M_R = Be^{i\alpha_1} \begin{pmatrix} 2re^{i\phi} & 1-re^{i\phi} & 1-re^{i\phi} \\ 1-re^{i\phi} & 1+2re^{i\phi} & -re^{i\phi} \\ 1-re^{i\phi} & -re^{i\phi} & 1+2re^{i\phi} \end{pmatrix} \tag{7}$$

where $B = 2|x_d|\upsilon_\varphi, C = 2|x_t|\upsilon_\Delta$ and $r = C/B$ are real and positive quantities and the phases α_1, α_2 are the arguments of $x_{d,t}$, and $\phi = \alpha_2 - \alpha_1$ is the only physical phase remained in M_R. The heavy neutrino mass matrix M_R is exactly diagonalized by the TBM mixing:

$$\begin{aligned} M_R^D &= V_R^T M_R V_R = \mathrm{Diag.}\big(M_1, M_2, M_3\big), \\ M_1 &= B|3re^{i\phi} - 1|,\ M_2 = 2B,\ M_1 = B|3re^{i\phi} + 1| && (8) \\ V_R &= U_{TB}V_P,\ V_P = \mathrm{Diag.}\big(e^{i\gamma_1/2}, 1, e^{i\gamma_2/2}\big), && (9) \\ \gamma_{1,2} &= -\arg(3re^{i\phi} \mp 1). && (10)\end{aligned}$$

Integrating out the heavy degrees of freedom, we get the effective light neutrino mass matrix, which is given by the seesaw relation [7], $m_{\text{eff}} = -(m_\nu^d)^T M_R^{-1} m_\nu^d$, and diagonalized by the TBM mixing matrix

$$\begin{aligned} U_\nu^T m_{\text{eff}} U_\nu &= \mathrm{Diag.}(m_1, m_2, m_3) = -\mathrm{Diag.}(\frac{x^2\upsilon_u^2}{M_1}, \frac{x^2\upsilon_u^2}{M_2}, \frac{x^2\upsilon_u^2}{M_3}), && (11) \\ U_\nu &= U_{TB}\mathrm{Diag.}(e^{-i\gamma_1/2}, 1, e^{-i\gamma_2/2}). && (12)\end{aligned}$$

In order to find the lepton mixing matrix we need to diagonalize the charged lepton mass matrix:

$$m_l^D = U_{l^c}^\dagger m_l U_l = \mathrm{Diag.}(y_e u^2 t, y_\mu u, y_\tau) u\upsilon_d, \tag{13}$$

where the unitary U_l results to be unity matrix. As a result we get

$$U_{\text{PMNS}} = U_l^\dagger U_\nu \equiv U_\nu = e^{-i\gamma_1/2}\, U_{\text{TB}}\ \mathrm{Diag.}(1, e^{i\beta_1}, e^{i\beta_2}), \tag{14}$$

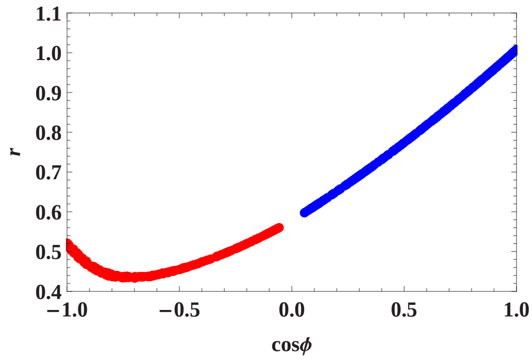

Fig. 1. Allowed parameter region of the ratio $r = b/a$ as a function of $\cos\phi$ constrained by the 1σ experimental data in Eq. (15). Here, the blue (dark) and red (light) curves correspond to the inverted and normal mass ordering of light neutrino, respectively.

where $\beta_1 = \gamma_1/2$, $\beta_2 = (\gamma_1 - \gamma_2)/2$ are the Majorana CP violating phases. The phase factored out to the left have no physical meaning, since it can be eliminated by a redefinition of the charged lepton fields. The light neutrino mass eigenvalues are simply the inverse of the heavy neutrino ones, a part from a minus sign and the global factor from m_ν^d, as can be seen in Eq. (11). There are the nine physical quantities consisting of the three light neutrino masses, the three mixing angles and the three CP-violating phases. The mixing angles are entirely fixed by the G_f symmetry group, predicting TBM and in turn no Dirac CP-violating phase, and the remaining 5 physical quantities $\beta_1, \beta_2, m_1, m_2$ and m_3, are determined by the five real parameters B, C, v_u, x and ϕ.

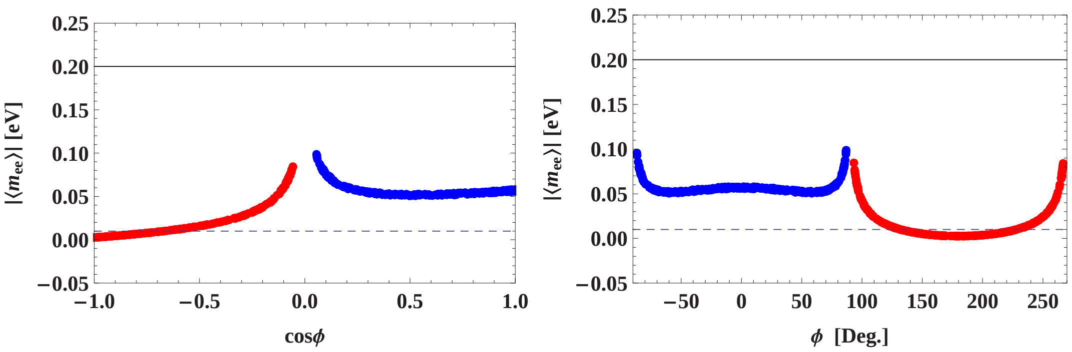

Fig. 2. Predictions of the effective mass $|\langle m_{ee}\rangle|$ for $0\nu2\beta$ as a function of $\cos\phi$ in the left panel and the phase ϕ in the right panel based on the 1σ experimental results given in Eq. (15). Here, in both panels the red (light) and blue (dark) curves correspond to the normal mass spectrum of light neutrino and the inverted one, respectively.

The light neutrino mass spectrum can be both normal or inverted hierarchy depending on the sign of $\cos\phi$. If $\cos\phi < 0$ one has normal hierarchy (NH) light neutrino mass ordering and inverted hierarchy (IH) ordering if $\cos\phi > 0$. In order to see how this correlation in the allowed parameter space is constrained by the experimental data, we consider the experimental data at 1σ [1]

$$\begin{aligned} |\Delta m^2_{31}| &= (2.29 - 2.52)\times 10^{-3}\mathrm{eV}^2 \ , \\ \Delta m^2_{21} &= (7.45 - 7.88)\times 10^{-5}\mathrm{eV}^2 \ . \end{aligned} \tag{15}$$

The correlations between r and $\cos\phi$ for normal mass spectrum [red (light) plot] and inverted one [blue (dark) plot] are presented in Fig. 1. Hereafter, we always use the 1σ confidence level experimental values of low energy observables for our numerical calculations.

Since the zero entry in U_{PMNS} implies that there is no Dirac CP-violating phase, the only contribution from the Majorana phases to the $0\nu 2\beta$ decay amplitude will come from the phase β_1. Then, the effective mass governing the $0\nu 2\beta$ decay is

$$\begin{aligned} |\langle m_{ee}\rangle| &= \frac{1}{3}|2m_1 + m_2 e^{2i\beta_1}| \qquad (16) \\ &= \frac{m_0}{3(1-6r\cos\phi+9r^2)}\sqrt{8.5+13.5r^2+20.25r^4-3r(13+12r^2)\cos\phi+9r^2\cos^2\phi}, \end{aligned}$$

where $m_0 = \frac{x^2 v_u^2}{B}$. The behavior of $|\langle m_{ee}\rangle|$ is plotted in Fig. 2 as a function of the phase ϕ. In the figure, the horizontal line is the current lower bound sensitivity (0.2 eV) [10] and the horizontal dotted line is the future lower bound sensitivity (10^{-2} eV) [11] of $0\nu 2\beta$ experiments.

Using Eq. (10) we can obtain the explicit correlation between the phase ϕ and the Majorana phase β_1

$$\sin 2\beta_1 = \frac{-3r\sin\phi}{1-6r\cos\phi+9r^2} \ . \tag{17}$$

Fig.3 represents the correlation the phase ϕ and the Majorana phase β_1 for normal mass ordering [red (light) plot] and inverted one [blue (dark) plot].

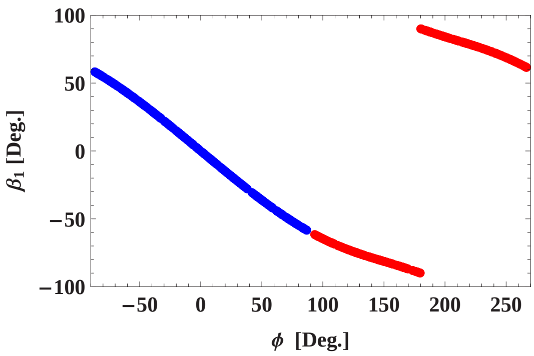

Fig. 3. Correlation of the Majorana CP phase β_1 with the phase ϕ constrained by the 1σ experimental data in Eq. (15). The red (light) and blue (dark) curves correspond to the normal mass spectrum of light neutrino and the inverted one, respectively.

In a basis where the charged current is flavor diagonal, and the heavy RH Majorana mass matrix M_R is diagonal and real, the Dirac mass matrix m_ν^d gets modified to

$$m_\nu^d \to Y_\nu \upsilon_u = V_R^T m_\nu^d \tag{18}$$

where $\upsilon_u = \upsilon \sin\beta$, $\upsilon = 176$ GeV, and the coupling N_i with leptons and scalar, Y_ν, is given as

$$Y_\nu = x e^{i\gamma_1/2} \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{-1}{\sqrt{6}} & \frac{-1}{\sqrt{6}} \\ \frac{e^{-i\beta_1}}{\sqrt{3}} & \frac{e^{-i\beta_1}}{\sqrt{3}} & \frac{e^{-i\beta_1}}{\sqrt{3}} \\ 0 & \frac{e^{-i\beta_2}}{\sqrt{2}} & \frac{-e^{-i\beta_2}}{\sqrt{2}} \end{pmatrix}. \tag{19}$$

Concerned with CP violation, we notice that the CP phase ϕ coming from m_ν^d obviously take part in low-energy CP violation as the Majorana phases β_1 and β_2 which are the only sources of low-energy CP violation in the leptonic sector. On the other hand, leptogenesis is associated with both Y_ν itself and the combination of Yukawa coupling matrix, $H \equiv Y_\nu Y_\nu^\dagger$, which is given as

$$H = Y_\nu Y_\nu^\dagger = x^2 \cdot \mathrm{Diag.}(1,1,1). \tag{20}$$

which directly indicates that all off-diagonal H_{ij} vanish, so CP asymmetry could not be generated and neither leptogenesis. *For leptogenesis to be viable, the off-diagonal H_{ij} have to be generated.*

III. RADIATIVELY INDUCED FLAVORED LEPTOGENESIS

As mention in the previous section, the leptogenesis can not be realized in the S_4 models under consideration at the leading order, so this section is devoted to study the flavored leptogenesis with the effects of RG evolution. The lepton asymmetries which are produced by out-of-equilibrium decays of the heavy RH neutrinos in the early Universe, at temperatures above $T \sim (1+\tan^2\beta) \times 10^{12}$ GeV, do not distinguish lepton flavors (conventional or unflavored leptogenesis). However, if the scale of the heavy RH neutrino masses are about $M \leq (1+\tan^2\beta)\times 10^{12}$ GeV, we needs to take into account the lepton flavor effects and this is said as the flavored leptogenesis. In this case, the CP asymmetry generated by the decay of the i-th heavy RH neutrino, provided the heavy neutrino masses are far from almost degenerate, would then be given by [12, 13]

$$\varepsilon_i^\alpha = \frac{1}{8\pi H_{ii}} \sum_{j\neq i} \mathrm{Im}\Big[H_{ij}(Y_\nu)_{i\alpha}(Y_\nu)^*_{j\alpha}\Big] g\Big(\frac{M_j^2}{M_i^2}\Big), \tag{21}$$

where $H = Y_\nu Y_\nu^\dagger$ and Y_ν in the basis where M_R is real and diagonal. In the above, the loop function $g\Big(\frac{M_j^2}{M_i^2}\Big)$ is given by

$$g\Big(\frac{M_j^2}{M_i^2}\Big) \equiv g_{ij}(x) = \sqrt{x}\Big[\frac{2}{1-x} - \ln\frac{1+x}{x}\Big]. \tag{22}$$

Notice however that, a nonvanishing CP asymmetry requires $\mathrm{Im}\Big[H_{ij}(Y_\nu)_{i\alpha}(Y_\nu)^*_{j\alpha}\Big] \neq 0$ with Y_ν defined in Eq. (19). Therefore, to have a viable radiative leptogenesis we need to induce nonvanishing $H_{ij}(i \neq j)$ at the leptogenesis scale. This is indeed possible since RG effects due to the τ-Yukawa charged-lepton contribution imply in leading order [14]

$$H_{ij}(t) \quad = \quad 2y_\tau^2(Y_\nu)_{i3}(Y_\nu)^*_{j3} \times t, \; t = \frac{1}{16\pi^2}\ln\frac{M}{\Lambda'}, \tag{23}$$

where Y_ν is defined in Eq. (19). The cut-off scale is chosen to be equal to the G_f breaking scale Λ and close to GUT scale, $\Lambda' = 10^{16}$ GeV. The CP flavoured asymmetries ε_i^α can then be obtained from Eqs. (19)-(23).

Once the initial values of ε_i^α are fixed, the final result of BAU, η_B, can be obtained by solving a set of flavor dependent Boltzmann equations including the decay, inverse decay, and scattering processes as well as the nonperturbative sphaleron interaction. In order to estimate the wash-out effects, we introduce the parameters K_i^α which are the wash-out factors due to the inverse decay of the Majorana neutrino N_i into the lepton flavor α. The explicit form of K_i^α is given by

$$K_i^\alpha = \frac{\Gamma_i^\alpha}{H(M_i)} = (Y_\nu^\dagger)_{\alpha i}(Y_\nu)_{i\alpha}\frac{\upsilon_u^2}{m_* M_i} \tag{24}$$

where Γ_i^α is the partial decay width of N_i into the lepton flavors and Higgs scalars, $H(M_i) \simeq (4\pi^3 g_*/45)^{\frac{1}{2}} M_i^2/M_{Pl}$ with the Planck mass $M_{Pl} = 1.22 \times 10^{19}$ GeV and the effective number of degrees of freedom $g_* \simeq 228.75$ is the Hubble parameter at temperature $T = M_i$, and the equilibrium neutrino mass $m_* \simeq 10^{-3}$. From Eqs. (19, 24), we can obtain the washout parameters of the model.

Each lepton asymmetry for a single flavor ε_i^α is weighted differently by the corresponding washout parameter K_i^α, and appears with different weight in the final formula for the baryon asymmetry [15],

$$\eta_B \simeq -10^{-2}\sum_{N_i}\left[\varepsilon_i^e\kappa\Big(\frac{93}{110}K_i^e\Big) + \varepsilon_i^\mu\kappa\Big(\frac{19}{30}K_i^e\Big) + \varepsilon_i^\tau\kappa\Big(\frac{19}{30}K_i^e\Big)\right], \tag{25}$$

if the scale of heavy RH neutrino masses are about $M \leq (1+\tan^2\beta)\times 10^9$ GeV where the charged μ and τ Yukawa couplings are in equilibrium and all the flavors are to be treated separately. And

$$\eta_B \simeq -10^{-2}\sum_{N_i}\left[\varepsilon_i^2\kappa\Big(\frac{541}{761}K_i^2\Big) + \varepsilon_i^\tau\kappa\Big(\frac{494}{761}K_i^e\Big)\right], \tag{26}$$

if $(1+\tan^2\beta)\cdot 10^9$ GeV $\leq M_i \leq (1+\tan^2\beta)\cdot 10^{12}$ GeV where only the τ Yukawa coupling is in equilibrium and is treated separately while the e and μ flavors are indistinguishable. And $\varepsilon_i^2 = \varepsilon_i^e + \varepsilon_i^\mu$, $K_i^2 = K_i^e + K_i^\mu$. And the wash-out factors are defined as

$$\kappa_i^\alpha \simeq \Big(\frac{8.25}{K_i^\alpha} + \Big(\frac{K_i^\alpha}{0.2}\Big)^{1.16}\Big)^{-1}. \tag{27}$$

In this model, the RH neutrino masses are strongly hierarchical. For the NH case, the lightest RH neutrino mass is M_3, then the leptogenesis is governed by the decay of

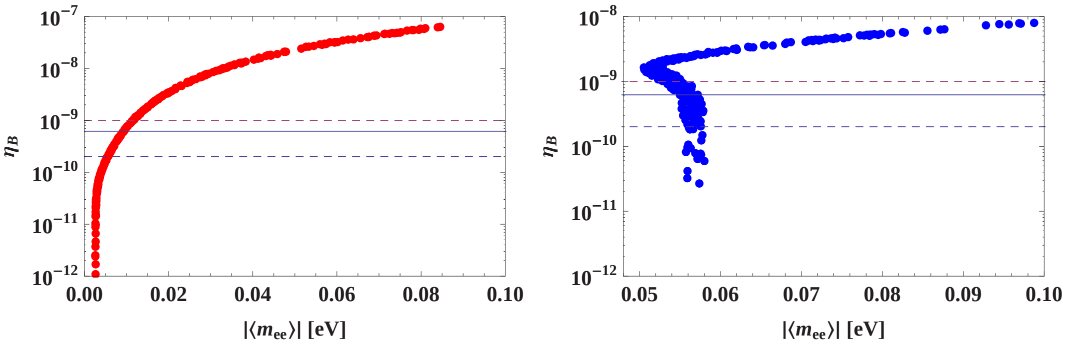

Fig. 4. The prediction of η_B as a function of $|\langle m_{ee}\rangle|$ for $B = 10^{13}$ GeV for the NH case (left-plot), $B = 10^{12}$ GeV for the IH case (right-plot) and $\tan\beta = 30$. The solid horizontal line and the dotted horizontal lines correspond to the experimental value of baryon asymmetry, $\eta_B^{\rm CMB} = 6.1 \times 10^{-10}$, and phenomenologically allowed regions $2 \times 10^{-10} \leq \eta_B \leq 10^{-9}$.

the neutrino with mass M_3. The explicit form of the CP flavoured asymmetries ε_3^α are obtained

$$\begin{aligned} \varepsilon_3^e &\simeq 0, \\ \varepsilon_3^\mu &\simeq \varepsilon_3^\tau \simeq \frac{y_\tau^2 x^2}{24\pi}\left(\frac{1}{2}\sin 2\beta_2 \cdot g_{31} - \sin 2(\beta_1 - \beta_2)\cdot g_{32}\right)\cdot t. \end{aligned} \tag{28}$$

The corresponding washout parameters, K_3^α, are obtained as

$$K_3^e = 0, \; K_3^{\mu,\tau} \simeq \frac{3}{4}K_1^e. \tag{29}$$

For the IH case, the lightest RH neutrino is of M_1, then leptogenesis is governed by the decay of the M_1 mass neutrino, and the CP flavored asymmetries ε_1^α are obtained as follow

$$\begin{aligned} \varepsilon_1^e &\simeq \frac{-y_\tau^2 x^2}{36\pi}\sin 2\beta_1 \cdot g_{12}\cdot t, \\ \varepsilon_1^\mu &\simeq \frac{y_\tau^2 x^2}{24\pi}\left(\frac{1}{3}\sin 2\beta_1 \cdot g_{12} - \frac{1}{2}\sin 2\beta_2 \cdot g_{13}\right)\cdot t, \\ \varepsilon_1^\tau &\simeq \frac{y_\tau^2 x^2}{24\pi}\left(\frac{1}{3}\sin 2\beta_1 \cdot g_{12} + \frac{1}{2}\sin 2\beta_2 \cdot g_{13}\right)\cdot t, \end{aligned} \tag{30}$$

with corresponding washout parameters K_i^α

$$K_1^e \simeq \frac{2m_0}{3m_*(1 - 6r\cos\phi + 9r^2)}, \; K_1^{\mu,\tau} \simeq \frac{1}{4}K_1^e. \tag{31}$$

Together with properly applying Eqs. (25, 26, 27), the BAU for two cases are then obtained. Notice that, in the NH case, the leptogenesis has no contribution from the electron flavor decay channel which makes the scale of the heavy RH neutrino mass for a successful leptogenesis higher than that of the IH case.

The predictions for η_B as a function of $|\langle m_{ee}\rangle|$ are shown in Fig. 4 where we have used $B = 10^{13}$ GeV for the NH case, $B = 10^{12}$ GeV for the IH case and $\tan\beta = 30$

as inputs. The horizontal solid and dashed lines correspond to the central value of the experiment result of BAU $\eta_B^{\rm CMB} = 6.1 \times 10^{-10}$ [16] and the phenomenologically allowed regions $2 \times 10^{-10} \leq \eta_B \leq 10^{-9}$, respectively. As shown in Fig. 4, the current observation of $\eta_B^{\rm CMB}$ can narrowly constrain the value of $|\langle m_{ee}\rangle|$ for the NH mass spectrum of light neutrinos and IH one, respectively. Combining the results presented in Figs. 2 and 3 with those from the leptogenesis, we can pin down the Majorana CP phase β_1 via the parameter ϕ.

IV. CONCLUSION

We study the S_4 models in the context of a seesaw model which naturally leads to the TBM form of the lepton mixing matrix. In this model, the combination $Y_\nu Y_\nu^\dagger$ is proportional to unity, this reason forbids the leptogenesis to occur. Therefore, for leptogenesis to become viable, the off-diagonal terms of $Y_\nu Y_\nu^\dagger$ have to be generated. This can be easily achieved by renormalization group effects from high energy scale to low energy scale which then naturally leads to a successful leptogenesis.

We have also studied the implications for low-energy observables where the $0\nu\beta\beta$ decay as a specific case. It gives definite predictions for the $0\nu2\beta$ decay parameter $|\langle m_{ee}\rangle|$. It is interestingly that we find a link between leptogenesis and the amplitude in neutrinoless double beta decay $|\langle m_{ee}\rangle|$ through a high energy CP phase ϕ. We show how the high energy CP phase ϕ is correlated to a low energy Majorana CP phase, and examine how leptogenesis can be related with the neutrinoless double beta decay. We also show that our predictions for $|\langle m_{ee}\rangle|$ for normal mass spectrum of light neutrino and inverted one can be constrained by the current observation of baryon asymmetry 6.1×10^{-10}.

REFERENCES

[1] T. Schwetz, M. Tortola, J. W. F. Valle, *New J. Phys.* **10** (2008) 113011 [arXiv:0808.2016 [hep-ph]]; M. Maltoni, T. Schwetz, arXiv:0812.3161 [hep-ph].

[2] P. F. Harrison, D. H. Perkins, W. G. Scott, *Phys. Lett. B* **530** (2002) 167 [arXiv:hep-ph/0202074]; P. F. Harrison, W. G. Scott, *Phys. Lett. B* **535** (2002) 163 [arXiv:hep-ph/0203209]; P. F. Harrison, W. G. Scott, *Phys. Lett. B* **547** (2002) 219; P. F. Harrison, W. G. Scott, *Phys. Lett. B* **557** (2003) 76.

[3] E. Ma, G. Rajasekaran, *Phys. Rev. D* **64** (2001) 113012 [arXiv:hep-ph/0106291]; K. S. Babu, E. Ma, J. W. F. Valle, *Phys. Lett. B* **552** (2003) 207 [arXiv:hepph/0206292]; G. Altarelli, F. Feruglio, *Nucl. Phys. B* **720** (2005) 64 [arXiv:hep-ph/0504165]; F. Bazzocchi, S. Kaneko, S. Morisi, *JHEP* **0803** (2008) 063 [arXiv:0707.3032 [hepph]].

[4] F. Feruglio, C. Hagedorn, Y. Lin, L. Merlo, *Nucl. Phys. B* **775** (2007) 120 [arXiv:hep-ph/0702194]; M. C. Chen, K. T. Mahanthappa, *Phys. Lett. B* **652** (2007) 34 [arXiv:0705.0714 [hep-ph]]; P. H. Frampton, T. W. Kephart, *JHEP* **0709** (2007) 110 [arXiv:0706.1186 [hep-ph]]; G. J. Ding, arXiv:0803.2278 [hep-ph]; P. H. Frampton, S. Matsuzaki, arXiv:0902.1140 [hep-ph].

[5] S. Pakvasa, H. Sugawara, *Phys. Lett. B* **82** (1979) 105; T. Brown, N. Deshpande, S. Pakvasa, H. Sugawara, *Phys. Lett. B* **141** (1984) 95; T. Brown, S. Pakvasa, H. Sugawara, Y. Yamanaka, *Phys. Rev. D* **30** (1984) 255; D. G. Lee, R. N. Mohapatra, *Phys. Lett. B* **329** (1994) 463 [arXiv:hep-ph/9403201]; E. Ma, *Phys. Lett. B* **632** (2006) 352 [arXiv:hep-ph/0508231]; Gui-Jun Ding, *Nucl. Phys. B* **827** (2010) 82 [arXiv:0909.2210 [hep-ph]].

[6] Federica Bazzocchi, Luca Merlo, Stefano Morisi, *Phys. Rev. D* **80** (2009) 053003.

[7] P. Minkowski, *Phys. Lett. B* **67** (1977) 421; M. Gell-Mann, P. Ramond, R. Slansky, *Proceedings of the Supergravity Stony Brook Workshop*, 1979 New York, eds. P. Van Nieuwenhuizen, D. Freedman; T. Yanagida, *Proceedinds of the Workshop on Unified Theories and Baryon Number in the Universe*,

1979 Tsukuba, Japan, eds. A. Sawada, A. Sugamoto; R. N. Mohapatra, G. Senjanovic, *Phys. Rev. Lett.* **44** (1980) 912.

[8] M. Fukugita, T. Yanagida, *Phys. Lett. B* **174** (1986) 45; G. F. Giudice *et al.*, *Nucl. Phys. B* **685** (2004) 89 [arXiv:hep-ph/0310123]; W. Buchmuller, P. Di Bari, M. Plumacher, *Annals Phys.* **315** (2005) 305 [arXiv:hep-ph/0401240]; A. Pilaftsis, T. E. J. Underwood, *Phys. Rev. D* **72** (2005) 113001 [arXiv:hep-ph/0506107].

[9] S. M. Bilenky, S. Pascoli, S. T. Petcov, *Phys. Rev. D* **64** (2001) 053010; S. Pascoli, S. T. Petcov, L. Wolfenstein, *Phys. Lett. B* **524** (2002) 319; **549** (2002) 177; S. T. Petcov, *New J. Phys.* **6** (2004) 109.

[10] H. V. Klapdor-Kleingrothaus *et al.*, *Eur. Phys. J. A* **12** (2001) 147 [arXiv:hep-ph/0103062]; H. V. Klapdor-Kleingrothaus, I. V. Krivosheina, A. Dietz, O. Chkvorets, *Phys. Lett. B* **586** (2004) 198 [arXiv:hep-ph/0404088]; C. Arnaboldi *et al.* [CUORICINO Collaboration], *Phys. Rev. C* **78** (2008) 035502 [arXiv:0802.3439 [hep-ex]]; J. Wolf *et al.* [KATRIN Collaboration], arXiv:0810.3281 [physics.ins-det].

[11] C. Aalseth *et al.*, arXiv:hep-ph/0412300; I. Abt *et al.*, arXiv:hep-ex/0404039.

[12] L. Covi, E. Roulet, F. Vissani, *Phys. Lett. B* **384** (1996) 169; A. Pilaftsis, *Int. J. Mod. Phys. A* **14** (1999) 1811 [arXiv:hep-ph/9812256].

[13] T. Endoh, T. Morozumi, Z. Xiong, *Prog. Theor. Phys.* **111** (2004) 123 [arXive:hep-ph/0308276]; T. Fujihara, S. Kaneko, S. K. Kang, D. Kimura, T. Morozumi, M. Tanimoto, *Phys. Rev. D* **72** (2005) 016006 [arXive:hep-ph/0505076]; A. Abada, S. Davidson, A. Ibarra, F. X. Josse-Michaux, M. Losada, A. Riotto, *JHEP* **0609** (2006) 010 [arXiv:hep-ph/0605281]; S. Blanchet, P. Di Bari, *JCAP* **0703** (2007) 018 [arXiv:hep-ph/0607330]; S. Antusch, S. F. King, A. Riotto, *JCAP* **0611** (2006) 011 [arXiv:hep-ph/0609038].

[14] R. Gonzalez Felipe, F. R. Joaquim, B. M. Nobre, *Phys. Rev. D* **70** (2004) 085009 [arXiv:hep-ph/0311029]; K. Turzynski, *Phys. Lett. B* **589** (2004) 135 [arXiv:hep-ph/0401219]; G. C. Branco, R. Gonzalez Felipe, F. R. Joaquim, B. M. Nobre, *Phys. Lett. B* **633** (2006) 336 [arXiv:hep-ph/0507092]; J. A. Casas, J. R. Espinosa, A. Ibarra, I. Navarro, *Nucl. Phys. B* **573** (2000) 652 [arXiv:hep-ph/9910420]; J. A. Casas, J. R. Espinosa, A. Ibarra, I. Navarro, *Nucl. Phys. B* **569** (2000) 82 [arXiv:hep-ph/9905381].

[15] A. Abada, S. Davidson, F. X. Josse-Michaux, M. Losada, A. Riotto, *JCAP* **0604** (2006) 004 [arXiv:hep-ph/0601083]; S. Antusch, S. F. King and A. Riotto, *JCAP* **0611** (2006) 011 [arXiv:hep-ph/0609038].

[16] D. N. Spergel *et al.* [WMAP Collaboration], *Astrophys. J. Suppl.* **148** (2003) 175; M. Tegmark *et al.*, *Phys. Rev. D* **69** (2004) 103501; C. L. Bennett *et al.*, *Astrophys. J. Suppl.* **148** (2003) 1 [arXiv:astro-ph/0302207].

Received 30-09-2011.