Family replicated calculation of baryogenesis

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Abstract. In our model with a Standard Model gauge group extended with a baryon number minus lepton number charge for each family of quarks and leptons, we calculate the baryon number relative to entropy produced in early Big Bang by the Fukugita-Yanagida mechanism. With the parameters, i.e., the Higgs VEVs already fitted in a very successful way to quark and lepton masses and mixing angles we obtain the order of magnitude pure prediction $Y_B = 2.59^{+17.0}_{-2.25} \times 10^{-11}$ which according to a theoretical estimate should mean in this case an uncertainty of the order of a factor 7 up or down (to be compared to $Y_B = (1.7 - 8.1) \times 10^{-11}$) using a relatively crude approximation for the dilution factor, while using another estimate based on Buchmüller and Plumacher a factor 500 less, but this should rather be considered a lower limit. With a realistic uncertainty due to wash-out of a factor 100 up or down we even with the low estimate only deviate by $1.5\sigma$.

1 Introduction

Using the model for mass matrices presented by us in an other contribution at this conference we want to compute the amount of baryons produced in the early universe. This model works by having the mass matrix elements being suppressed by approximately conserved quantum numbers from a gauge group repeated for each family of quarks and leptons and also having a $(B-L)$ charge for each family.

The baryon number density relative to entropy density, $Y_B$, is one of the rather few quantities that can give us information about the laws of nature beyond the Standard Model and luckily we have from the understanding of the production of light isotopes at the minute scale in Big Bang fits to this quantity. The “experimental” data of the ratio of baryon number density to the entropy density is

$$Y_B \bigg|_{\text{exp}} = (1.7 - 8.1) \times 10^{-11}. \quad (1)$$

We already had a good fit of all the masses and mixings for both quarks and leptons measured so far and agreeing with all the bounds such as neutrinoless beta decay and proton decay not being seen and matching on the borderline but consistent with the accuracy of our model and of the experiment of CHOOZ the
electron to heaviest left-handed neutrino mixing, and that in a version of our model in which the dominant matrix element in the right-handed neutrino mass matrix is the diagonal one for the “third” (i.e. with same \((B-L)\), as the third family) family \(\nu_{R3}\) right-handed neutrino. This version of our model which fits otherwise very well does not give sufficient \((B-L)\) excess, that survives, but the by now the best model in our series should have the right-handed mass matrix dominated by the off-diagonal elements \((2,3)\) and \((3,2)\), so that there appears two almost mass degenerate see-saw neutrinos, in addition to the third one (first family) which is much lighter.

2 Mass matrices and results for masses and mixing angles

Our model produces mass matrix elements – or effective Yukawa couplings – which are suppressed from being of the order of the top-mass because they are forbidden by the conservation of the gauge charges of our model and can only become different from zero using the 6 Higgs fields \(\phi\) which we have in addition to the field replacing the Weinberg-Salam one. In the neutrino sector according to the see-saw mechanism \(\phi\) we have to calculate Dirac- and Majorana-mass matrices, \(M_{\text{eff}} \approx M^D M_{R^{-1}}^T \left(M^D_{\nu}\right)^T\), to obtain the effective mass matrix \(M_{\text{eff}}\) for the left handed neutrinos we in practice can “see”. Here we present all mass matrices as they follow from our choice of quantum numbers for the 7 Higgs fields in our model and for the quarks and leptons (as they can be found in the other contribution). Only the quantum numbers for the field called \(\phi_{B-L}\) is – in order to get degenerate see-saw neutrinos – changed into having the \((B-L)\) quantum numbers of family 2 and 3 equal to 1, i.e., \((B-L)_2 = (B-L)_3 = 1\), while the other family quantum numbers are just zero:

the up-type quarks:

\[
M_{\nu} \simeq \frac{\langle \phi_{WS} \rangle^1}{\sqrt{2}} \left( \begin{array}{ccc}
(\omega^1)^3 W^T T^2 & \omega \rho^1 W^T T^2 & \omega \rho^1 (W^1)^2 T \\
(\omega^1)^4 \rho W^T T^2 & W^T T^2 & (W^1)^2 T \\
(\omega^1)^4 \rho & 1 & W^T T^1
\end{array} \right)
\] (2)

the down-type quarks:

\[
M_D \simeq \frac{\langle \phi_{WS} \rangle}{\sqrt{2}} \left( \begin{array}{ccc}
\omega^2 W(T^1)^2 & \omega \rho^1 W(T^1)^2 & \omega \rho^1 T^3 \\
\omega^2 \rho W(T^1)^2 & W(T^1)^2 & T^3 \\
\omega^2 \rho W^2(T^1)^2 & W^2(T^1)^4 & W T
\end{array} \right)
\] (3)

the charged leptons:

\[
M_E \simeq \frac{\langle \phi_{WS} \rangle}{\sqrt{2}} \left( \begin{array}{ccc}
\omega^3 W(T^1)^2 & (\omega^1)^3 \rho^3 W(T^1)^2 & (\omega^1)^3 \rho^3 W T^4 \\
\omega^6 (\rho^1)^3 W(T^1)^2 & W(T^1)^2 & W T^4 \\
\omega^6 (\rho^1)^3 (W^1)^2 T^4 & (W^1)^2 T^4 & W T
\end{array} \right)
\] (4)

the Dirac neutrinos:

\[
M^D_{\nu} \simeq \frac{\langle \phi_{WS} \rangle}{\sqrt{2}} \left( \begin{array}{ccc}
(\omega^1)^3 W^T T^2 & (\omega^1)^3 \rho^3 W^T T^2 & (\omega^1)^3 \rho^3 W^T T^2 \\
(\rho^1)^3 W^T T^2 & W^T T^2 & W^T T^2 \\
(\rho^1)^3 W^T T^1 \chi^1 & W^T T^1 \chi & W^T T^1
\end{array} \right)
\] (5)
and the Majorana (right-handed) neutrinos:

$$M_R \simeq \langle \phi_{b-L} \rangle \begin{pmatrix} (\rho^1)^6 \chi^\dagger & (\rho^1)^3 \chi^\dagger /2 & (\rho^1)^3 /2 \\ (\rho^1)^3 /2 & \chi^\dagger & 1 \\ \chi & 1 & \chi \end{pmatrix}$$  \hspace{1cm} (6)

We shall remember that it is here understood that all the matrix elements are to be provided with order of unity factors which we do not know and in practice have treated by inserting random order of unity factors over which we then average at the end (in a logarithmic way).

### 3 Renormalisation group equations

The model for the Yukawa couplings we use gives, in principle, these couplings at the fundamental scale, taken to be the Planck scale, at first, and we then use the renormalisation group to run them down to the scales where they are to be confronted with experiment. From the Planck scale down to the see-saw scale or rather from where our gauge group is broken down to SMG or rather from where our gauge group is broken down to $SMG \times U(1)_{B-L}$ we use the one-loop renormalisation group running of the Yukawa coupling constant matrices and the gauge couplings in GUT notation including the running of Dirac neutrino Yukawa coupling:

$$16\pi^2 \frac{dg_1}{dt} = \frac{41}{16} g_1^3 , \quad 16\pi^2 \frac{dg_2}{dt} = \frac{19}{16} g_2^3 , \quad 16\pi^2 \frac{dg_3}{dt} = -7 g_3^3 ,$$

$$16\pi^2 \frac{dY_U}{dt} = 3 \left[ (Y_U(Y_U)^\dagger - Y_U(Y_U)^\dagger) Y_U + \left\{ Y_s - \left( \frac{17}{20} g_1^2 + \frac{9}{4} g_2^2 + 8 g_3^2 \right) \right\} Y_U , \right.$$  

$$16\pi^2 \frac{dY_D}{dt} = \frac{3}{2} \left( Y_D(Y_D)^\dagger - Y_D(Y_D)^\dagger \right) Y_D + \left\{ Y_s - \left( \frac{1}{4} g_1^2 + \frac{9}{4} g_2^2 + 8 g_3^2 \right) \right\} Y_D , \right.$$  

$$16\pi^2 \frac{dY_E}{dt} = \frac{3}{2} \left( Y_E(Y_E)^\dagger - Y_E(Y_E)^\dagger \right) Y_E + \left\{ Y_s - \left( \frac{9}{16} g_1^2 + \frac{9}{4} g_2^2 \right) \right\} Y_E , \right.$$  

$$16\pi^2 \frac{dY_\nu}{dt} = \frac{3}{2} \left( Y_\nu(Y_\nu)^\dagger - Y_\nu(Y_\nu)^\dagger \right) Y_\nu + \left\{ Y_s - \left( \frac{9}{20} g_1^2 + \frac{9}{4} g_2^2 \right) \right\} Y_\nu , \right.$$  

where $t = \ln \mu$ and $\mu$ is the renormalisation point.

In order to run the renormalisation group equations down to 1 GeV, we use the following initial values:

$$U(1) : \quad g_1(M_Z) = 0.462 , \quad g_1(M_{\text{Planck}}) = 0.614 , \quad (7)$$

$$SU(2) : \quad g_2(M_Z) = 0.651 , \quad g_2(M_{\text{Planck}}) = 0.504 , \quad (8)$$

$$SU(3) : \quad g_3(M_Z) = 1.22 , \quad g_3(M_{\text{Planck}}) = 0.491 . \quad (9)$$

We varied the 6 free parameters and found the best fit, corresponding to the lowest value for the quantity g.o.f. $\equiv \sum \left[ \ln \left( \frac{m_{\text{meas}}}{m_{\text{pred}}} \right) \right]^2 = 3.38$, with the following...
values for the VEVs:
\[ \langle \phi_{WS} \rangle = 246 \text{ GeV}, \quad \langle \phi_{B-L} \rangle = 1.23 \times 10^{10} \text{ GeV}, \quad \langle \omega \rangle = 0.245, \quad \langle \rho \rangle = 0.256, \quad \langle W \rangle = 0.143, \quad \langle T \rangle = 0.0742, \quad \langle \chi \rangle = 0.0408, \]

where, except for the Weinberg-Salam Higgs field and \( \langle \phi_{B-L} \rangle \), the VEVs are expressed in Planck units. Hereby we have considered that the Weinberg-Salam Higgs field VEV is already fixed by the Fermi constant. The results of the best fit, with the VEVs in eq. (10), are shown in Table 1.

4 Quantities to use for baryogenesis calculation

Since the baryogenesis in the Fukugita-Yanagida scheme \[7\] arises from a negative excess of lepton number being converted by Sphalerons to a positive baryon number excess partly and this negative excess comes from the \( CP \) violating decay of the see-saw neutrinos we shall introduce the parameter \( \epsilon_i \) giving the measure of the relative asymmetry under \( C \) or \( CP \) in the decay of neutrino number \( i \): Defining the measure \( \epsilon_i \) for the \( CP \) violation

\[
\epsilon_i \equiv \frac{\sum_{\alpha,\beta} \Gamma(N_{Ri} \to \ell^\alpha \phi_{WS}^{\beta}) - \sum_{\alpha,\beta} \Gamma(N_{Ri} \to \ell^\alpha \phi_{WS}^{\beta})}{\sum_{\alpha,\beta} \Gamma(N_{Ri} \to \ell^\alpha \phi_{WS}^{\beta}) + \sum_{\alpha,\beta} \Gamma(N_{Ri} \to \ell^\alpha \phi_{WS}^{\beta})},
\]

where \( \Gamma \) are \( N_{Ri} \) decay rates (in the \( N_{Ri} \) rest frame), summed over the neutral and charged leptons (and Weinberg-Salam Higgs fields) which appear as final states in the \( N_{Ri} \) decays one sees that the excess of leptons over anti-leptons produced in the decay of one \( N_{Ri} \) is just \( \epsilon_i \). The total decay rate at the tree level is given by

\[
\Gamma_{N_i} = \Gamma_{N_i,\ell} + \Gamma_{N_i,\ell} = \frac{((M^{D}_\nu)^\dagger M^{D}_\nu)_{ii}}{4\pi \langle \phi_{WS} \rangle^2} M_i,
\]

Table 1. Best fit to conventional experimental data. All masses are running masses at 1 GeV except the top quark mass which is the pole mass. Note that we use the square roots of the neutrino data in this Table, as the fitted neutrino mass and mixing parameters \( \langle m \rangle \), in our goodness of fit (g.o.f.) definition.
where $\tilde{M}_\nu^D$ can be expressed through the unitary matrix diagonalising the right-handed neutrino mass matrix $V_R$:

$$\tilde{M}_\nu^D \equiv M_\nu^D V_R,$$

$$V_R^{\dagger} M_R V_R = \text{diag}\left( M_1^2, M_2^2, M_3^2 \right).$$

The CP violation rates are computed according to \cite{8,9}

$$\epsilon_i = \frac{\sum_{j \neq i} \text{Im}[((M_\nu^D)^{\dagger} \tilde{M}_\nu^D)_{ij}^2] \left[ f \left( \frac{M_i^2}{M_j^2} \right) + g \left( \frac{M_i^2}{M_j^2} \right) \right]}{4\pi \langle \phi_{WS} \rangle^2 ((M_\nu^D)^{\dagger} M_\nu^D)_{ii}}$$

where the function, $f(x)$, comes from the one-loop vertex contribution and the other function, $g(x)$, comes from the self-energy contribution. These $\epsilon$'s can be calculated in perturbation theory only for differences between Majorana neutrino masses which are sufficiently large compared to their decay widths, i.e., the mass splittings satisfy the condition, $|M_i - M_j| \gg |\Gamma_i - \Gamma_j|:

$$f(x) = \sqrt{x} \left[ 1 - (1 + x) \ln \frac{1 + x}{x} \right], \quad g(x) = \frac{\sqrt{x}}{1 - x}.$$  

We as usual \cite{2} introduce the decay rate relative to

$$K_i \equiv \frac{\Gamma_i}{2H} \bigg|_{T = M_i} = \frac{M_{\text{Planck}}}{1.66 \langle \phi_{WS} \rangle^2 8\pi g_{*i}^{1/2}} \frac{((M_\nu^D)^{\dagger} \tilde{M}_\nu^D)_{ii}}{M_i} \quad (i = 1, 2, 3),$$

where $\Gamma_i$ is the width of the flavour $i$ Majorana neutrino, $M_i$ is its mass and $g_{*i}$ is the number of degrees of freedom at the temperature $M_i$ (in our model $\sim 100$).

In order to estimate the effective $K$ factors we first introduce some normalized state vectors for the decay products:

$$|i\rangle \equiv \left( \sum_{k=1}^{3} \left| \tilde{M}_\nu^D(M_i)_{ki} \right|^2 \right)^{-\frac{1}{2}} \left( \left[ \tilde{M}_\nu^D(M_i) \right]_{1i}, \left[ \tilde{M}_\nu^D(M_i) \right]_{2i}, \left[ \tilde{M}_\nu^D(M_i) \right]_{3i} \right).$$

Then we may take an approximation for the effective $K$ factors:

$$K_{\text{eff}1} = K_1(M_1),$$

$$K_{\text{eff}2} = K_2(M_2) + |2\rangle|3\rangle^2 K_3(M_3) + |2\rangle|1\rangle^2 K_1(M_1),$$

$$K_{\text{eff}3} = K_3(M_3) + |3\rangle|2\rangle^2 K_2(M_2) + |3\rangle|1\rangle^2 K_1(M_1).$$

### 5 Result for baryogenesis

Using the Yukawa couplings – as coming from the VEVs of our seven different Higgs fields – the numerical calculation of baryogenesis were performed using
our random order unity factor method. In order to get baryogenesis in Fukugita-
Yanagida scheme, we calculated the see-saw neutrino masses, $K_{eff}$ factors and
$CP$ violation parameters using $N = 10,000$ random number combinations and
logarithmic average method:

\[
M_1 = 2.1 \times 10^5 \text{ GeV} \quad K_{eff1} = 31.6 \quad |\epsilon_1| = 4.62 \times 10^{-12}
\]

\[
M_2 = 8.8 \times 10^9 \text{ GeV} \quad K_{eff2} = 116.2 \quad |\epsilon_2| = 4.00 \times 10^{-6}
\]

\[
M_3 = 9.9 \times 10^9 \text{ GeV} \quad K_{eff3} = 114.7 \quad |\epsilon_3| = 3.27 \times 10^{-6}
\]

The sign of $\epsilon_i$ is unpredictable due to the complex random number coefficients
in mass matrices, therefore we are not in the position to say the sign of $\epsilon$'s. Using
the complex order unity random numbers being given by a Gaussian distribution
we get after logarithmic averaging using the dilution factors as presented by [2,3]

\[
Y_B = 2.59^{+17.0}_{-2.25} \times 10^{-11}, \tag{22}
\]

where we have estimated the uncertainty in the natural exponent according
ref. [10] to be $64 \% \cdot \sqrt{10} \approx 200 \%$.

The understanding of how this baryon to entropy prediction $Y_B$ comes about
in the model may be seen from the following (analytical) estimate

\[
Y_B \approx \frac{1}{3} \cdot \frac{\chi}{g_s T^2} \cdot \frac{M_3}{M_{\text{Planck}}} \approx \frac{1}{3} \cdot 10^{-9} \tag{23}
\]

where we left out for simplicity the ln $K$ factor in the denominator of the dilution
factor $\kappa$ and where $M_3$ is the mass of one of the heavy right-handed neutrinos in
our model $M_3 \approx \langle \phi_{B-L} \rangle$. Since the atmospheric mass square difference square
root $\sqrt{\Delta m_{\text{atm}}^2} \approx 0.05 \text{ eV} \approx \langle \phi_{WS} \rangle^2 (WT)^2/M_3$ we see that keeping it leaves us
with the dependence

\[
Y_B \approx \frac{\langle \phi_{WS} \rangle^2 \chi}{3 \sqrt{0.05 \text{ eV} \cdot g_s M_{\text{Planck}} W^2 T^4}} \approx \frac{1}{5} \times 10^{-4} \cdot \frac{\chi}{\sqrt{g_s W^2 T^4}} \tag{24}
\]

6 Problem with wash-out effects?

To make a better estimate of the wash-out effect we may make use of the calcula-
tions by [11] by putting effective values for the see-saw neutrino mass $M$ and
$m$. The most important wash-out is due to “on-shell” formation of right-handed
neutrinos and only depends on $K$ or the thereto proportional $m$, but next there
are wash-out effects going rather than by $K$ or $m$ as $M \tilde{m}^2$. In the presentation
of the results by [11] fixed ratios between right-handed neutrino masses were
assumed. However, in reality a very important wash-out comes form the off-shell
inverse decay and that goes as

\[
M_1 \sum_j \frac{M_j^2}{M_1} \tilde{m}_j^2 \quad \text{with} \quad \tilde{m}_j = \frac{[\langle \tilde{M}^D \rangle^j_{ij} \langle \tilde{M}^D \rangle_{ij}]}{M_j} \tag{25}
\]
Here we use the notation with $\tilde{m}_j$ from [11]:

$$\tilde{m}_j \approx K_j \cdot 2.2 \cdot 10^{-3} \text{eV}.$$  

Using such a term (see eq. 25) with the ansatz ratios used in [11], $M_1^2 = 10^6 M_1^2$ and $M_2^2 = 10^3 M_1^2$ one gets for eq. (24) $\approx 10^6 \tilde{m}_3^2$, while we would with our mass ratios (eq. 22) $M_1^2 \approx 1/4 \cdot 10^{10} M_1^2$ and $M_2^2 \approx 1/4 \cdot 10^{10} M_1^2$ obtain correspondingly $2 \cdot 10^5 \text{GeV} \cdot 1/4 \cdot 10^{10} \tilde{m}_3^2 \approx 1/2 \cdot 10^{15} \text{GeV} \tilde{m}_3^2$, which then being identified with $10^6 M_{1,\text{use}}^2 \tilde{m}_3^2$ would lead to that we should effectively use for simulating our model the mass of the right handed neutrino – which is a parameter in the presentation of the dilution effects in [11] – $M_{1,\text{use}} = 1/2 \cdot 10^{15} \text{GeV}/10^6 = 1/2 \cdot 10^9 \text{GeV}$. Inserting this $M_{1,\text{use}}$ value for our estimate $\tilde{m}_2 \approx \tilde{m}_3 \approx 0.1 \text{eV}$ gives a dilution factor $\kappa \approx 10^{-4}$, i.e., a factor 500 less than what we used with our estimate using the $K_{\text{eff}}$’s. (Our $\tilde{m}_3 = \tilde{m}_2$ are surprisingly large compared to the $\sqrt{\Delta m_{\text{atm}}^2}$ because of renormalzation running.) Using the better calculation of [11] which has a very steep dependence – a fourth power say – as function of $\tilde{m}$ our uncertainty should also be corrected to a factor 100 up or down. So then we have one and a half standard deviations of getting too little baryon number.

### 7 Conclusion

We calculated the baryon density relative to the entropy density – baryogenesis – from our model order of magnitudewise. This model already fits to quark and lepton masses and mixing angles using only six parameters, vacuum expectation values. We got a result for the baryon number predicting about a factor only three less than the fitting to microwave background fluctuations obtained by Buchmüller et al. [12], when we used our crude $K_{\text{eff}}$’s approximation. However, using the estimate extracted from the calculations of [11] we got three orders of magnitude too low prediction of the baryon number. This estimate must though be considered a possibly too low estimate because there is one scattering effect that is strongly suppressed with our masses but which were included in that calculation. But even the latter estimate should because of the steep dependence of the result on the parameters be considered more uncertain and considering the deviation of our prediction only $1.56\sigma$ is not unreasonable.

Since we used the Fukugita-Yanagida mechanism of obtaining first a lepton number excess being converted (successively by Sphalerons) into the baryon number, our success in this prediction should be considered not only a victory for our model for mass matrices but also for this mechanism. Since our model would be hard to combine with supersymmetry – it would loose much of its predictive power by having to double the Higgs fields – we should consider it in a non-SUSY scenario and thus we can without problems take the energy scale to inflation/reheating to be so high that the plasma had already had time to go roughly to thermal equilibrium before the right-handed neutrinos go out-of-equilibrium due to their masses. We namely simply have no problem with getting too many gravitinos because gravitinos do not exist at all in our scheme.

Another “unusual” feature of our model is that the dominant contribution to the baryogenesis comes from the heavier right-handed neutrinos. In our model it
could be arranged without any troubles that the two heaviest right-handed neutrinos have masses only deviating by 10% namely given by our VEV parameters $\chi$. This leads to significant enhancement of the $\epsilon_2$ and $\epsilon_3$ which is crucial for the success of our prediction. There is namely a significant wash-out taking place, by a factor of the order of $\kappa = 10^{-3}$ to $10^{-6}$. It is remarkable that we have here worked with a model that order of magnitudewise has with only six adjustable parameters been able to fit all the masses and mixings angles for quarks and leptons measured so far, including the Jarlskog $CP$ violation area and most importantly and interestingly the baryogenesis in the early Universe. To confirm further our model we are in strong need for further data – which is not already predicted by the Standard Model, or we would have to improve it to give in principle accurate results rather than only orders of magnitudes. The latter would, however, be against the hallmark of our model, which precisely makes use of that we can guess that the huge amount of unknown coupling constants in our scheme with lots of particles can be counted as being of order unity.

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