Lab-to-Genesis

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We show that existing laboratory experiments have the potential to unveil the origin of matter by probing leptogenesis in the type-I seesaw model with three right-handed neutrinos and Majorana masses in the GeV range. The baryon asymmetry is generated by CP-violating flavour oscillations during the production of the right-handed neutrinos. In contrast to the case with only two right-handed neutrinos, no degeneracy in the Majorana masses is required. The right-handed neutrinos can be found in meson decays at BELLE II and LHCb.

INTRODUCTION

All matter particles in the Standard Model (SM) except neutrinos have been observed with both, left-handed (LH) and right-handed (RH) chirality. If RH neutrinos exist, they can explain several phenomena which cannot be understood in the framework of the SM, for a review see e.g. Refs. [1, 2]. In particular, they give neutrinos masses via the seesaw mechanism [3] and can at the same time generate the baryon asymmetry of the universe (BAU) via leptogenesis [4], making this one of the most attractive scenarios for baryogenesis. Leptogenesis with $n = 2$ RH neutrinos has been studied in detail, and it was found that the BAU can only be explained if their masses are either very heavy [5, 10] or degenerate [11], see e.g. [12, 13] and [14, 20]. In the former case the new particles are too heavy to be seen in any experiment. In the latter case it was found that their interaction strengths, characterised by mixing angles with ordinary neutrinos, are generally too feeble to give measurable branching ratios in existing experiments [17, 18, 21, 22] and could only be accessed by dedicated future experiments [23]. In this work we show that both shortcomings, the “tuned” mass degeneracy and suppressed production rates at colliders, are specific to the scenario with $n = 2$ and can be avoided if three or more RH neutrinos participate in leptogenesis even if there is no other physics beyond the SM.

THE MODEL

We consider the most general renormalisable Lagrangian in Minkowski space that only contains SM fields and RH neutrinos $\nu_R$,

$$
\mathcal{L} = \mathcal{L}_{SM} + \overline{\nu_R} \gamma^\mu \nu_R - \overline{L} F_{LR} \Phi - \overline{R} F^{\dagger} L_R \Phi^\dagger
- \frac{1}{2} (\overline{\nu_R} M_M \nu_R + \overline{\nu_R} M_M^\dagger \nu_R^\dagger).
$$

Here flavour and isospin indices are suppressed. $\mathcal{L}_{SM}$ is the SM Lagrangian, $L_L = (\nu_L, e_L)^T$ are the left handed SM lepton doublets, $\Phi$ is the Higgs doublet with $\Phi = (e \Phi)^T$, where $e$ is the antisymmetric $SU(2)$ tensor, $F$ is a matrix of Yukawa couplings and $M_M$ a Majorana mass term for $\nu_R$ with $\nu_R^C = C \nu_R^T$. The charge conjugation matrix is $C = i \gamma_2 \gamma_0$. For $n$ flavours of $\nu_R$, the eigenvalues of $M_M$ introduce $n$ new mass scales in nature. In analogy with the LH sector we consider the case of $n = 3$ flavours of RH neutrinos. This is the minimal number required to generate three non-zero light neutrino masses. We work in a flavour basis where $M_M = \text{diag}(M_1, M_2, M_3)$. For $M_I > eV$ one observes two distinct sets of mass eigenstates, which we represent by flavour vectors of Majorana spinors $\nu$ and $N$. The $\nu = V_{\nu}^L \nu_L - U_{\nu}^R \theta \nu_R^T + c.c$ are mainly superpositions of the “active” $SU(2)$ doublet states $\nu_L$ and have light masses $\sim m_\nu = -\theta M_M \theta^T \ll M_M$. The $N = V_{N}^L \nu_L + \Theta \nu_R^T + c.c.$ are mainly superpositions of the “sterile” singlet states $\nu_R$ and have masses of the order of $M_I$. Here c.c. stands for the $C$-conjugation defined above, $\Theta \ll 1$ is the mixing matrix between active and sterile neutrinos and $\theta \equiv \Theta_{N_L}^T$. $V_{\nu}$ is the usual neutrino mixing matrix and $U_{\nu}$ its unitary part, $V_N$ and $U_N$ are their equivalents in the sterile sector. To be precise: $V_{\nu} \equiv (1 - \frac{1}{2} \theta \theta^T) U_{\nu}$ with $\theta \equiv m_D M_M^{-1}, m_D \equiv F v$ and the temperature dependent Higgs field expectation value $v (v = 174$ GeV at temperature $T = 0)$. The unitary matrices $U_{\nu}$ and $U_N$ diagonalise the mass matrices $m_\nu \sim -\theta M_M \theta^T$ and $M_N = M_M + \frac{1}{2} (\theta^T \theta M_M + M_M^T \theta^T \theta^T)$, respectively. Experimentally the magnitude of the $M_I$ is almost unconstrained, as neutrino oscillation experiments at energies $E \ll M_I$ only involve the light states $\nu_L$ and probe the combination $m_\nu = -F M_M^{-1} F^T$.

For $n = 3$ the Lagrangian contains 18 new physical parameters. The phenomenological implications for different choices of these parameters can be extremely different, see e.g. Refs. [1, 2] for a summary. Confirmation of the model requires the masses of the new states $N_I$ to be within reach of experiments. We use the Casas-Ibarra parametrisation [24] for $F = \frac{1}{2} U_{\nu} \sqrt{m_{\text{diag}}} R \sqrt{M_M}$ of the Yukawa matrices. Here $m_{\text{diag}}^L = U_{\nu}^L m_\nu U_{\nu}^T = \text{diag}(m_1, m_2, m_3)$ and $R$ is a matrix with $R^T R = 1$ that can be parametrised by complex mixing angles $\omega_{ij}$. This allows to directly encode all constraints from neutrino oscillation experiments in $U_{\nu}$ and $m_{\text{diag}}$. For $n = 3$ sterile flavours there are three complex “Euler angles” $\omega_{ij}$ in $R$, while for $n = 2$ there would be only one such angle $\omega$. We study the perspectives to find the new states $N_I$ in laboratory experiments, in particular LHCb and BELLE II, and focus on the mass range $M_I < 5$ GeV.
LEPTOGENESIS

Leptogenesis requires a deviation from thermal equilibrium \[25\], hence it can occur either during the production \[14, 26\] or the freezeout and decay \[3\] of \(N_f\) in the early universe. We focus on the scenario where the BAU is generated during \(N_f\) production, which is often referred to as baryogenesis from neutrino oscillations. For the parameters we consider, the CP-violation contained in \(F\) typically acts most efficiently when the primordial plasma has a temperature \(T \sim 10^9\) GeV, where sphaleron processes rapidly violate baryon number \(B\) \[27\], but the violation of total lepton \(L\) number is suppressed by \(M_f/T \ll 1\). However, there can be significant asymmetries \(L_\alpha\) in the individual flavours. For \(M_f/T \ll 1\) the helicity states of the Majorana fields \(N_f\) effectively act as “particles” and “antiparticles”, and one can assign approximately conserved lepton charges to the sterile flavours. Flavour dependent \(F\) fields, where they are hidden from the sphaleron processes, can contribute to the sterile flavour asymmetry \(\delta L\) into \(B\). The \(L_\alpha\) and \(B\) get washed out once the \(N_f\) come into equilibrium. If this process is incomplete at the time of sphaleron freezeout at \(T = T_{\text{sph}} \sim 130 - 140\) GeV \[28, 29\], then a net \(B\) \(\neq 0\) remains protected from further washout at lower temperatures, when \(B\) is conserved. This mechanism is explained in more detail in Refs. \[1, 17, 19, 31, 53\].

The rate of thermal \(N_f\) production is given by \(\Gamma_f = (F^\dagger F)_I \gamma_{\alpha\nu} T\). The quantity \(\gamma_{\alpha\nu}\) is a numerical coefficient that depends on \(M_f/T\) and has to be calculated in thermal field theory. The asymmetry is bigger if generated at earlier times, hence larger couplings \(F\) give a larger BAU. On the other hand, larger \(F\) also imply larger washout rates \(\Gamma_\alpha = (F^\dagger F)_{\alpha\alpha} \gamma_{\alpha\nu} T\). Hence, it is crucial that the Yukawa interactions \(F\) are large enough to generate significant lepton asymmetries \(L_\alpha\) at \(T \gg T_{\text{sph}}\), but small enough to prevent a complete washout of all \(L_\alpha\) before \(T = T_{\text{sph}}\). This is most easily achieved if individual elements \(F_{\alpha I}\) are sufficiently different in size that one active flavour \(\alpha\) couples much more weakly to the \(N_f\) than the other two, leading to a flavour asymmetric washout that allows the asymmetry in that flavour to survive until \(T = T_{\text{sph}}\). For the sake of definiteness we assume in the following that this is the electron flavour, i.e. \(\Gamma_e \ll \Gamma_\mu, \tau\).

In the minimal scenario with \(n = 2\) this is difficult to achieve because there is only one complex angle \(\omega\) in \(R\). The strengths of the active-sterile couplings in all flavois tied together, as they are essentially governed by just one parameter \(\Im \omega\) \[19, 34, 37\]. This generally leads to very small baryon asymmetries because a large asymmetry generation at \(T \gg T_{\text{sph}}\) necessarily implies a large washout for all flavours at \(T \gtrsim T_{\text{sph}}\), and the observed BAU can only be explained if it is resonantly enhanced by a degeneracy in the masses at the level \(< 10^{-3}\) \[17, 19\]. At the same time the non-observation of \(\mu \rightarrow e\gamma\) implies strong upper bounds on the interactions of all flavours, which makes a detection at colliders difficult \[22\]. The situation changes drastically in the \(n = 3\) scenario. The reason is that in this case there are three complex angles \(\omega_{ij}\) in \(R\). This enlarged parameter space contains considerable regions in which \(\Gamma_e \ll \Gamma_\mu, \tau\).

In the following we exclude the mass degenerate case \(|M_f - M_f| \lesssim \Gamma_f\) from our analysis, which requires a more sophisticated treatment of flavour oscillations \[38-43\] and makes up only a small fraction of the parameter space. This allows to approximate \(V_{\nu} = U_{\nu}\) and \(U_N = 1\). The lepton charge \(q_\alpha\) in flavour \(\alpha\) at \(T \gg T_{\text{sph}}\) can be estimated as

\[
q_\alpha/s \approx -\frac{\Gamma F_{\alpha I} F_{\beta J} F_{IJ}}{\sigma} \frac{m^2_{\nu_I}}{(M^2_{\nu_I} - M^2_{\nu_J})^2} \text{sign}(M^2_{\nu_I} - M^2_{\nu_J})
\]

\[
\times \left(\frac{m^2_{\nu_I}}{(M^2_{\nu_I} - M^2_{\nu_J})}\right)^\frac{2}{3} \times 1.2 \times 10^{-4} M^2_{\nu_I}. \tag{2}\]

Here \(s\) is the entropy density and \(m_{\nu_i}\) the Planck mass. We define asymmetries \(q_{\nu_I}\) in the \(N_f\) via their helicity states. The expression \[2\] has been derived in \[32\] the framework of the nonequilibrium quantum field theory approach to leptogenesis \[32, 38-43\] and allows to systematically include the different quantum and thermodynamical effects that affect the asymmetry generation in a controlled approximation scheme. Up to numerical coefficients it agrees with an expression found in \[14\] in the framework of density matrix equations \[53\]. In this work we want to show, as a proof of principle, that leptogenesis is possible with experimentally accessible \(N_f\). For this purpose we restrict ourselves to the case

\[
\Gamma_\mu/H, \Gamma_\tau/H > 1 \text{ at } T = T_{\text{sph}}. \tag{3}\]

Here \(H\) is the Hubble rate. We denote charge densities in the \(\mu, \tau\)-leptons and the \(N_f\) after their equilibration by \(q_{\nu_I}^W\) and \(q_f^W\). Equilibrium thermodynamics gives the relation \(2q_{\nu_I}^W = 2q_f^W = q_f^W\), where the factor 2 counts the SU(2) doublet components. Lepton number conservation implies \(q_{\mu}^W + q_e^W + q_\tau^W = q_\mu + q_e + q_\tau = -q_e\), hence \(q_{\mu}^W + q_e^W = -(4/7)q_e\) is the part of the asymmetry that is cancelled before sphaleron freezeout. Taking account of the \(q_e\) washout and the sphaleron conversion factor \[58, 60\], the BAU can be obtained as

\[
\frac{q_B/s}{s} \approx \frac{28}{79} \times -\frac{\Gamma_{\nu_e}/H}{s}. \tag{4}\]

PARAMETER SCAN

We aim to identify the overlap between the parameter region where baryogenesis is possible and the experimentally accessible range of masses and mixings. We expect that the baryogenesis region for given \(M_f\) extends
between a lower and upper bound on the angles $|\Theta_{\alpha I}|$. The lower bound comes from the requirement to produce enough asymmetry (2), the upper bound from the requirement to keep at least one of the $\Gamma_\alpha$ small enough to prevent a complete washout of the flavoured asymmetries before sphaleron freezeout. To determine the overlap with the experimentally accessible region we perform a parameter scan to identify the largest mixing $|\Theta_{\alpha I}|$ for which the observed BAU can be explained. We compare it to current experimental upper bounds and to the expected future sensitivity. For the sake of definiteness we choose $N_2$ and study the mixing with $\nu_\mu$, which has been probed at LHCb. We have checked that the perspectives for $N_1$ and $N_3$ are similar. We restrict ourselves to the fraction of the parameter space where (3) is fulfilled and (4) can be used to compute the BAU. This is precisely the region where one can expect large $|\Theta_{\mu I}|$.

We choose the Casas-Ibarra parametrisation 24 defined above and fix $M_1 = 1$ GeV, $M_3 = 3$ GeV, $m_1 = 2.5 \times 10^{-3}$ eV, $m_2 = 9.05 \times 10^{-3}$ eV and $m_3 = 5 \times 10^{-2}$ eV. We fix all other known neutrino parameters according to the global fits given in [61] and vary $M_2$. For each choice of $M_2$ we perform a Monte Carlo scan of $5 \times 10^8$ points over the Majorana phases $\alpha_1$ and $\alpha_2$, the Dirac phase $\delta$ and all three complex mixing angles $\omega_{ij}$ to identify the parameter region where the observed BAU is explained, using 10$^8$ points per mass parameter. For all Im$\omega_{ij}$ we scan the interval $[-5, 5]$, the dependence on all other parameters is periodic. The parameter $\gamma_{\alpha I}$ can be determined from the results for $\Gamma_\ell$ found in Refs. [62, 63], which slightly differ from each other. We use the results from Ref. [63], which imply $\gamma_{\alpha I} = 0.015$ at $T = T_{\text{sph}}$ and $\gamma_{\alpha I} = 0.013$ at $T = 10^5$ GeV for $M_1 \ll T_{\text{sph}}$.

The BAU can be measured in different ways, see e.g. Ref. 60 for a review. Here we use the value $q_{\mu I} / s = 8.58 \times 10^{-11}$ inferred from the Planck data [67]. We accept a point if (4) gives at least this value, as the asymmetry can always be reduced by varying the CP-violating phases. We also require each point to be consistent with bounds on lepton flavour violation from the rare decay $\mu \rightarrow e \gamma$, which has a branching ratio 68, 69.

$$B(\mu \rightarrow e \gamma) = \frac{\Gamma(\mu \rightarrow e \gamma)}{\Gamma(\mu \rightarrow e \nu_\mu \bar{\nu}_e)} = \frac{3\alpha_{em}}{32\pi} |R|^2$$

with

$$R = \sum_i (V_{\nu i})^\ast (V_{\nu i} c_1 G \left( \frac{m_i^2}{M_W^2} \right) + \sum_I \Theta_{\mu I} \Theta_{e I} G \left( \frac{M_I^2}{M_W^2} \right)$$

and the loop function

$$G(x) = \frac{10 - 43x + 78x^2 - 49x^3 + 4x^4 + 18x^3 \log(x)}{3(x-1)^4}.$$ 

This is the currently strongest bound on lepton flavour violation 22, 70, 71, see 1, 72 for a discussion of other experimental constraints. In the low mass region bounds from neutrinoless double $\beta$-decay on the quantity

$$m_{ee} = \left| \sum_i (U_{\nu i})^2 m_i + \sum_I \Theta_{\mu I}^2 M_I f_A(M_I) \right|$$

have to be considered 73, where $f_A = (M_A/M_1)^2 f_A$, $M_A \approx 0.9$ GeV and $f_A = 0.079$ for $^{76}$Ge. We use $m_{ee} < 0.2$ eV 74. Finally, the lifetime of the RH neutrinos is constrained by the requirement that they decay faster than about 0.1s. Otherwise they would affect the formation of light elements in big bang nucleosynthesis (BBN) in the early universe. The results of the scan are displayed in figure 1.

![Figure 1](image)

**FIG. 1.** The red line shows the maximal mixing $|\Theta_{\mu I}|^2$ we found consistent with baryogenesis, i.e. below the line there exist parameter choices for which the observed BAU can be generated. The scatter is a result of the Monte Carlo method and not physical. It indicates that we have not found the global maxima, rather that the density of valid points decreases rapidly for larger $|\Theta_{\mu I}|^2$. The gray area represents bounds on $U_{\mu I}^2$ from the past experiments PS191 75, NuTeV 76 (both re-analysed in 77), NA3 78, CHARMII 79 and DELPHI 80 (as given in 72). The blue lines indicate the current bounds on $U_{\mu I}^2$ from LHCb 81 (dotted) and BELLE 82 (dashed), which will improve in the future.

**DISCUSSION**

From an experimental viewpoint there are three qualitatively different mass regions. In all regions $N_2$ can be produced in $Z$-boson decays. In region i) with $M_2 < 2$ GeV $N_1$ can also be produced in the decays $D$-mesons and $B$-mesons, in region ii) with $2 \text{GeV} < M_2 < 5$ GeV $N_2$ can be produced in the decay of $B$-mesons and in region iii) with $M_2 > 5$ GeV $N_2$ is too heavy to be produced in meson decays. In FIG. 1 we show the largest $|\Theta_{\mu I}|^2$ we found that can lead to baryogenesis as a function of $M_2$ in regions i) and ii). This need not be an absolute upper bound, as there may be parameter choices
outside the region we scanned that yield an even larger mixing. However, the precise value of the largest mixing that would be consistent with baryogenesis is practically not relevant in the mass range we consider because the values we found lie considerably above the experimental limits. This is also the reason why the uncertainties in our calculation in the coefficient $\gamma_{\text{av}}$, the temperature dependence of the sphaleron rate near $T_{\text{ sph}}$ [30] and from the neglected momentum dependence [16] in (4) do not affect our conclusion. Moreover, when comparing our bounds to limits inferred from experimental searches, it should be kept in mind that experiments usually quote bounds on $N_i$ should be kept in mind that experiments usually quote bounds on $U_{\mu}^2 = \sum I |\Theta_{\mu I}|^2$. These are obtained by measuring the branching ratio for different processes and converting them into a bound on $U_{\mu}^2$ under the assumption that there is only $n = 1$ RH neutrino (in which case $U_{\mu}^2 \propto |\Theta_{\mu I}|^2$). For $n = 3$ the relation between the measured branching ratios and $|\Theta_{\mu I}|^2$ is more complicated; it depends on several parameters and cannot be displayed easily. Since $U_{\mu}^2 > |\Theta_{\mu I}|^2$, comparing the theoretical $|\Theta_{\mu I}|^2$ to the bound on $U_{\mu}^2$ should therefore be regarded as a conservative estimate of the experimental perspectives.

FIG. 1 shows that any experiment which improves the known bounds has the potential to discover the $N_I$ responsible for baryogenesis. The most stringent bounds from past experiments have been summarised in [17, 72, 73, 83]. In region i) these have already deeply entered into the cosmologically relevant parameter space, they impose $U_{\mu}^2 < 10^{-8} - 10^{-6}$ for $M_I$ below the Kaon mass and $U_{\mu}^2 < 10^{-7} - 10^{-6}$ below the masses of D-mesons. No existing experiment has the potential to improve these bounds. However, the SHIP experiment proposed in [22] would be able to probe a significantly larger fraction of the cosmologically interesting parameter space down to $U_{\mu}^2 \sim 10^{-9}$. In region ii) the strongest bounds come from the search for heavy neutral leptons in $Z$-boson decays in the DELPHI experiment [30], from LHCb [51] and from the BELLE experiment [82]. All of them have already entered the parameter region where baryogenesis is possible. The published LHCb bounds are below those from DELPHI, but LHCb will continue to take data after the upgrade to 14 TeV. The displayed bounds were obtained with an integrated luminosity $L_{\text{int}} = 3fb^{-1}$ from the process $B^- \rightarrow \pi^+ \mu^- \mu^-$. The branching ratio for this decay is $\propto |\Theta_{\mu 2}|^4$, hence the bound on $|\Theta_{\mu 2}|$ under ideal conditions improves as $\propto \sqrt{L_{\text{int}}}$. With the anticipated $L_{\text{int}} = 50fb^{-1}$ the bound will improve by a factor $\sim (2 \times 3/50)^{1/2} \sim 6$ in the region where the background is low, just enough to outperform DELPHI and current BELLE bounds. The factor 2 comes from the enhanced production of $B$-mesons at the 14 TeV LHC. Further improvement can be achieved by analysing additional processes, e.g., the leptonically and semi-leptonic decays listed in [15, 34, 72]. These include decays with other mesons or electrons in the final state. Though heavier mesons in the final state kinematically restrict the range of accessible $M_I$ and the reconstruction efficiency for electrons is lower, in combination these could significantly improve the bounds at least in some part of the mass region below 5 GeV. Bounds from BELLE are stronger and cover much of the parameter space accessible to LHCb. The increase in $L_{\text{int}}$ alone will make BELLE II an order of magnitude more sensitive to $U_{\mu}^2$ than BELLE. Further improvement is possible if data from all channels is used in the analysis. This includes “peak searches” for missing four-momentum, which can be competitive in spite of a $\sim 10^3$ times worse reconstruction efficiency because the branching ratio scales $\propto U_{\mu}^2$, and the sensitivity improves linearly with $L_{\text{int}}$. Though not shown in FIG. 1 also SHIP could also probe region iii). The expected sensitivity has not been calculated yet. Region iii) could be probed in $Z$-boson decays, but no dedicated experiment of this kind is currently planned.

To see if any realistic experiment could completely rule out this baryogenesis scenario one has to determine the lower bound on $U_{\mu}^2$. Our formula (4) to calculate the BAU can only be applied in the parameter region where $\Theta_{\mu I}$ applies, which is also the experimentally most easily accessible region due to the large mixing with $\nu_{\mu}$. This strategy does not allow to find the strict lower bound on $U_{\mu}^2$ for which the BAU can be generated. A complete analysis requires the numerical solution of quantum kinetic equations with coefficients that can be derived systematically in thermal field theory, which we postpone this to future work. The smallest mixings we find for $0.5 GeV < M_2 < 5 GeV$ within the range of validity of [33] and in absence of mass degeneracies are $U_{\mu}^2 < 10^{-10}$, which is an order of magnitude below the anticipated SHIP sensitivity and close to the strict lower bound from neutrino oscillation experiments [37].

CONCLUSIONS

We have shown that three RH neutrinos in the type-I seesaw model (1) with masses in the GeV range and experimentally accessible mixings can explain the BAU via leptogenesis. No degeneracy in the Majorana masses is required. For $M_1 = 1 GeV, M_2 = 2 GeV, M_3 = 3 GeV$ the couplings can be as large as $\sqrt{\text{tr}(F F)} > 10^{-4}$, larger than the electron Yukawa coupling. A discovery of heavy neutral leptons with masses and mixings in this range at LHCb or BELLE II would be smoking gun evidence that these particles are the common origin of matter in the universe and the observed neutrino masses. A non-degenerate mass spectrum makes this scenario clearly distinguishable from resonant leptogenesis. Both of these experiments have already entered the cosmologically interesting parameter space. The chances for a discovery can be optimised by studying all possible decay channels of $B$-mesons that involve $N_I$. The perspectives would be...
even better at the proposed SHIP experiment, for which our findings provide strong motivation.

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