

Resonant τ Leptogenesis with Observable Lepton Number Violation

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We consider a minimal extension of the standard model with one singlet neutrino per generation that can realize resonant leptogenesis at the electroweak scale. In particular, the baryon asymmetry in the Universe can be created by lepton-to-baryon conversion of an individual lepton number, for example, that of the τ lepton. The current neutrino data can be explained by a simple CP -violating Yukawa texture. The model has several testable phenomenological implications. It contains heavy Majorana neutrinos at the electroweak scale, which can be probed at e^+e^- linear colliders, and predicts e - and μ -lepton-number-violating processes, such as $0\nu\beta\beta$ decay, $\mu \rightarrow e\gamma$, and μ - e conversion in nuclei, with rates that are within reach of experimental sensitivity.

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The origin of our matter-antimatter-asymmetric Universe is one of the central themes in particle cosmology. In the light of the recent high-precision observation of the baryon-to-photon ratio of number densities, $\eta_B \approx 6.1 \times 10^{-10}$ [1], finding a laboratory testable solution to this problem becomes even more motivating. A consensus has been reached that a possible solution to the problem of the baryon asymmetry in the Universe (BAU) requires physics beyond the standard model (SM). In this context, an interesting suggestion has been that neutrinos, which are strictly massless in the SM, may acquire their observed tiny mass naturally by the presence of superheavy partners through the so-called seesaw mechanism [2]. These superheavy neutrinos have Majorana masses that violate the lepton number (L) by two units. Their out-of-equilibrium decay in an expanding universe may initially produce a leptonic asymmetry, which is then converted into the observed BAU [3] by equilibrated ($B + L$)-violating sphaleron interactions [4].

In ordinary seesaw models embedded in grand unified theories (GUTs), the natural mass scale of the heavy Majorana neutrinos is expected to be of order the GUT scale 10^{16} GeV. However, the reheating temperature T_{reh} in these theories is generically of order 10^9 GeV, thus requiring for one of the heavy neutrinos, e.g., N_1 , to be unnaturally light below T_{reh} , so as to be abundantly produced in the early Universe. On the other hand, successful leptogenesis and compatibility with the existing neutrino data put a lower bound on the N_1 mass: $m_{N_1} \gtrsim 10^9$ GeV [5]. To avoid this narrow window of viability of the model around 10^9 GeV, one needs to assume that the second heaviest neutrino N_2 is as light as N_1 [6], an assumption that makes this thermal GUT leptogenesis scenario even more unnatural.

A solution that avoids the aforementioned T_{reh} problem is to have low-scale thermal leptogenesis [7,8]. To accomplish this, one may exploit the fact that heavy-neutrino self-energy effects [9,10] on the leptonic asymmetry get resonantly enhanced, even up to order 1, when a pair of

heavy Majorana neutrinos has a mass difference comparable to the heavy-neutrino decay widths [7]. In this case, the scale of leptogenesis can be lowered to the TeV range [7,8] in complete agreement with the current neutrino data [11]. Even though the discussion will be focused on a minimal nonsupersymmetric 3-generation model, the ideas presented here could be extended to unified and supersymmetric theories as well [12,13].

In this Letter we study a potentially important variant of resonant leptogenesis, where a given individual lepton number is resonantly produced by out-of-equilibrium decays of heavy Majorana neutrinos of a particular family type. For the case of the τ -lepton number, we call this mechanism *resonant τ leptogenesis*. Since sphalerons preserve the individual quantum numbers $\frac{1}{3}B - L_{e,\mu,\tau}$ [14] in addition to the $B - L$ number, an excess in L_τ will be converted into the observed BAU, provided the possible L_τ -violating reactions are not strong enough to wash out such an excess. Moreover, a chemical potential analysis [14] shows that the generated baryon asymmetry is $B = -\frac{28}{51}L_\tau$ at temperatures T above the electroweak phase transition, i.e., for $T \gtrsim T_c \approx 150$ – 200 GeV. Hence, generating the BAU from an individual lepton-number excess is very crucial for the resonant τ -leptogenesis scenario presented below to have phenomenologically testable signatures of lepton-number violation.

The model under discussion is the SM symmetrically extended with one singlet neutrino ν_R per family. The leptonic flavor structure of the Yukawa and Majorana sectors of such a model may be described by the Lagrangian

$$\begin{aligned}
 -\mathcal{L}_{Y,M} = & \frac{1}{2}(\bar{\nu}_{iR})^C(M_S)_{ij}\nu_{jR} + \hat{h}_{ii}^l\bar{L}_i\Phi l_{iR} \\
 & + h_{ij}^{\nu_R}\bar{L}_i\tilde{\Phi}\nu_{jR} + \text{H.c.},
 \end{aligned} \tag{1}$$

where $i, j = 1, 2, 3$, and $\tilde{\Phi}$ is the isospin conjugate of the Higgs doublet Φ . We define the individual lepton numbers in (1) in the would-be charged-lepton mass basis, where the

charged-lepton Yukawa matrix \hat{h}^l is diagonal. Note that all SM reactions, including those that involve the e -Yukawa coupling, will be in thermal equilibrium for temperatures $T \lesssim 10$ TeV [15,16], relevant to low-scale leptogenesis models. The calculation of the BAU will be performed in the heavy-neutrino mass basis, where the 3 heavy-neutrino mass eigenstates are denoted by $N_{1,2,3}$. Such a selection could be justified from arguments based on decoherential in-thermal equilibrium dynamics, and by the fact that heavy Majorana neutrino decays are thermally blocked already at temperatures $T \gtrsim 3m_{N_i}$ [17].

We now present a generic scenario for resonant τ leptogenesis. The neutrino Yukawa sector of this scenario has the following maximally CP -violating form:

$$h^{\nu_R} = \begin{pmatrix} \varepsilon_e & ae^{-i\pi/4} & ae^{i\pi/4} \\ \varepsilon_\mu & be^{-i\pi/4} & be^{i\pi/4} \\ \varepsilon_\tau & ce^{-i\pi/4} & ce^{i\pi/4} \end{pmatrix}. \quad (2)$$

For nearly degenerate N_i masses in the range $m_{N_i} \approx 0.5$ – 1 TeV, the moduli of the complex parameters a, b have to be smaller than about 10^{-2} for phenomenological reasons to be discussed below. On the other hand, the requirement to protect an excess in L_τ from washout effects leads to the relatively stronger constraint $|c| \lesssim 10^{-4}$. Furthermore, the parameters ε_l , with $l = e, \mu, \tau$, are taken to be small perturbations of the order of the e Yukawa coupling, i.e., $|\varepsilon_l| \sim 10^{-6}$. Here, we should stress that at least 3 singlet heavy neutrinos are needed to obtain a phenomenologically relevant model.

It is now important to notice that for exactly degenerate heavy Majorana neutrinos $M_S = m_N \mathbf{1}_3$ and $\varepsilon_l = 0$, the light-neutrino mass matrix vanishes identically, i.e., $(m^\nu)_{ll'} = -v^2 h_{li}^{\nu_R} (M_S^{-1})_{ij} h_{lj'}^{\nu_R} = 0$, where $v \approx 175$ GeV is the usual SM vacuum expectation value. The resulting vanishing of the light-neutrino masses will be an all-orders result, protected by a $U(1)_l$ leptonic symmetry, where each lepton doublet couples to the linear combination: $(\nu_{2R} + i\nu_{3R})$ [18]. If the symmetry-breaking parameters are $|\varepsilon_l| \sim 10^{-6}$ and $(\Delta M_S)_{ij} = (M_S)_{ij} - m_N \delta_{ij} \lesssim 10^{-7} \times m_N$ (we shall not address here in detail the origin of these small breaking parameters, but they could result from different sources, e.g., the Froggatt-Nielsen mechanism [11,19], Planck- or GUT-scale lepton-number breaking [7,20], etc.), the entries of m^ν fall within the observed region of less than ~ 0.1 eV for $m_N \sim 1$ TeV. At this point, we should emphasize that our scenario is radiatively stable. For a TeV-scale leptogenesis scenario, renormalization-group running effects on m^ν are very small [21]. In addition, there are Higgs- and Z-boson-mediated threshold effects δm^ν of the form [22]:

$$(\delta m^\nu)_{ll'} \sim 10^{-3} \frac{v^2}{m_N^2} h_{li}^{\nu_R} (\Delta M_S)_{ij} h_{lj'}^{\nu_R}. \quad (3)$$

Given the constraints on the Yukawa parameters discussed

above, one may estimate that the finite radiative effects δm^ν stay well below 0.01 eV for $(\Delta M_S)_{ij}/m_N \lesssim 10^{-7}$ and $|a|, |b| \lesssim 10^{-2}$. Hence, the perturbation parameters ε_l and $(\Delta M_S)_{ij}$ provide sufficient freedom to describe the existing neutrino data. For our resonant τ -leptogenesis scenario, the favored solution is an inverted hierarchical neutrino mass spectrum with large $\nu_e \nu_\mu$ and $\nu_\mu \nu_\tau$ mixings [23]. An explicit example for a scenario with $m_N = 500$ GeV is given in [24].

It is instructive to give an order-of-magnitude estimate of the BAU generated by resonant τ leptogenesis. In such a model, only the heavy Majorana neutrino N_1 will decay relatively out of thermal equilibrium. Instead, N_2 and N_3 will decay in thermal equilibrium predominantly into e and μ leptons. To avoid erasure of a potential L_τ excess, the decay rates of N_2 and N_3 to τ leptons should be rather suppressed. To be specific, in this framework the predicted BAU is expected to be

$$\eta_B \sim -10^{-2} \frac{\delta_{N_1}^\tau}{K_{N_1}} \frac{\Gamma(N_1 \rightarrow L_\tau \Phi)}{\Gamma(N_{2,3} \rightarrow L_\tau \Phi)} \sim -10^{-2} \frac{\delta_{N_1}^\tau}{K_{N_1}} \frac{\varepsilon_\tau^2}{c^2}, \quad (4)$$

where $\delta_{N_1}^\tau$, computed analytically in [11] for a 3-generation model, is the τ -lepton asymmetry and $K_{N_1} = \Gamma_{N_1}/H(z=1)$ is an out-of-equilibrium measure of the N_1 -decay rate Γ_{N_1} with respect to the Hubble rate $H(z) \approx 17m_{N_1}^2/(z^2 M_{\text{Planck}})$, with $z = m_{N_1}/T$. For $\varepsilon_l \sim 10^{-6}$, it is $K_{N_1} \sim 10$. The size of η_B is determined by the key parameters: K_{N_1} , $\delta_{N_1}^\tau$, and ε_τ/c . To account for the observed BAU, one would need, e.g., $|\delta_{N_1}^\tau| \sim 10^{-5}$ and $\varepsilon_\tau/c \sim 10^{-1}$. Instead, the parameters a and b could be as large as $\sim 10^{-2}$, potentially giving rise to observable effects of lepton-number violation at colliders and laboratory experiments (see discussion below).

We now perform a simplified numerical analysis of the BAU in this scenario of resonant τ leptogenesis. Detailed results of this study are given in [25]. Since the $N_{2,3}$ heavy Majorana neutrinos will be in thermal equilibrium, their contribution to the L_τ asymmetry will be vanishingly small. A conservative numerical estimate may be obtained by solving the Boltzmann equation (BE):

$$\begin{aligned} \frac{d\eta_{L_\tau}}{dz} = & -\frac{z}{H(z=1)n_\gamma} \left[\delta_{N_1}^\tau \left(1 - \frac{\eta_{N_1}}{\eta_{N_1}^{\text{eq}}} \right) \gamma_{L_\tau \Phi}^{N_1} + \frac{\eta_{L_\tau}}{4} \right. \\ & \left. \times \left(\sum_{i=1}^3 \gamma_{L_\tau \Phi}^{N_i} + \gamma_{\ell\ell}^S \right) \right], \end{aligned} \quad (5)$$

where n_γ is the photon number density, and η_{N_1} and η_{L_τ} are the N_1 -number-to-photon and L_τ -number-to-photon ratios of number densities, respectively. We follow the conventions of [11] for the collision terms $\gamma_{L_\tau \Phi}^{N_i}$ related to the decays and inverse decays of the $N_{1,2,3}$ neutrinos into $L_{e,\mu,\tau}$ and Φ . The collision term $\gamma_{\ell\ell}^S$ describes the L_τ -violating $2 \leftrightarrow 2$ scatterings: (i) $L_\tau \Phi \leftrightarrow L_{e,\mu,\tau}^C \Phi^\dagger$ and

$L_\tau \Phi \leftrightarrow L_{e,\mu} \Phi$; (ii) $L_\tau L_{e,\mu,\tau}^C \leftrightarrow \Phi \Phi$ and $L_\tau L_{e,\mu} \leftrightarrow \Phi \Phi^\dagger$. The collision terms for the reactions (i) can be shown to be always smaller than $\Sigma_{i=1}^3 \gamma_{L_\tau \Phi}^{N_i}$ for the temperature domain $z \lesssim 10$ of interest, while those for the reactions (ii) are suppressed by factors proportional to $(m_{N_i} - m_{N_j})/T$, $(m^\nu)^2/v^2$, and $(a+b)^2 \sim 10^{-4}$, and can therefore be neglected. To obtain a conservative estimate, we set $\gamma_{L_\tau}^S = \Sigma_{i=1}^3 \gamma_{L_\tau \Phi}^{N_i}$.

Figure 1 shows numerical estimates of η_{L_τ} as functions of $z = m_{N_1}/T$, for the resonant τ -leptogenesis scenario given in [24]. In this scenario, it is $\delta_{N_1}^\tau \approx -0.3 \times 10^{-5}$ and $K_{N_1} \approx 15$. We find that $\eta_{L_\tau}(T_c)$ is independent of the initial values $\eta_{N_1}^{\text{in}}$ and $\eta_{L_\tau}^{\text{in}}$. Thus, the heavy-neutrino mass m_{N_1} could in principle be as low as the critical temperature T_c , namely, at the electroweak scale. Employing the lepton-to-baryon conversion formula for $T \ll T_c$ [11], $\eta_B \approx -\frac{1}{54} \eta_{L_\tau}$, we find that our numerical results are compatible with the estimate in (4). Instead, we have carefully checked that the usual formalism of BEs does not properly incorporate single lepton flavor effects and leads to an erroneous result for the BAU which is a factor $\eta_L/\eta_{L_\tau} \sim (\delta_{N_1}/\delta_{N_1}^\tau)[|c|^2/(|a|^2 + |b|^2)] \sim 10^{-8}$ [26] too small.

Our model of resonant τ leptogenesis has several phenomenological consequences. Since the model realizes an inverted light-neutrino mass spectrum [24,27], it leads to a sizeable neutrinoless double beta ($0\nu\beta\beta$) decay with an effective neutrino mass $|(m^\nu)_{ee}| \approx 0.013$ eV, which could be tested in future $0\nu\beta\beta$ experiments. The model also predicts $\mu \rightarrow e\gamma$ with a branching ratio $B(\mu \rightarrow e\gamma) \approx 6 \times 10^{-4} (a^2 b^2 v^4)/m_N^4$ in the heavy-neutrino limit [28]. Confronting this prediction with the experimental limit $B^{\text{exp}}(\mu \rightarrow e\gamma) \lesssim 1.2 \times 10^{-11}$ [23], the resulting constraint is $(abv^2)/m_N^2 \lesssim 1.4 \times 10^{-4}$. For electroweak-scale heavy neutrinos and $a, b \sim 3 \times 10^{-3}$, there should be observable effects in foreseeable experiments sensitive to $B(\mu \rightarrow e\gamma) \sim 10^{-13}$ [29,30] and to a μ - e conversion rate in ^{48}Ti (normalized to the μ capture rate) to the 10^{-16} level [31,32]. A much higher signal in the latter observable would indicate the presence of possible sizeable nondecoupling terms of the form $(a^2 b^2 v^2)/m_N^2$, which dominate for $a, b \gtrsim 0.5$ [33]. This different kinematic dependence of the two observables on the product of the Yukawa couplings ab would enable one to get some idea about the size of the heavy-neutrino mass scale m_N . On the other hand, the possible existence of electroweak-scale heavy neutrinos $N_{2,3}$ with appreciable e -Yukawa couplings $a \gtrsim 3 \times 10^{-3}$ could be directly tested by studying their production at e^+e^- linear colliders [34]. Although it would be difficult to produce N_1 directly, a characteristic signature of $N_{2,3}$ is that they will decay predominantly to e and μ leptons, but not to τ 's. Moreover, since $N_{2,3}$ play an important synergetic role in resonantly enhancing $\delta_{N_1}^\tau$, potentially large

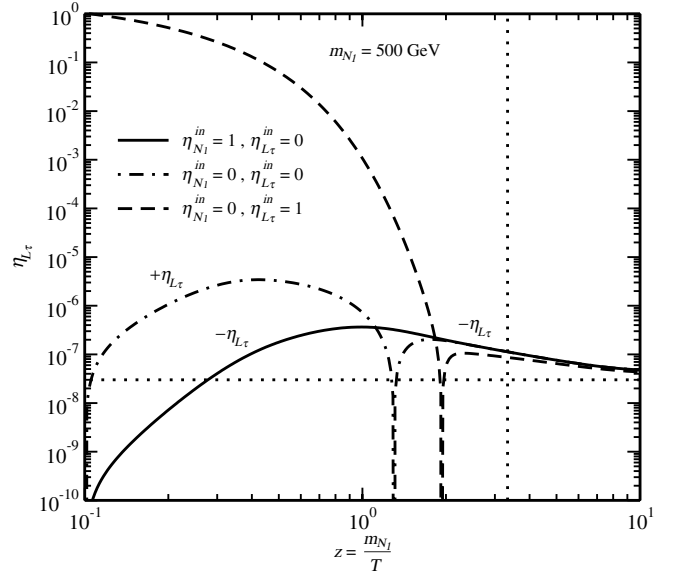


FIG. 1. Numerical values for η_{L_τ} vs $z = m_{N_1}/T$, for different initial conditions for η_{N_1} and η_{L_τ} , and for the model parameters given in [24]. The horizontal dotted line at $\eta_{L_\tau} \approx -3 \times 10^{-8}$ indicates the value needed to obtain the observed BAU, while the vertical dotted line corresponds to $T = T_c = 150$ GeV.

CP -violating effects in their decays will determine the theoretical parameters further. Obviously, further detailed studies are needed to obtain a conclusive answer to the question of whether electroweak-scale resonant τ -leptogenesis could, in principle, provide a laboratory testable solution to the cosmological problem of the baryon asymmetry in the Universe.

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