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Leptogenesis at the Electroweak Scale

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In this note we propose a model of leptogenesis in which the scale for the mass of the necessary heavy neutral lepton is similar to the scale of electroweak symmetry breaking.

I. INTRODUCTION

Leptogenesis [1]-[3] appears to provide a natural explanation of the cosmic baryon-antibaryon asymmetry. In leptogenesis, CP-violating decays of heavy Majorana neutrinos produce a lepton-antilepton asymmetry, and then sphaleron processes at and above the electroweak symmetry breaking scale convert part of this asymmetry into the observed baryon-antibaryon asymmetry. The heavy neutrinos are see-saw partners of the observed light ones. In the standard type-I see-saw picture, one and the same matrix of Yukawa coupling constants leads to the CP-violating decays of the heavy neutrinos, to the Dirac masses of the light neutrinos, and to all CP-violating effects among the Standard Model leptons. This linking of diverse physical phenomena is an attractive feature of leptogenesis, and of the see-saw picture from which it springs. However, this linking also leads to an important constraint: if heavy neutrino decay is to provide the degree of CP violation needed to explain the observed baryon-antibaryon asymmetry, and in addition light neutrino masses of the observed order of magnitude are to be obtained, then the heavy neutrinos must have masses of $10^{(8-9)}$ GeV or more [4], putting them far out of reach of current or foreseeable accelerators.

In this paper, we propose a new version of leptogenesis in which the heavy neutrinos have masses of the order of the electroweak scale, (100 – 200) GeV. This puts them well within reach of the Large Hadron Collider [5]. Our proposal is not without its drawbacks, and the heavy neutrinos may prove difficult to observe despite their low masses. However, we believe the scheme is interesting enough to warrant serious consideration, and hope that this paper will stimulate that.

In either "standard" leptogenesis or the alternative being proposed here, the heavy neutrinos

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must decay out of equilibrium. That is, when a heavy neutrino N, with mass m_N, decays to a Standard Model (SM) lepton L and a Higgs boson ϕ via a Yukawa coupling constant y, then the N decay rate $\Gamma_D \sim (y^2/8\pi)\, m_N$ must not exceed the Hubble expansion rate of the universe, H, when the temperature T is m_N. Since

$$H(T = m_N) = 1.66\sqrt{g^*}\, \frac{T^2}{m_{Pk}}\bigg|_{T=m_N} \quad , \tag{1}$$

where $g^* \sim 100$ is the number of relativistic degrees of freedom, and $m_{Pk} \sim 10^{19}$ GeV is the Planck mass, we require that

$$y^2 \lesssim 400 \frac{m_N}{m_{Pk}} \quad . \tag{2}$$

In the see-saw picture [6], the masses m_ν of the light neutrinos are related to the masses m_N of their heavy see-saw partners by a relation of the form

$$m_\nu \sim \frac{(vy)^2}{m_N} \quad , \tag{3}$$

where $v = 174$ GeV is the vacuum expectation value of the SM neutral Higgs field. Combining Eqs. (2) and (3), we see that leptogenesis requires that

$$m_\nu \lesssim 10^{-3}\text{eV} \quad . \tag{4}$$

Interestingly, the light neutrino masses do come within a few orders of magnitude of satisfying this approximate relation, which is generic to leptogenesis models.

In the heavy neutrino decays that drive leptogenesis, the CP violation that is needed to produce a matter-antimatter asymmetric universe arises from interference between a dominating tree-level decay diagram and various loop diagrams. Suppose there are three heavy neutrinos N_i, $i = 1, 2, 3$. In the standard version of leptogenesis, the tree diagram for the decay $N_1 \to L\phi$ of the lightest heavy neutrino N_1, and one of the loop corrections to this decay, are the diagrams shown in Fig. 1. Let us call the Yukawa coupling constants at the various vertices in these diagrams generically

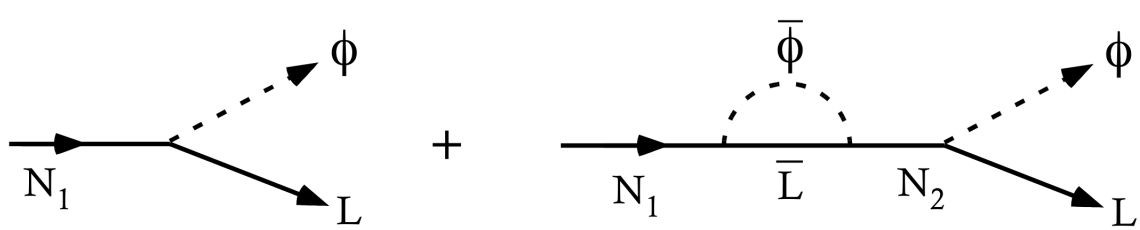

FIG. 1: The tree diagram and an illustrative loop diagram whose interference can lead to leptogenesis.

y. For the CP-violating asymmetry produced by the interference between the diagrams,

$$\epsilon_{CP} \equiv \frac{\Gamma(N_1 \to L\phi) - \Gamma(N_1 \to \bar{L}\bar{\phi})}{\Gamma(N_1 \to L\phi) + \Gamma(N_1 \to \bar{L}\bar{\phi})} \quad , \tag{5}$$

we have

$$\epsilon_{CP} \approx \frac{1}{\pi} \frac{\mathcal{O}(|y|^4)}{\mathcal{O}(|y|^2)} \eta \quad , \tag{6}$$

where η is a factor parametrizing the CP-violating phases. As this illustrates, in standard leptogenesis, the CP-violating asymmetry ϵ_{CP} arising from heavy neutrino decays is of 2nd order in the Yukawa coupling constants. More specifically, $\epsilon_{CP} \sim |y|^2/(10 \text{ to } 100)$[2]. Since ϵ_{CP} must be $\sim 10^{-6}$ in order for leptogenesis to yield the observed baryon to photon number density ratio of the universe[3], this implies that y^2 must be in the range $10^{-4} - 10^{-5}$. This range seems very reasonable, given prevailing prejudices regarding the acceptable values of coupling constants.

From cosmological observations and tritium β decay experiments, we know that the light neutrino masses lie in the eV range or below. From neutrino oscillation experiments, we know that at least one light neutrino has a mass of 0.04 eV or above. Therefore, we assume the light neutrino masses m_ν to be of order 10^{-1} eV. If the see-saw relation, Eq. (3), is to yield light neutrino masses of this order when $y^2 \sim 10^{-(4-5)}$, the heavy neutrinos must have masses $m_N \sim 10^{(9-10)}$ GeV[3]. Thus, in standard leptogenesis, the heavy neutrinos are very far beyond the range of any present or foreseeable particle accelerator. In addition, they raise the question of what physics generates their $10^{(9-10)}$ GeV mass scale.

We would like to present a novel version of leptogenesis in which the heavy neutrinos have masses that are at the electroweak scale. This puts them kinematically within reach of the Large Hadron Collider, and eliminates the need for a new high-mass scale of unknown origin. Our model hinges on Higgs boson quartic couplings.

Assuming that the light neutrino masses are still generated by the see-saw mechanism, we see from the see-saw relation, Eq. (3), that if m_N is only at the electroweak scale, then the coupling y^2 must be quite small. In particular, if $m_N \sim 200$ GeV, then $y^2 \sim 10^{-12}$. The out-of-equilibrium condition, Eq. (2), requires a somewhat smaller coupling, $y^2 \lesssim 10^{-14}$. While such a coupling constant is indeed small, we note that the Yukawa coupling constant g_{ee} that is generally thought to lead to the electron's mass is not markedly larger: $g_{ee}^2 \sim 10^{-11}$.

As we have noted, standard leptogenesis requires that $y^2 \sim 10^{-(4-5)}$ in order that the CP-violating asymmetry ϵ_{CP} produced by N decays be sufficiently large. Thus, in standard leptogenesis, the Yukawa coupling $y^2 \sim 10^{-(12-14)}$ appropriate to our alternative scenario would be far too small. However, as we shall see, in this new scenario, ϵ_{CP} is actually independent of y.

II. THE ELECTROWEAK-SCALE SCENARIO

We will assume that there are three SU(2) X U(1) scalar doublets,

$$\phi_a = \begin{pmatrix} \phi_a^+ \\ \phi_a^0 \end{pmatrix} \quad , \quad a = 1, 2, 3 \quad , \tag{7}$$

that couple to quarks and leptons. We will also assume that the potential is such that ϕ_1^0 acquires a nonvanishing vacuum expectation value, $< \phi_1^0 > \equiv v_1 \neq 0$, but the vacuum expectation values of all the other scalar fields vanish. That is, $< \phi_a^0 > \equiv v_a = 0$ for $a = 2$, 3. The potential will naturally lead to these vacuum expection values (vevs) when only the ϕ_1 mass term is negative, and there are no terms linear in ϕ_2 or ϕ_3.

The Yukawa interactions that are of primary interest to us in the consideration of leptogenesis are the ones that couple the scalar fields to leptons. Those interactions are given by

$$\begin{aligned} -\mathcal{L}_{\text{Yukawa}} \;=\; & g_a^{\alpha i}(\overline{\nu_{\alpha L}}\,\phi_a^+ + \overline{\ell_{\alpha L}}\,\phi_a^0)\ell_{iR} \\ & + y_a^{\alpha}(\overline{\nu_{\alpha L}}\,\overline{\phi_a^0} - \overline{\ell_{\alpha L}}\,\phi_a^-)N_R \quad . \end{aligned} \tag{8}$$

(Summation over repeated indices is assumed.) Here, $\nu_{\alpha L}$ and $\ell_{\alpha L}$, $\alpha = e, \mu, \tau$, are, respectively, the neutrino and charged lepton of the Standard Model left-handed lepton doublets. Similarly, ℓ_{iR} and N, are, respectively, the charged and neutral right-handed electroweak-singlet leptons. We note that in the conventional model of leptogenesis, as illustrated in Figure 1, at least two massive singlet N fields are necessary to obtain a non-vanishing effect while, as we shall show, one is sufficient in our case.

The generic class of diagrams on which we wish to focus is illustrated in Figure 2. These are

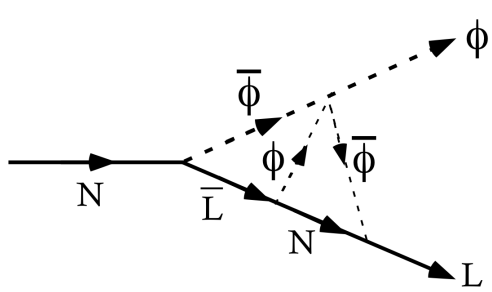

FIG. 2: Two loop diagram contributing to leptogenesis.

not taken into account in the conventional estimates of leptogenesis because their contributions are smaller than those of Figure 1 by a factor of $\lambda/4\pi^2$, where λ is a generic four scalar field coupling

constant and such constants are usually taken to be $\mathcal{O}(10^{-2})$ in order for perturbation theory to be meaningful in calculating Higgs potentials.

In our model, we assume that the scalar mesons and the N all have comparable masses that are of the order of the electroweak symmetry breaking scale. We assume that the N acquires its mass through a Majorana mass term which serves as our source of lepton-number nonconservation. The scalar doublet ϕ_1 will of course not acquire mass until after the symmetry breaking has occurred, while ϕ_2 and ϕ_3, with positive mass terms in the Lagrangian, will already be massive before such symmetry breaking has occurred.

We will choose our masses to be ordered such that the third scalar doublet has the largest mass, noting that this does not require any fine tuning. The order we select is

$$M_3 > M_N > M_{1,2} \quad . \tag{9}$$

This means that the decays $N \to L + \phi_{1,2}$ are allowed, while $N \to L + \phi_3$ is forbidden. This leads to an interesting possibility. Since $M_3 > M_N$, we need not restrict y_3 to be as small as $y_{1,2}$, for ϕ_3 neither contributes to neutrino masses nor to N decay modes. In fact, there is no reason that y_3 cannot be $\mathcal{O}(1)$. In this case, the diagrams illustrated in Figure 3, a subclass of those shown in Figure 2, can give a large contribution to leptogenesis.

We also note that loop diagrams for which the initial coupling is $N \to L + \phi_3$ are also of course present but they will not contribute to leptogenesis since $M_3 > M_N$ implies that they have no discontinuity, and such a discontinuity is necessary in order to make a non-zero contribution to leptogenesis.

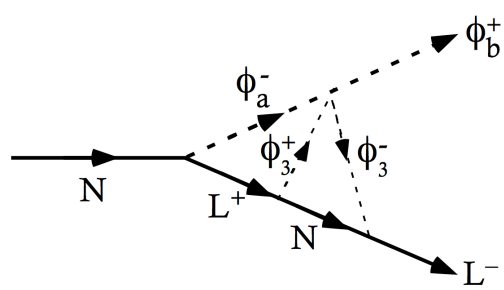

FIG. 3: Significant two loop diagram contributing to leptogenesis in this model.

The quartic couplings of the scalar fields are generally of the form

$$\begin{aligned} V \;=\; & \sum_{a,b=1,2} (\lambda_{33ab}\, \phi_3^\dagger \cdot \phi_3\, \phi_a^\dagger \cdot \phi_b + \lambda_{3a3b} \phi_3^\dagger \phi_a \phi_3^\dagger \phi_b + \lambda_{3ab3} \phi_3^\dagger \cdot \phi_a\, \phi_b^\dagger \cdot \phi_3) \\ & + \lambda_{3333}\, \phi_3^\dagger \cdot \phi_3\, \phi_3^\dagger \cdot \phi_3 \;\; + \text{h.c.} \quad , \end{aligned} \tag{10}$$

where we have written only those terms in the potential that involve the ϕ_3 field. We anticipate that all the λ coupling constants are of the same order of magnitude, with one exception. The quartic couplings involving two ϕ_3 and two ϕ_1 fields must be chosen so that $y_3^2\lambda_{3131} \leq 10^{-12}$. Otherwise neutrinos will acquire unacceptably large masses through the type of one-loop diagrams studied by Ma [7] . They are not, however, all real even though the potential is Hermitian.

Generically writing y for $y_{1,2}$, assumed to be comparable in magnitude, we see that diagrams such as the ones of Figure 3, interfering with the tree diagram, make a contribution to the lepton asymmetry of Eq. (5) that is of order

$$\epsilon_{CP} \approx \frac{|y|^2\,|y_3|^2\,|\lambda_{3a3b}|}{4\pi^3\,|y|^2}\;\eta' \quad , \tag{11}$$

where η' is a factor that depends on the detailed evaluation of the diagram, and on CP-violating phases, as in Eq. (6), but is generally $\mathcal{O}(1)$. If M_N were appreciably smaller than M_3 , η' would contain a suppression of order $(M_N/M_3)^2$ that came from the evaluation of the loop diagram in Figure 3, but we have assumed M_N and M_3 are comparable in magnitude. The additional $1/4\pi^2$ in Eq. (11) relative to the analogous Eq. (6) follows because the appropriate diagrams generating ϵ_{CP} involve two loops rather than one. Since y_3 is $\mathcal{O}(1)$ and λ is $\mathcal{O}(10^{-2})$, we see that the lepton asymmetry can readily reach the desired value of 10^{-6}.

To illustrate how the CP violation and nonvanishing lepton number actually arise in our model, let us assume that ϕ_3 couples to ϕ_2 but not ϕ_1. Let us also assume that the N mass is such that leptogenesis takes pace at a temperature below 1 TeV, but well above the electroweak phase transition. Then, at the time of leptogenesis, the Standard Model leptons ℓ_α and ν_α will all be massless. With ϕ_3 coupling to ϕ_2 but not ϕ_1, the two-loop diagrams of the kind illustrated in Figure 3 will contribute to N decays yielding a ϕ_2, but not to those yielding a ϕ_1. Omitting irrelevant factors, the amplitude for the decay $N \to \ell_\alpha^- + \phi_2^+$, $\mathrm{Amp}(N \to \ell_\alpha^-\phi_2^+)$, is given by

$$\mathrm{Amp}(N \to \ell_\alpha^-\phi_2^+) = y_2^\alpha + \sum_{\beta=e,\mu,\tau} y_2^{\beta *} y_3^\beta y_3^\alpha \lambda_{3232}^* K \;, \tag{12}$$

where K is a kinematical factor. The first term in this amplitude is from the tree diagram, and the second is from the loop. This amplitude takes into account all the lepton flavors β, and both the $\ell_\beta^+\phi_2^-$ and $\overline{\nu_\beta}\overline{\phi_2^0}$ configurations, in the intermediate state of the two-loop diagram. Omitting an overall phase space factor, we find from this amplitude that for the charged-lepton final state, the lepton-antilepton difference, including all final lepton flavors α, is given by

$$\sum_\alpha \Gamma(N \to \ell_\alpha^-\phi_2^+) - \sum_\alpha \Gamma(N \to \ell_\alpha^+\phi_2^-) = 4\Im\left[(\sum_\alpha y_2^\alpha y_3^{\alpha *})^2 \lambda_{3232}\right]\,\Im K \;. \tag{13}$$

For the neutrino final state, we find that

$$\sum_\alpha \Gamma(N \to \nu_\alpha \phi_2^0) - \sum_\alpha \Gamma(N \to \overline{\nu_\alpha}\overline{\phi_2^0}) = 4\Im \left[(\sum_\alpha y_2^\alpha y_3^{\alpha *})^2 \lambda_{3232} \right] \Im K \ . \tag{14}$$

That is, we find exactly the same lepton-antilepton difference as in the charged-lepton case, and the two lepton-antilepton differences add. Since the intermediate $\ell_\beta^+ \phi_2^-$ or $\overline{\nu_\beta}\overline{\phi_2^0}$ state in the loop diagram can be on shell, K will have a nonvanishing imaginary part, and there is no reason to expect the lepton-antilepton difference to vanish.

To be sure, it is the baryon asymmetry in which we are ultimately interested, and therefore there is the added complication in this picture of having, unlike in the conventional model, the lepton asymmetry and the sphaleron processes that convert this asymmetry into one of baryons occurring at the same scale. Should the generation of the lepton asymmetry at the electroweak scale be occurring too late for the sphaleron processes to effectively convert this asymmetry into one of baryons, one could remedy the situation while maintaining the main features of the model by shifting the N and the third scalar doublet's masses upwards so that the creation of the lepton asymmetry occurred somewhat earlier, say at a scale of 500 GeV. We are optimistic that this might not be necessary (see the discussion in Section 3 of [2]). It is comforting to note that the magnitude of the lepton asymmetry that is generated in this model is potentially large enough that even some diminution of the conversion is not likely to make its contribution insignificant.

III. EXPERIMENTAL TESTS

An additional attractive feature of such a low scale model of leptogenesis lies in its being in principle testable, unlike the more conventional model in which the neutrino singlet mass is beyond the reach of anticipated accelerators. Experimental tests are foreseeable because one can anticipate that the ϕ_3 field's coupling to quarks and charged leptons could be large, just like its coupling to $N + \nu$. In that case, ϕ_3 could be produced relatively abundantly at a particle accelerator once the energy threshold has been passed. To be sure, the couplings of ϕ_3 to fermions are constrained by the upper limits on neutrino masses. The see-saw expression for these masses, Eq. (3), may be pictured as arising from a diagram in which $\nu \to N$ via an interaction with the ϕ_1^0 vev, and then $N \to \nu^c$ via a second interaction with this vev. As already noted, if $m_N \sim 200$ GeV and light neutrino masses of the observed order of magnitude are to be obtained from this see-saw diagram, we must have $y_1^2 \sim 10^{-12}$. Now, neutrino masses can also be induced by a diagram in which the $\nu \to N$ transition, or the $N \to \nu^c$ transition, or both, result from the absorption of a ϕ_3^0 (which does not have a vev) that has come, via a fermion loop, from a ϕ_1^0 (which does have a vev). The

fermion-antifermion pair in the loop may be an up-type quark and antiquark, a down-type quark and antiquark, charged leptons, or neutrinos. Considering all possible diagrams of this kind, we find that, given that y_1 must be $\sim 10^{-6}$, y_3 can be $\mathcal{O}(1)$ as desired for successful leptogenesis, and the upper bounds on neutrino masses will not be violated, so long as $f(3,j)\, f(1,j) \lesssim 10^{-6}$. Here, j runs over all possible fermion-antifermion pairs that can be in the loop, $f(3,j)$ is the coupling of ϕ_3 to the pair j, and $f(1,j)$ is the coupling of ϕ_1 to this pair. For example, if the loop contains an e^-e^+ pair, we have the constraint $g_3^{ee} g_1^{ee} \lesssim 10^{-6}$ (in the notation of Eq. (8)). This constraint is not at all severe. If ϕ_1 is the Standard Model Higgs doublet, then $g_1^{ee} = m_e/v_1 \simeq 3 \times 10^{-6}$. Thus, the coupling of ϕ_3 to an electron, g_3^{ee}, can be $\mathcal{O}(10^{-1} - 1)$.

At a future electron-positron collider, one might look for e.g.

$$\begin{aligned} e^+ + e^- \to \phi_3^0 \to \nu + \;\; & N \\ & \hookrightarrow \mu^+ + \;\; \phi_{1,2}^- \\ & \qquad\qquad \hookrightarrow \tau^- + \overline{\nu_\tau} \end{aligned} \tag{15}$$

Taking $g_3^{ee} = 1/3$ and the ϕ_3^0 mass to be ~ 300 GeV, and estimating the total ϕ_3^0 width from its principal decay modes, we find that at the peak of the ϕ_3^0 resonance, $\sigma(e^+e^- \to \phi_3^0 \to \nu N) \sim 2$ nb. This would be a dramatically large cross section.

A similar picture could emerge in a hadron collider, where a comparable process could occur. If, for instance, a down quark and an up anti-quark were to produce a ϕ_3^-, a possible result might be

$$\begin{aligned} \bar{u} + d \to \phi_3^- \to e^- + \;\; & N \\ & \hookrightarrow \mu^- + \;\; \phi_{1,2}^+ \\ & \qquad\qquad \hookrightarrow \tau^+ + \nu_\tau \end{aligned} \tag{16}$$

A process such as the one indicated in Eq. (16) would be quite striking. The presence of three charged leptons of different flavors and a neutrino would indicate a new type of physics, since the only reasonable alternative explanation would be leptonic flavor changing neutral currents. The $e + \mu + \tau + \nu$ final state could not come from a pair of Higgs particles with couplings that, as usual, are diagonal in the fermion mass eigenstate basis.

IV. CONCLUSIONS

We have presented a model for the creation of the cosmic baryon asymmetry via leptogenesis that has some attractive features. The most notable of these is not requiring a significant new mass

scale between the one of electroweak symmetry breaking and that of grand unification. We do not claim, of course, that this is the first attempt to achieve such a result. Our model has, as all others, features that may seem contrived, but we believe it is both sufficiently interesting and novel to warrant consideration and perhaps to focus attention once again on leptogenesis at a much lower scale. The model has the not-inconsiderable merit of suggesting experimental tests at colliders.

Acknowledgments

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