Leptogenesis with Dirac Neutrinos

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We describe a "neutrinogenesis" mechanism whereby, in the presence of right-handed neutrinos with sufficiently small pure Dirac masses, $(B + L)$-violating sphaleron processes create the baryon asymmetry of the Universe, even when $B = L = 0$ initially. It is shown that the resulting neutrino mass constraints are easily fulfilled by the neutrino masses suggested by current experiments. We present a simple toy model which uses this mechanism to produce the observed baryon asymmetry of the Universe.

The existence of rapid $(B + L)$-violating sphaleron processes above the electroweak phase transition [1] tends to wash out any net baryon number which might have been produced at higher temperatures and energies. This washout, it is often argued, makes higher scale [including grand unified theory (GUT) scale] theories of baryogenesis which begin from $(B - L) = 0$ untenable. It is important to keep in mind that sphaleron processes do not directly affect right-handed particles and one might hope that, while sphalerons deplete left-handed $(B + L)_L$, right-handed $(B + L)_R$ could survive the electroweak epoch and emerge afterward as the observed baryon asymmetry of the Universe. The Yukawa couplings of the standard model (SM) quarks and leptons to the Higgs, however, lead to processes which equilibrate left- and right-handed particles so rapidly that, as sphalerons destroy left-handed $(B + L)$, right-handed $(B + L)$ is converted to fill the void and is also depleted. On the other hand, if fermions which carry B or L and have sufficiently small Yukawa couplings were to exist, then $(B + L)$ could be hidden in right-handed particles until long after the electroweak phase transition.

In this Letter we point out that neutrinos with masses as implied by current experiments (see, e.g., [2]) can play exactly such a role. If the neutrinos have pure Dirac masses, as is, for example, demanded by $(B - L)$ conservation, then their Yukawa couplings are small enough to hide their right-handed lepton number from the sphalerons during the entire electroweak epoch.

The mechanism presented here should be called *neutrinogenesis,* since the baryon asymmetry of the Universe would be a consequence of the smallness of neutrino masses. It shares with the well-known leptogenesis scenario [3] the exploitation of the sphaleron in order to convert a lepton asymmetry into a baryon asymmetry, but differs from it in important and related aspects. First, instead of introducing lepton number violating Majorana masses and a seesaw mechanism, this mechanism requires only an extended Dirac mass structure in the neutrino sector, which implies, however, that the seesaw mass

relation cannot be used to "explain" the smallness of neutrino mass. The puzzle of the smallness of the Yukawa couplings, which exists already in the standard model and in models employing the seesaw mechanism, becomes even more puzzling in the face of the yet smaller neutrino Yukawa couplings (at least one coupling less than 10^{-8}) our scenario demands. Finally, instead of producing a lepton asymmetry via the decay of a heavy Majorana neutrino, this mechanism allows the revival of old-style out-of-equilibrium decays of massive particles, but with a twist: instead of producing a baryon asymmetry directly, the decays should produce a neutrino asymmetry.

I. Neutrinogenesis. —Let us consider in more detail how the quantity of left- and right-handed B and L change in the early Universe, as illustrated in Fig. 1 for a universe with $(B - L) = 0$. Initially, some process (e.g., at the GUT scale) produces a total baryon number B and lepton number L which are distributed between the left-handed (L) and right-handed (R) sectors. Both left-handed and right-handed particles are exposed to LR equilibration processes (marked in Fig. 1 by ⓔ) which interconvert left- and right-handed particles and conserve B and L. Sphaleron processes (marked in Fig. 1 by ⓢ) affect only left-handed particles and violate B and L by moving left-handed B_L and L_L along a line of constant $(B - L)_L$.

The interplay of the LR equilibration and the sphaleron washout is essentially a comparison of their time scales. For all standard model particles, the equilibration processes are in equilibrium during the epoch in which the sphalerons are active. A baryon asymmetry is therefore completely washed out in a theory with $(B - L) = 0$, as illustrated in the inset of Fig. 1. The situation is different with a very weakly coupled right-handed neutrino. Since LR conversion ⓔ is not in equilibrium for these particles, not all L_R can be depleted; LR equilibration occurs only after the sphalerons are ineffective. Thus only the left-handed components are washed out while the right-handed components are preserved, as shown in the main diagram in Fig. 1.
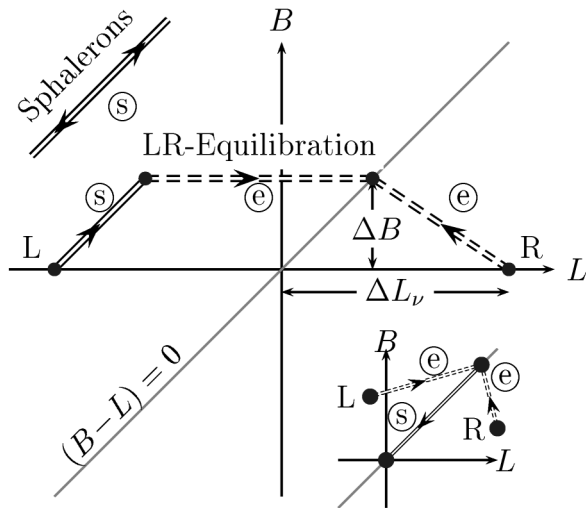
FIG. 1. Comparison of sphaleronic Ⓢ and LR-equilibration Ⓔ processes affecting B and L. For standard model particles (inset) LR equilibration occurs completely before or during the sphaleron washout. Thus no baryon asymmetry can be generated if in total $(B - L) = 0$. For sufficiently small Yukawa couplings the LR equilibration time scale becomes longer than the washout period; ΔB is then generated by the sphalerons, even in a theory with $B = L = 0$ initially.

In a more detailed, quantitative picture, we use the chemical equilibrium of sphaleron and Higgs-mediated reactions

$$S \leftrightarrow 3q + \ell, \tag{1a}$$

$$\phi \leftrightarrow q + \bar{u}, \tag{1b}$$

$$\bar{\phi} \leftrightarrow q + \bar{d}, \tag{1c}$$

$$\bar{\phi} \leftrightarrow \ell + \bar{e}, \tag{1d}$$

and the condition of charge or hypercharge neutrality of the plasma to relate the chemical potentials of all the SM and ν_R fields [4]. One then obtains for $(B - L) = 0$

$$n_B = n_L = -\frac{28}{79} n_{\nu_R}, \tag{2}$$

in the case of three generations and one Higgs doublet. This confirms our qualitative considerations.

II. How (not) to equilibrate ν_R. —For the success of this scenario, it is necessary that right-handed neutrinos not be equilibrated quickly above the electroweak phase transition. Schematic Feynman diagrams for the processes contributing to their equilibration are shown in Fig. 2. These processes include Higgs decay and inverse decay, s- and t-channel scattering off SM fermions, and s- and t-channel scattering off Higgs bosons in combination with the emission or absorption of an electroweak gauge boson.

The rate of these processes at a temperature T above the electroweak phase transition is easily estimated on dimensional grounds to be

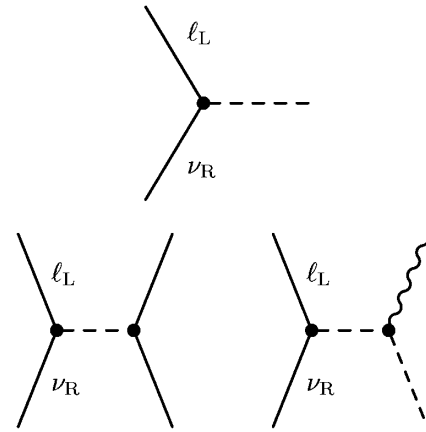$$\Gamma \sim \lambda^2 g^2 T, \tag{3}$$

FIG. 2. Processes contributing to the equilibration of ν_R. Dashed lines are Higgs bosons, wavy lines are gauge bosons, and unlabeled solid lines are SM fermions.

where λ is the neutrino Yukawa coupling appearing in the $\lambda(H \cdot \ell_L)\nu_R^c$ term of the Lagrangian and g is a gauge or top Yukawa coupling of $\mathcal{O}(1)$. This rate should be compared to the expansion rate of the Universe

$$H \sim \frac{T^2}{M_{Pl}}. \tag{4}$$

If $\Gamma > H$ at a temperature T above the electroweak phase transition T_c, left- and right-handed species are equilibrated. By demanding that this not occur, we obtain the condition

$$\lambda \lesssim \sqrt{\frac{T_c}{M_{Pl}}} \sim 10^{-8}, \qquad m \sim \lambda T_c \lesssim 1 \text{ keV}. \tag{5}$$

Detailed numerical computation of the corresponding collision terms in the Boltzmann equations refines this bound to ~ 10 keV. Although this condition is not fulfilled by electrons, it is easily fulfilled by Dirac neutrinos with masses in the range necessary to explain super-Kamiokande, solar neutrino, and LSND data.

III. Producing ν_R: a toy model. —The neutrinogenesis mechanism allows the revival of GUT-scale baryogenesis by having heavy particles decay into right-handed neutrinos instead of directly into particles carrying B. We present here a simple toy model for B generation via this scenario, which is loosely based on an old GUT-scale scenario [5]. In this model, two very heavy SU(2)-doublet scalars (which carry the same quantum numbers as the SM Higgs, but will not get vacuum expectation values) couple to the SM fields via the Lagrangian

$$\mathcal{L} = F(\ell_L \cdot \Phi)\nu_R^c + F'(\ell_L \cdot \Phi^c)e_R^c$$
$$\times G(\ell_L \cdot \Psi)\nu_R^c + G'(\ell_L \cdot \Psi^c)e_R^c + \text{H.c.} \tag{6}$$

They then decay according to

$$\left.\begin{matrix} \Phi \\ \Psi \end{matrix}\right\} \rightarrow \begin{cases} \bar{\ell}_L + \nu_R \\ \ell_L + \bar{e}_R \end{cases}. \tag{7}$$

Since the elements of F, F', G, and G' can have relative phases, interference between the tree-level decay amplitude and the one-loop corrections shown in Fig. 3 gives rise to a small CP-violating effect [6,7]:

$$\epsilon_\Phi = \frac{\Gamma(\Phi \to \bar{\ell}\nu) - \Gamma(\overline{\Phi} \to \ell\bar{\nu})}{\Gamma(\Phi \to \bar{\ell}\nu) + \Gamma(\overline{\Phi} \to \ell\bar{\nu})} \tag{8}$$

$$= \frac{\operatorname{Im} \operatorname{tr}(F^* G F' G'^*)}{16\pi \operatorname{tr}(F^* F)}$$

$$\times \left[1 - \frac{M_\Psi^2}{M_\Phi^2} \ln\left(1 + \frac{M_\Phi^2}{M_\Psi^2}\right) - \frac{M_\Phi^2}{M_\Phi^2 - M_\Psi^2} \right]. \tag{9}$$

When a bath containing an equal number of Φ and $\overline{\Phi}$ particles decays, a net right-handed neutrino number $n_\nu = \epsilon_\Phi n_\Phi$ is produced, which is not equilibrated as long as the mass condition derived in the previous section is fulfilled. An analogous result holds for the decays of Ψ particles.

The formalism required to calculate the lepton number stored in right-handed neutrinos from such an out-of-equilibrium decay has been developed by [8–10], who derive an approximate expression for the neutrino number to entropy ratio

$$Y_\nu = \frac{n_\nu}{s} \sim \frac{\epsilon_\Phi + \epsilon_\Psi}{g_*} \tag{10}$$

produced in out-of-equilibrium decays. Here $g_* \sim \mathcal{O}(100)$ is the total number of relativistic degrees of freedom in the early Universe. To make sure that inverse decays do not erase the asymmetry produced in the decays, we require

$$K_\Phi = \frac{\Gamma_\Phi}{2H(M_\Phi)} \sim \frac{\lambda^2}{g_*^{1/2}} \frac{M_{\rm Pl}}{M_\Phi} \lesssim 1 \tag{11}$$

and similarly for the analogously defined K_Ψ.

In a simplified analysis, one assumes that $M_\Phi \sim M_\Psi \sim \mathcal{O}(M)$ and that the largest Yukawa couplings of these scalars are all $\mathcal{O}(\lambda)$. In this case

$$\epsilon \sim \frac{\lambda^2}{16\pi}, \qquad \frac{\lambda^2}{g_*^{1/2}} \frac{M_{\rm Pl}}{M} \lesssim 1. \tag{12}$$

Combining this estimate (12) with Eqs. (10) and (2) with the observed baryon asymmetry $Y_B = (6\text{–}8) \times 10^{-11}$ [11] implies $\lam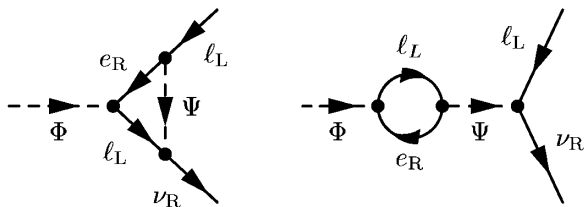bda \sim 10^{-3}$ and $M \gtrsim 10^{12}$ GeV. This simple estimate shows that, e.g., a weakly coupled GUT could produce the observed baryon number of the Universe via the neutrinogenesis mechanism.

The results of a more detailed quantitative analysis are shown in Fig. 4, which shows the mass parameters that produce a baryon asymmetry consistent with observations for various choices of $K = \max\{K_\Phi, K_\Psi\}$.

Note that the neutrinogenesis scenario does not require (although it does allow) decays that violate B or L at the GUT scale; only an asymmetry between right-handed neutrinos and antineutrinos is necessary, since it alone determines the final baryon asymmetry via Eq. (2).

IV. Discussion and conclusions.—We presented in this Letter a "neutrinogenesis" mechanism by which $(B + L)$-violating sphaleron processes produce a baryon asymmetry instead of destroying it, provided that neutrinos have sufficiently small Dirac masses. The key observation is that sphalerons couple only to left-handed particles, while right-handed particles [SU(2)$_L$ singlets] participate in the washout only indirectly via their Dirac Yukawa coupling to their respective left-handed partners. The masses of ordinary quarks and leptons imply Yukawa couplings for which left-right equilibration occurs quickly compared to the duration of the sphaleronic epoch in the early Universe. However, for Dirac masses below roughly 10 keV, equilibration takes longer than the washout period. Neutrinos with Dirac masses in the experimentally allowed range therefore store part of the total lepton number long enough in right-handed neutrinos. The sphaleronic washout affects in this case only the left-handed neutrinos and ΔB can be generated from the neutrino sector for a theory where initially $(B - L) = 0$ or even $B = L = 0$.

In the neutrinogenesis mechanism, baryogenesis is the result of an amusing conspiracy of GUT scale and electroweak-scale effects. The three Shakarov conditions [12] are realized in the following way: CP violating is achieved at some large (e.g., GUT) scale to produce

FIG. 3. Production of $\nu_{\rm R}$ via decay of GUT scalars. The interference of these diagrams with the tree-level decay amplitude produces the CP violation necessary to produce a net neutrino number.
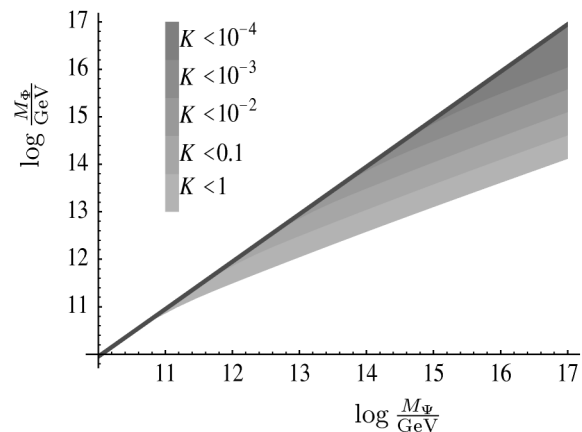

FIG. 4. Allowed masses of the scalars of our toy model from the requirements for the K values and $n_B/s = 8 \times 10^{-11}$, where we assume $M_\Phi < M_\Psi$. The $M_\Phi = M_\Psi$ line has to be excluded since there Eq. (8) cannot be applied.

a neutrino asymmetry. Baryon and lepton number are violated only by the electroweak sphalerons, and both the heavy (e.g., GUT) parents and the light neutrinos are out of equilibrium. We presented a toy model which illustrates some details and which shows that the right amount of baryon asymmetry can be produced for reasonable GUT mass scales. One can easily check that constraints coming from big bang nucleosynthesis and from the matter density in the Universe are not violated.

Neutrinogenesis should in principle also work in the presence of Majorana mass terms for sufficiently small Dirac mass entries. One would expect in this case GUT-scale Majorana masses for ν_R and lepton number would be broken. It is also conceivable that neutrinogenesis can be combined in this way with the known leptogenesis mechanism. In this case the seesaw mass relation might be used again to explain the smallness of neutrino masses. The most beautiful version of neutrinogenesis is, however, the case of pure Dirac masses and for initial $B = L = 0$. This could, e.g., be realized in suitable GUTs.

A more detailed study of this mechanism and its phenomenology will be presented in a longer paper.

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