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Electroweak fermion-number non-conservation and the scale of $B-L$ breaking

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In a simplest extension of the standard model containing one extra gauge boson, it is pointed out that the interplay between electroweak fermion-number non-conserving processes at high temperatures, neutrino masses and an associated scale of $B-L$ breaking of order 1 TeV can be compatible both with particle physics and cosmology. Baryogenesis can take place through the decays of right-handed Majorana neutrinos.

Fermion-number violating processes are of the most important ones from the particle physics and cosmological point of view. Baryogenesis, due to non-equilibrium processes that violate B, C and CP, has been one of the most appealing ideas for developing the net baryon number of the universe, usually at very early times $t \leqslant 10^{-34}$ s due to a GUT physics beyond the standard $SU(3) \times SU(2) \times U(1)$ model [1]. Baryon (B) and lepton (L) violating processes, however, might be generated by the usual electroweak interactions with the known particles only due to the anomaly [2]. The effect is connected with quantum tunneling in the functional space of gauge fields and so it is exponentially suppressed, $\exp(-2\pi/a_W)$. However, by raising the temperature above M_W/a_W, B- and L-violating transitions could proceed [3] not via quantum tunneling, but due to classical motion over the barrier (sphaleron [4] transitions). Actually, the rate Γ_B of B non conserving processes has been calculated [3,5] to be bigger than the rate H of the expansion of the universe $\Gamma_B \gg H$ for temperatures T above a few hundred GeV and then quickly drops to zero. This has a result that, because of thermal equilibrium at higher than electroweak temperatures, it may erase any preexisting B-asymmetry, whereas later on B-violating processes go out of equilibrium so fast that there is no time to generate a new baryon asymmetry. The above is true if initially $B-L=0$, because electroweak interactions even with quantum anomaly conserve $B-L$.

If, however, $B-L$ is not absolutely conserved and a $B-L$ asymmetry is not imposed as an initial condition, but rather generated dynamically, then $B-L$ must be violated at some scale. Below that scale, there may be residual $(B-L)$-violating interactions, which together with the electroweak anomalous sphaleron-induced $(B+L)$-violating interactions could drive any B- and/or L-preexisting asymmetry to zero should they come into equilibrium. Since the dominant $(B-L)$-violating processes are connected with Majorana neutrino masses, there is in the literature an interesting discussion on the relation between neutrino masses and the scale of $(B-L)$-violation [6,7].

In the present letter, we will consider a minimal case in which the extended gauge group beyond that of the standard model contains just one extra $U(1)'$ factor, which is related to $U(1)_{B-L}$. So, $B-L$ is a spontaneously broken local symmetry and the extended gauge group can be considered to be contained in SO(10). Neutrinos acquire masses related to the scale of $B-L$ breaking, of which little is known. We will point out that a scale of $B-L$ breaking as low as of the order of 1 TeV is in fact possible both from the particle physics point of view, as well as when examined in relation to the above cosmological considerations. The baryon number of the universe can then

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be generated through the out-of-equilibrium decays of right-handed Majorana neutrinos with masses ~ 1 TeV. Such a low scale for the $B-L$ violation makes this minimal extension of the standard model very appealing and testable in the near future.

The model we consider is based on the gauge group $SU(2)_L \times U(1)_Y \times U(1)_{Y'}$ (we omit the strong interactions gauge group $SU(3)_C$) with the sequential breaking

$$SU(2)_L \times U(1)_Y \times U(1)_{Y'} \xrightarrow{v'} SU(2)_L \times U(1)_Y \xrightarrow{v} U(1)_{em}, \tag{1}$$

where v' and v are the vacuum expectation values, which break respectively the $U(1)_{Y'}$ and the standard group $SU(2)_L \times U(1)_Y$ to $U(1)_{em}$. The model contains a right-handed ν_R in addition to the known Weyl fermions of the standard model. For completeness we list below the full lagrangian [8], which includes the minimal Higgs content necessary to implement the breaking of the above gauge symmetry

$$\begin{aligned} L = & -\tfrac{1}{4} W_{\mu\nu} W^{\mu\nu} - \tfrac{1}{4} B_{\mu\nu} B^{\mu\nu} - \tfrac{1}{4} B'_{\mu\nu} B'^{\mu\nu} \\ & + \mathrm{i}\bar{l} D l + \mathrm{i}\bar{e}_R D e_R + \mathrm{i}\bar{\nu}_R D \nu_R \\ & - \bar{l}\phi g_e e_R - \bar{e}_R g_e^+ \tilde{\phi}^+ l - \bar{l}\phi g_\nu \nu_R - \bar{\nu}_R g_\nu^+ \phi^+ l \\ & - \tfrac{1}{2}\varphi \bar{\nu}_R^c h \nu_R - \tfrac{1}{2}\varphi^+ \bar{\nu}_R h^+ \nu_R^c \\ & + (D_\mu \phi)^+ (D^\mu \phi) + (D_\mu \varphi)^+ (D^\mu \varphi) - V(\phi, \varphi) . \end{aligned} \tag{2}$$

In the above lagrangian, $\phi = (\phi^0, \phi^-)$ and φ are complex SU(2) doublet and singlet Higgs fields, respectively, and g and h are complex 3×3 Yukawa matrices. The covariant derivatives differ from the standard model expressions by the term $-\mathrm{i}\sqrt{\frac{2}{3}} g'_1 Y' B'_\mu$. The couplings of the gauge field B'_μ are determined by the orthonormality conditions for the U(1) charges (the trace extends over all fermions)

$$\mathrm{tr}(YY') = 0, \quad \mathrm{tr}(Y^2) = \tfrac{2}{3}\,\mathrm{tr}(Y'^2) , \tag{3}$$

which yield for the $U(1)_{Y'}$ charges the linear combination

$$Y' = Y - \tfrac{5}{4}(B-L) . \tag{4}$$

The coupling constant g'_1 of the $U(1)_{Y'}$ is apparently equal to the $U(1)_Y$ gauge coupling g_1 of the standard model.

The most general Higgs potential is given by

$$\begin{aligned} V(\phi, \varphi) = & \mu_1 \phi^+ \phi + \mu_2 \varphi^+ \varphi \\ & + \tfrac{1}{2}\lambda_1 (\phi^+ \phi)^2 + \tfrac{1}{2}\lambda_2 (\phi^+ \phi)^2 + \lambda_3 (\phi^+ \phi)(\varphi^+ \varphi) , \end{aligned} \tag{5}$$

with $\lambda_3 > -(\lambda_1 \lambda_2)^{1/2}$ for the potential to be bounded from below. The above minimal Higgs sector is identical with that of the singlet majoron model [9] associated with the spontaneous breaking of the lepton number. Here, however, we have a local symmetry. In any case, it is straightforward to minimize the potential (5) in order to determine the vacuum expectation values $v' = \langle \varphi \rangle$ of the $(B-L)$-breaking and $v = \langle \phi^0 \rangle = (2\sqrt{2} G_F)^{-1/2}$ of the standard model. We assume $v' > v$ for the two mass scales of interest. We have the neutral bosons H and χ

$$\phi^+ \phi = (v + H/\sqrt{2})^2, \quad \phi^+ \phi = (v' + \chi/\sqrt{2})^2 , \tag{6}$$

which are related to the mass eigenstates h and h' by the relations

$$\begin{aligned} H &= \cos\beta\, h + \sin\beta\, h' , \\ \chi &= -\sin\beta\, h + \cos\beta\, h' , \end{aligned} \tag{7}$$

with the mixing angle given by

$$\tan 2\beta = \frac{2\lambda_3 v v'}{\lambda_2 v'^2 - \lambda_1 v^2} . \tag{8}$$

The corresponding scalar boson masses are

$$\begin{aligned} m_h^2 = & \lambda_1 v^2 + \lambda_2 v'^2 \\ & - \sqrt{(\lambda_1 v^2 - \lambda_2 v'^2)^2 + 4\lambda_3^2 v^2 v'^2} , \\ m_{h'}^2 = & \lambda_1 v^2 + \lambda_2 v'^2 \\ & + \sqrt{(\lambda_1 v^2 - \lambda_2 v'^2)^2 + 4\lambda_3^2 v^2 v'^2} , \end{aligned} \tag{9}$$

In the neutrino sector we have the Dirac mass matrix $m_D = g_\nu v$ and the Majorana mass matrix $m = hv'$. To leading order in $1/m$ [10] the mass eigenstates ν and N are related with the chiral fields ν_L and ν_R by the relations

$$\nu = L + L^c, \quad N = R + R^c , \tag{10}$$

where

$$\nu_{\mathrm{L}}=L+m_{\mathrm{D}}\frac{1}{m}R^{\mathrm{c}},\quad \nu_{\mathrm{R}}=R-\frac{1}{m}m_{\mathrm{D}}^{\mathrm{T}}L^{\mathrm{c}}\,. \tag{11}$$

The masses of the light ν and the heavy N Majorana neutrinos are given by the eigenvalues of the mass matrices

$$m_\nu=-m_{\mathrm{D}}\frac{1}{m}m_{\mathrm{D}}^{\mathrm{T}}\,, \tag{12}$$

$$M_N=m\,. \tag{13}$$

Let us first notice two potentially significant points concerning the scalar bosons H and χ. Since χ has interactions only with ν_{R}, H and B'_μ, the mass eigenstates h and h' interact with matter and radiation through H and these interactions are essentially as in the standard model, but with their size reduced by $\cos\beta$ and $\sin\beta$, respectively. On the other hand, the mixing and the mass splitting between the two scalar bosons may be large, so that χ could be mainly the light mass eigenstate and H the heavy one. Let us precisely entertain for the moment the possibility of having one boson being light with "invisible" interactions and the other one being heavy, as expected with the standard model Higgs boson. The scale parameter v' of $(B-L)$-violation is associated with the mass scale characterizing the coupling of the light boson χ to ordinary particles. In the model under discussion, at scales below the weak scale, due to the weak anomaly of the standard lepton current, there is a suppressed χ-photon interaction given [11] by the effective term in the lagrangian

$$L\sim\frac{\alpha}{4\pi}\frac{\alpha_{\mathrm{W}}}{4\pi}\frac{m_\nu}{M_N}\frac{1}{v'}\chi F^{\gamma}_{\mu\nu}\tilde{F}^{\gamma\mu\nu}\,, \tag{14}$$

where $F^{\gamma}_{\mu\nu}$ is the electromagnetic field strength. As a result, there is here an effective mass scale $v'_{\mathrm{eff}}\sim(M_N/m_\nu)v'$ for the light boson χ. Astrophysics and cosmology provide good bounds on weakly coupled light bosons (compare with the case of the majoron and axion). We expect [11,12] that $10^7\leqslant v'_{\mathrm{eff}}\leqslant10^{15}$ GeV. We see then that it is safe to take $v'\sim1$ TeV. In fact, assuming neutrino Dirac masses m_{D} close to the corresponding charged-lepton masses and a heavy Majorana neutrino mass $M_N\sim1$ TeV with light neutrino masses $m_\nu\sim m_{\mathrm{D}}^2/M_N$, we get an effective mass scale in agreement with the above bounds. So, in this case $(B-L)$-violation can take place at scales as low as of the order of 1 TeV.

Let us now come to the neutrino sector. We want to explore the consequences of having a $(B-L)$-violating scale of order 1 TeV and see if we can get an acceptable physical scenario. First, from the particle physics point of view, in order to evade the double β-decay constraints the Majorana mass m_{ν_e} imparted to the electron neutrino must satisfy the bound [13]

$$\langle m_{\nu_e}\rangle=\sum_{i=e,\mu,\tau}U^2_{e\nu_i}m_{\nu_i}<1\text{–}3\ \mathrm{eV} \tag{15}$$

where $U_{e\nu_i}$ denotes the corresponding elements of the lepton mixing matrix. For $M_N\sim1$ TeV and assuming $U_{e\nu_i}\sim\mathrm{O}(\sqrt{m_{\nu_e}/m_{\nu_i}})$ as for the quark mixing matrix elements, the bound (15) is satisfied for the neutrino masses $m_{\nu_i}=m^2_{\mathrm{D}_i}/m_{N_i}$.

Let us now turn to cosmological considerations and examine the heavy neutrino decays. As we mentioned in the introduction, the combination of $(B-L)$-violating processes with the electroweak $(B+L)$-violating ones can erase any B- and/or L-preexisting asymmetry. A common conclusion of the analysis of refs. [6,7] is that this happens if the neutrino masses m_{ν_i} are heavier than about 0.1 eV. Given this, baryon number generation must take place at scales significantly below the GUT scale. In the model under discussion, this is evidently the case, if $M_{N_i}\sim1$ TeV and the Dirac masses m_{D_i} for the neutrinos are the corresponding charged-lepton masses m_i. In fact we have $m_{\nu_e}\sim1$ eV, $m_{\nu_\mu}\sim10$ keV, $m_{\nu_\tau}\sim1$ MeV, which are near their experimental upper limits [14] $m_{\nu_e}<17$ eV, $m_{\nu_\mu}<270$ keV, $m_{\nu_\tau}<35$ MeV. In the above we have taken a common value $M_{N_i}\sim1$ TeV for the heavy Majorana masses M_{N_i}, although there may actually be $M_{N_1}<M_{N_2}<M_{N_3}$. In the remaining, we will consider the out of equilibrium L-number violating decays of the lightest heavy neutrino N_1 into a lepton and a Higgs, in an attempt to generate the cosmological baryon asymmetry. This is an old idea [3,15], but we will discuss it in the context of the present model in order to realize if the scale of the $(B-L)$-violation can be indeed of the order of 1 TeV and still be acceptable within cosmology.

The lightest heavy neutrino N_1 can decay into a lepton and a Higgs, thus violating lepton number, according to

$$N_1 \to l_i \bar{\phi}\,, \tag{16a}$$

$$N_1 \to \bar{l}_i \phi\,, \tag{16b}$$

where there appears a difference between the branching ratios for (16a) and (16b), if CP is violated through the one-loop diagram with a Higgs exchange (see fig. 1). The CP asymmetry arising from the interference of the two diagrams of fig. 1 for the decay of the heavy neutrino N_1 is calculated to be

$$\varepsilon = \frac{1}{\pi}\frac{\mathrm{Im}[(g_\nu^+ g_\nu)_{1i}(g_\nu^{\mathrm{T}} g_\nu^*)_{i1}]}{(g_\nu^+ g_\nu)_{11}}\, I\!\left(\frac{M_{N_i}}{M_{N_1}}\right), \tag{17}$$

where

$$I(x) = x^{1/2}\left(1 + (1+x)\ln\frac{x}{1+x}\right).$$

Assuming that $(g_\nu)_{33}$ gives the largest contribution, we estimate

$$\varepsilon \approx \frac{1}{\pi}\frac{m_{\mathrm{D}3}^2}{v^2}\frac{M_{N_1}}{M_{N_3}}\,\delta\,, \tag{18}$$

where δ is the CP-violating phase.

Now, the out of equilibrium condition is satisfied if the decay rate

$$\Gamma_{\mathrm{D}} = \frac{(g_\nu^+ g_\nu)_{11}}{16\pi} M_{N_1} = \frac{1}{16\pi}\frac{m_{\mathrm{D}1}^2}{v^2} M_{N_1} \tag{19}$$

becomes less than the expansion rate of the universe $H = 1.7\, g_*^{1/2} T^2/M_{\mathrm{Pl}}$ at temperatures $T \sim M_{N_1}$ ($g_* \approx 100$ is the number of degrees of freedom). That is if we have

$$(\Gamma_{\mathrm{D}} M_{\mathrm{Pl}} g_*^{-1/2})^{1/2} < M_{N_1}\,. \tag{20}$$

Of course to obtain a better solution to such a condition, we have to solve the relevant Boltzmann equations [1]. For our case, assuming that the decay terms are the dominant ones and defining $z = M_{N_1}/T$ to be the evolution variable, $N_1 = n_1/s$ the N_1 particle number per comoving volume (s is the entropy density), $\Delta = N_1 - N_1^{\mathrm{EQ}}$ the departure from equilibrium and $N_{B-L} = n_{B-L}/s$ the $(B-L)$-number, these are

$$\frac{\mathrm{d}\Delta}{\mathrm{d}z} = -\frac{\mathrm{d}N_1^{\mathrm{EQ}}}{\mathrm{d}z} - z\gamma_{\mathrm{D}} K\Delta\,, \tag{21}$$

$$\frac{\mathrm{d}N_{B-L}}{\mathrm{d}z} = \varepsilon z K \gamma_{\mathrm{D}} \Delta - z\, K g_* \frac{N_1^{\mathrm{EQ}} \gamma_{\mathrm{D}} N_{B-L}}{\Gamma_{\mathrm{D}}(z=1)}\,, \tag{22}$$

where

$$\gamma_{\mathrm{D}} = \frac{\Gamma_{\mathrm{D}}(z)}{\Gamma_{\mathrm{D}}(z=1)}\,,$$

$$K = \frac{\Gamma_{\mathrm{D}}(z=1)}{2H(M_{N_1})} = \frac{1}{32\pi}\frac{m_{\mathrm{D}1}^2}{v^2}\frac{1}{1.7 g_*^{1/2}}\frac{M_{\mathrm{Pl}}}{M_{N_1}}\,. \tag{23}$$

For our assumptions K is larger than 1, but not larger than 100. In that case, the solution of eqs. (21), (22) give for the final value of N_{B-L} (for details see ref. [1]) that

$$N_{B-L} \approx \frac{0.3\varepsilon}{g_* K (\ln K)^{0.6}}\,. \tag{24}$$

As long as the $(B+L)$-violating interactions are in equilibrium, the baryon number N_B is related to N_{B-L} by the relation [16]

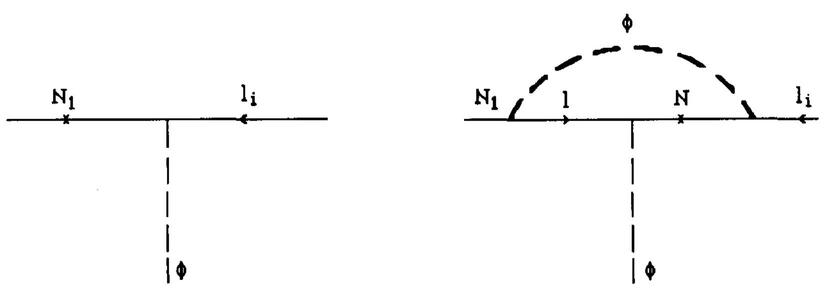

Fig. 1. Tree-level and one-loop diagrams contributing to a lepton-number violating heavy neutrino decay.

$$N_B = \tfrac{28}{79} N_{B-L} \,. \tag{25}$$

In the model we examine, we have supposed that the Dirac masses m_{D_i} are of the order of the corresponding charged-lepton masses m_i, whereas for the heavy Majorana masses we have $M_{N_i} \geqslant 1$ TeV. Then from expressions (18) and (23) we get the corresponding values of ε and K and from expressions (24) and (25) we estimate the produced baryon number N_B, to be compared with the observed value $N_B^{\rm obs} \approx 10^{-10}$. We find that it is possible to obtain a value of N_B near the observed one. For example, for $m_{D_1} \sim 1$ MeV, $m_{D_3} \sim 1$ GeV, $M_{N_1} \sim 1$ TeV and assuming $(M_{N_1}/M_{N_2})\delta \leqslant 10^{-1}$, we find that $\varepsilon \leqslant 10^{-6}$, $K \sim 100$ and $N_B \leqslant 10^{-10}$–10^{-11}.

Of course there are many uncertainties in the model, but it is encouraging that a low value for the $(B-L)$-breaking of the order of 1 TeV can be made compatible with particle physics and cosmology. It has the advantage that its effects, through both the mixing of the two neutral gauge bosons and the light neutrino mixing on a variety of observables used for precision tests of the electroweak theory [8,10], can be tested in the near future. On the other hand, heavy Majorana neutrinos in the TeV region might be responsible for, or at least contribute to, N_B. Because of its $(B-L)$-nature, this can survive sphaleron damping effects and be possibly combined with other baryon number generation mechanisms at the electroweak phase transition [16]. It is also possible [17] that these heavy Majorana neutrinos constitute the dark matter of the universe.

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