Baryon Asymmetry from Leptomesons

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Abstract

The composite models are among the promising theories to explain the opened questions of the Standard Model (SM). Some of these models allow color-singlet leptohadrons, e.g., leptomesons that interact with lepton, quark and antiquark. I introduce possible generation of the baryon asymmetry of the universe and the neutrino masses by the effects of leptomesons that can be tested at the LHC.

Motivation

There are many indications on possible non-fundamentality of the SM fermions:

- Large number of these fermions: $\{e^-, \nu_e, u_c, d_c$, and their antiparticles$\} \times 3$ generations;
- Fractional electric charges of quarks;
- Arbitrary fermion masses and mixings;
- Similarity between leptons $\{\ell, \nu\}$ and quarks q in the SM flavor and gauge structure;
- Dark matter, baryon asymmetry, etc.

Some of these issues are addressed in models with elementary ℓ^-, ν_ℓ and q, and external relationships or symmetries: GUT, SUSY, etc.

Alternative possibility with non-elementary ℓ, ν and q is investigated in the models of particle **compositeness** [1, 2, 3]. Typically they predict new heavy composites constructed from their sets of preons. Some current bounds on the new composite fermion masses are [4]:

- Excited ℓ^* and q^*: $m^* > 100 - 1000$ GeV;
- Color (anti)sextet quarks q_6 ($\bar{3} \times \bar{3} = 3 + \bar{6}$): $m_{q_6} > 84$ GeV;
- Leptoquarks (LQ): $m_{\rm LQ} > 840$ GeV;
- Color octet neutrinos ν_8 ($3 \times \bar{3} = 1 + 8$): $m_{\nu_8} > 110$ GeV;
- Charged leptogluons ℓ_8: $m_{\ell_8} > 1.2$ TeV [5].

However there is no strong mass bound for a $SU(3)_c \times SU(2)_L \times U(1)_Y$ singlet composite.

Introduction

Leptomesons

Theories with a colored substructure of leptons may include $SU(3)_{\rm c}$ singlet leptohadrons, e.g., leptomeson (LM) that has the same preon content as a lepton-meson pair, and effectively couples to lepton, q and $\bar{q}$.

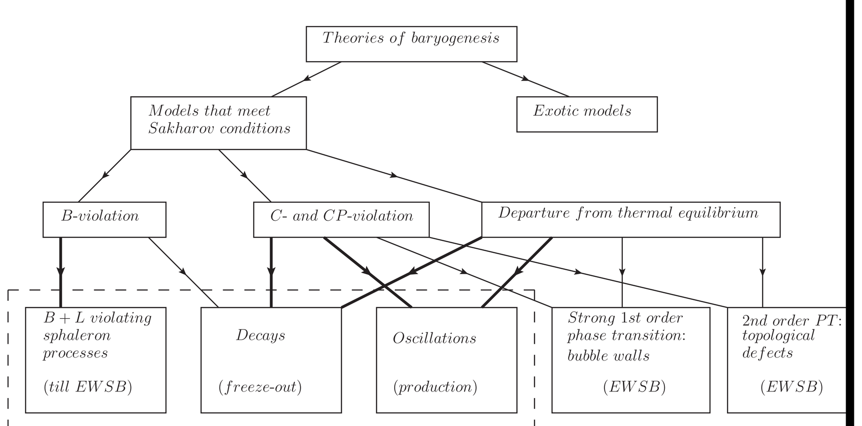
One example can be given in the haplon models [3, 6], which are based on the symmetry $SU(3)_c \times U(1)_{em} \times SU(N)_h$, and contain the two cathegories of colored preons (haplons): the fermions $\alpha^{-1/2}$ and $\beta^{+1/2}$, and the scalars $x^{-1/6}$, $y^{+1/2}$, ... In this framework the preon pairs can compose the SM particles as $\nu = (\bar{\alpha}y)_1$, $d = (\bar{\beta}\bar{x})_3$, $W^- = (\bar{\alpha}\beta)_1$, etc., and the new heavy composites, e.g., LQ $(\bar{x}y)_{\bar{3}}$ and leptogluon $(\bar{\beta}y)_8$. However there can exist also multipreon LM states such as $\bar{\alpha}y\bar{\beta}\bar{x}\beta x$. This possibility gets more points from recent discoveries of the multiquark states [7] due to the similarity between QCD and haplon dynamics. Essentially, LMs can be lighter than LQs and leptogluons due to the absence of the color dressing. Some phenomenological issues on LMs were discussed in Refs. [8, 9].

Baryogenesis

The observable universe is populated with baryonic matter rather than antimatter. The related baryon asymmetry (η_B) [4] can be dynamically generated in a baryogenesis (BG) mechanism during the evolution of the universe from a hot matter-antimatter symmetric stage. Typically BG satisfies the three Sakharov conditions [10], see the scheme below.

The SM does not provide a successful BG due to the lack of CP violation and not strongly 1st order electroweak phase transition. Though in the economical SM extensions η_B can be generated through the thermal leptogenesis (LG) [11] where the lepton number asymmetry is produced in the out-of-equilibrium decays of heavy Majorana particles, and further the SM sphaleron processes convert this lepton asymmetry into the baryon one.

However non-resonant LG in the supersymmetric generalizations of the SM suffers from the gravitino problem [12], which is related to the lower bound on the sterile neutrino mass.



We investigate how LMs may provide a successful BG at relatively low temperatures.

Baryogenesis from Leptomesons

BG from LM oscillations

In the vector case with B and L conservation the effective four-fermion interactions of LMs with the SM fermions can be written as

$$\frac{1}{\Lambda^2}\sum_{\psi_\ell, f, f'}\sum_{\alpha,\beta=L,R}\Big[\epsilon^{\alpha\beta}_{ff'\psi_\ell}(\bar{f}_\alpha\gamma^\mu f'_\alpha)(\bar{\psi}_{\ell\beta}\gamma_\mu\ell^0_{M\beta}) + \tilde{\epsilon}^{\alpha\beta}_{ff'\psi_\ell}(\bar{\psi}_{\ell\alpha}\gamma^\mu f'_\alpha)(\bar{f}_\beta\gamma_\mu\ell^0_{M\beta})\Big] + \text{H.c.},$$

where Λ is the new physics scale, ϵ and $\tilde{\epsilon}$ are the new couplings, $\psi_\ell = \ell, \nu_\ell$ ($\ell = e, \mu, \tau$) is the SM lepton, f and f' denote either two quarks or two leptons such that the sum of the electric charges of f_α, $f'^\dagger_\alpha$ and $\psi_{\ell\beta}$ is zero, and ℓ^0_M is the neutral LM flavor state that is related to the mass eigenstates L^0_{Mi} by the mixing matrix U:

$$\ell^0_{M\alpha} = \sum_{i=1}^{n} U^\alpha_{\ell i} L^0_{Mi}.$$

LMs can be produced thermally from the primordial plasma. Once created ℓ^0_M oscillate and interact with ordinary matter. These processes do not violate the total lepton number $L^{\rm tot}$, which is defined as usual lepton number plus that of LMs. However LM oscillations violate CP and therefore their individual lepton numbers (L_i) are not conserved. Hence the initial state with all zero lepton numbers evolves into a state with $L^{\rm tot} = 0$ but $L_i \neq 0$.

At the temperature T below Λ scale LMs communicate their lepton asymmetry to ν_ℓ and ℓ through the discussed effective interactions. Suppose that the neutral LMs of at least one type come into thermal equilibrium before the time $t_{\rm EW}$ at which sphalerons become ineffective, and those of at least one other type do not equilibrate by $t_{\rm EW}$. Hence L_i of the former (later) affects (has no effect on) BG. In result, the final baryon asymmetry is nonzero. At the time $t \gg t_{\rm EW}$ all LMs decay into the SM fermions. Hence they do not contribute to the dark matter in the universe, and do not destroy the Big Bang nucleosynthesis.

The system of n types of singlet LMs with a given momentum $k(t) \propto T(t)$ that interact with the primordial plasma can be described by the $n \times n$ density matrix $\rho(t)$. In a simplified picture this matrix satisfies the kinetic equation [13]

$$i\frac{d\rho}{dt} = [\hat{H}, \rho] - \frac{i}{2}\{\Gamma, \rho\} + \frac{i}{2}\{\Gamma^p, 1 - \rho\}, \qquad (1)$$

where Γ (Γ^p) is the destruction (production) rate, and the effective Hamiltonian is

$$\hat{H} = V(t) + U\frac{\hat{M}^2}{2k(t)}U^\dagger,$$

where V is a real potential, and $\hat{M}^2 = {\rm diag}(M_1^2, \dots, M_n^2)$ with LM masses M_i. In general, evolutions of LMs and the SM leptons can be considered together using the method of Ref. [14]. Here we concentrate on the essentially different temperature dependence of the interaction rate for LMs and the sterile neutrinos (N_R), which can make the LM scenario more attractive to the experimentalists.

The cross sections for $2 \leftrightarrow 2$ reactions that contribute to Γ can be written as

$$\sigma \equiv \sigma(a + b \leftrightarrow c + d) = C\epsilon^2\frac{s}{\Lambda^4}, \qquad (2)$$

where a, b, c and d denote the four interacting particles (f, f', ψ_ℓ and ℓ^0_M), $C = \mathcal{O}(1)$ is the constant that includes the color factor in the case of the interaction with q, and s is the total energy of the process. In the considered LM scenario the cross section in Eq. (2) is proportional to s in contrast to the inverse proportionality in the case of BG from N_R oscillations. The respective interaction rate that brings LMs into equilibrium can be written as

$$\Gamma \propto \epsilon^2\frac{T^5}{\Lambda^4}, \qquad [\text{instead of } \Gamma_{N_R} \propto T].$$

The conditions that LMs L^0_i come into equilibrium before $t_{\rm EW}$, while LMs L^0_j do not, are

$$\boldsymbol{\Gamma_i(T_{\rm EW}) > H(T_{\rm EW}),}$$
$$\boldsymbol{\Gamma_j(T_{\rm EW}) < H(T_{\rm EW}),}$$

where the Hubble expansion rate H is

$$H(T) \approx 1.66 g_*^{1/2}\frac{T^2}{M_{\rm Planck}},$$

where $M_{\rm Planck}$ is the Planck mass, and $g_* \sim 10^2$ is the number of relativistic degrees of freedom in the primordial plasma.

Due to $(T_{\rm EW}/\Lambda)^4$ suppression of these Γ with respect to the case of Γ_{N_R} the couplings ϵ can be significantly larger than the Yukawa couplings h_N of N_R. In particular, for $\Lambda \gtrsim 10$ TeV we have $\boldsymbol{\epsilon \gtrsim 10^{-4}}$ [$h_N \gtrsim 10^{-7}$]. Hence the considered scenario of the BG via neutral LMs can be relevant for the LHC and next colliders without unnatural hierarchy of couplings.

In the approximation of Eq. (1) the asymmetry transferred to usual leptons by $t_{\rm EW}$ is [13]

$$\frac{n_L - n_{\bar{L}}}{n_\gamma} = \frac{1}{2}\sum_j |S^M_j(t_{\rm EW}, 0)|^2_{CP-{\rm odd}},$$

where $1/2$ accounts for the photon helicities, and $S^M = U^\dagger S U$ is the evolution matrix in the mass eigenstate basis ($S(t, t_0)$ is the evolution matrix corresponding to $\hat{H} - (i/2)\Gamma$).

In the case of three LM mass states the respective CP-violating effects can be proportional to the related Jarlskog determinant. However additional CPV phases may come from the active ν sector and extra LM states.

BG from LM decays

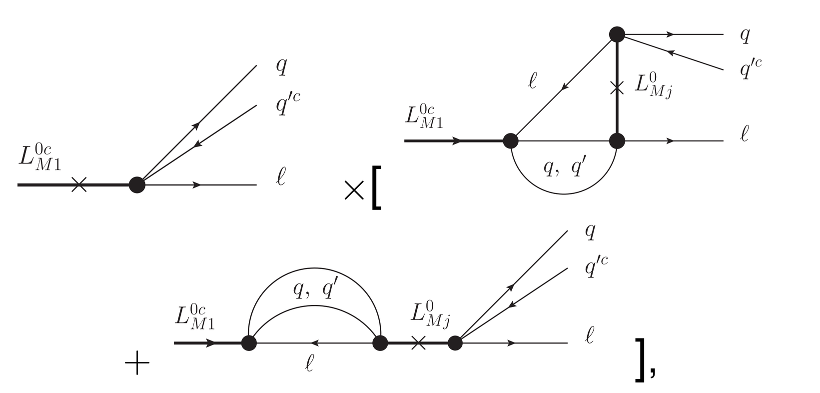
Suppose that the neutral LMs are Majorana particles ($\ell^0_{MR} = \ell^{0c}_{MR}$). Then an analog of usual LG can take place due to their out-of-equilibrium, CP and L non-conserving decays. Relevant B and L conserving terms are

$$\frac{\epsilon^{\alpha R}_{ff'\psi_\ell}}{\Lambda^2}(\bar{f}_\alpha\gamma^\mu f'_\alpha)(\bar{\psi}_{\ell R}\gamma_\mu\ell^0_{MR}) + \frac{\epsilon^{T}_{ff'\psi_\ell}}{\Lambda^2}(\bar{f}_R\sigma^{\mu\nu} f'_L)(\bar{\psi}_{\ell L}\sigma_{\mu\nu}\ell^0_{MR}) + \frac{\epsilon^{S}_{ff'\psi_\ell}}{\Lambda^2}(\bar{f}_R f'_L)(\bar{\psi}_{\ell L}\ell^0_{MR}) + \tilde{\epsilon}\ \text{terms} + \text{H.c.},$$

where the sum of the hypercharges of f, $f'^\dagger$ and ψ_ℓ is zero. To be more specific we take

$$\frac{\lambda_{\ell i}}{\Lambda^2}(\bar{q}_\alpha\gamma^\mu q'_\alpha)(\bar{\ell}_R\gamma_\mu L^0_{Mi}),$$

where $\lambda_{\ell i} = \epsilon^{\alpha R}_{qq'\ell}U^R_{\ell i}$ is the complex parameter. Now consider the interference of the diagrams



where L is violated by the Majorana mass insertion. The CP asymmetry produced in decays of the lightest LM L^0_{M1} can be defined as

$$\varepsilon_1 = \sum_\ell \frac{\Gamma(L^0_{M1} \to \ell_R q_\alpha q'^c_\alpha) - \Gamma(L^0_{M1} \to \ell^c_R q^c_\alpha q'_\alpha)}{\Gamma_1},$$

where the three-particle decay width is

$$\Gamma_1 = \sum_\ell [\Gamma(L^0_{M1} \to \ell_R q_\alpha q'^c_\alpha) + \Gamma(L^0_{M1} \to \ell^c_R q^c_\alpha q'_\alpha)] = \frac{1}{96\pi^3}(\lambda^\dagger\lambda)_{11}\frac{M_1^5}{\Lambda^4}$$

with the mass M_1 of L^0_{M1}. This CP asymmetry to be nonzero requires ${\rm Im}[(\lambda^\dagger\lambda)^2_{1j}] \neq 0$. Hence at least two LM mass states are needed. The out-of-equilibrium condition $\Gamma_1 < H(T = M_1)$ translates into the upper bound of

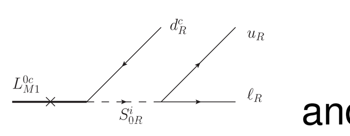
$$(\lambda^\dagger\lambda)_{11} \lesssim 4 \times 10^{-8}\left(\frac{\Lambda}{10\ \text{TeV}}\right)^4\left(\frac{1\ \text{TeV}}{M_1}\right)^3. \qquad (3)$$

Example: The discussed effective LM-q-$\bar{q}$-lepton vertices can be realized, e.g., through the exchange of a scalar $SU(2)_L$ singlet LQ S_{0R} with $Y = 1/3$. The relevant interaction terms in the Lagrangian can be written as

$$-\mathcal{L}_{\rm int} = (g_{ij}\,\bar{d}^c_R L^0_{Mi} + f_j\,\bar{u}^c_R\ell_R)S^j_{0R} + \text{H.c.}$$

Then the above expressions are valid with the replacements $\lambda \to gf^*$ and $\Lambda \to M_{S_{0R}}$. Hence Eq. (3) can be satisfied for relatively large values of the new couplings, e.g., $|g| \sim |f| \sim 10^{-2}$, which can be interesting for the LHC.

Notice that there is no contribution to the CP asymmetry from the interference among



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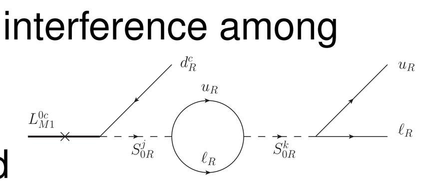


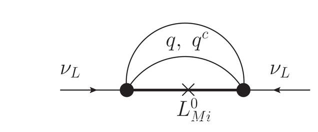
diagrams due to cancellation. However the compositeness models with LQs, which have at least 3 types of interactions, can realize the LG of the kind of Ref. [15] from LM decays.

Discussion and Conclusions

In the case of Majorana LMs among the discussed four-fermion interactions the terms

$$\frac{\tilde{\epsilon}^{LR}_{ff\nu_\ell}}{\Lambda^2}(\bar{\nu}_{\ell L}\gamma^\mu f_L)(\bar{f}_R\gamma_\mu\ell^0_{MR}) + \frac{\epsilon^{S}_{ff\nu_\ell}}{\Lambda^2}(\bar{f}_R f_L)(\bar{\nu}_{\ell L}\ell^0_{MR}) + \frac{\epsilon^{T}_{ff\nu_\ell}}{\Lambda^2}(\bar{f}_R\sigma^{\mu\nu} f_L)(\bar{\nu}_{\ell L}\sigma_{\mu\nu}\ell^0_{MR}) + \text{H.c.} \qquad (4)$$

can contribute to the neutrino masses. For $f = q$ this can be illustrated by the generic diagram (where the bulbs represent a subprocesses) and its particular realization in a model with LQs:



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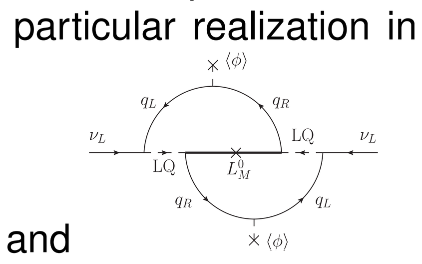

The resulting ν mass can be estimated as

$$m_{\nu_\ell} \sim \sum_i \frac{|\epsilon\, U_{\ell i}|^2}{(16\pi^2)^2}\frac{M_i^3 m_f^2}{\Lambda^4},$$

where ϵ is a relevant coupling from Eq. (4). Then present upper bound on the neutrino mass of $m(\nu_e) \lesssim 2$ eV can be easily satisfied for the discussed values of ϵ, M_i and Λ.

To conclude, we introduced the two possible generic scenarios of low temperature BG in the new class of models with leptomesons.

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References

[1] J. C. Pati and A. Salam, Phys. Rev. D **10** (1974) 275 [Phys. Rev. D **11** (1975) 703].

[2] H. Terazawa, K. Akama and Y. Chikashige, Phys. Rev. D **15** (1977) 480.

[3] H. Fritzsch and G. Mandelbaum, Phys. Lett. B **102** (1981) 319.

[4] K. A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38** (2014) 090001.

[5] D. Goncalves-Netto, D. Lopez-Val, K. Mawatari, I. Wigmore and T. Plehn, Phys. Rev. D **87** (2013) 094023 [arXiv:1303.0845 [hep-ph]].

[6] H. Fritzsch and J. Sola, Adv. High Energy Phys. **2014** (2014) 361587 [arXiv:1402.4106 [hep-ph]].

[7] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115** (2015) 072001 [arXiv:1507.03414 [hep-ex]].

[8] M. Pitkänen and P. Mähönen, Int. J. Theor. Phys. **31** (1992) 229.

[9] D. Zhuridov, Phys. Rev. D **93** (2016) no.3, 035025 [arXiv:1512.02152 [hep-ph]].

[10] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5** (1967) 32 [JETP Lett. **5** (1967) 24] [Sov. Phys. Usp. **34** (1991) 392] [Usp. Fiz. Nauk **161** (1991) 61].

[11] M. Fukugita and T. Yanagida, Phys.Lett.**B174**, 45 (1986).

[12] M. Yu. Khlopov and A. D. Linde, Phys.Lett.**B138**, 265-268 (1984).

[13] E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov, Phys. Rev. Lett. **81** (1998) 1359 [hep-ph/9803255].

[14] T. Asaka, M. Laine and M. Shaposhnikov, JHEP **0606** (2006) 053 [hep-ph/0605209].

[15] T. Hambye, Nucl. Phys. B **633** (2002) 171 [hep-ph/0111089].

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