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Composite Baryogenesis

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Abstract

The composite models, which address the existing problems of the Standard Model (SM), generally include the excited leptons. I introduce new scenarios for possible generation of the baryon asymmetry of the universe using these new particles. The scenarios do not contradict to the small neutrino masses and proton stability, and can be tested at the LHC.

Introduction

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

- Large number of them: $\{e^-, \nu_e, u_c, d_c$, and their antiparticles$\} \times 3$ generations;
- Arbitrary fermion masses and mixings;
- Fractional electric charges of quarks;
- Similarity between leptons $\{\ell, \nu\}$ and quarks q in the SM flavor and gauge structure;
- Dark matter (DM), 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** [1-4]. Typically they predict new heavy composites constructed from their sets of preons. Current bounds on some new composite fermion masses are [5]:

- Excited ℓ^*: $m^* > 103.2$ GeV (from $\ell^*\ell^*$);
- Color (anti)sextet quarks q_6 ($\bar{3} \times \bar{3} = 3 + \bar{6}$): $m_{q_6} > 84$ GeV;
- Color octet neutrinos ν_8 ($3 \times \bar{3} = 1 + 8$): $m_{\nu_8} > 110$ GeV;
- Charged leptogluons ℓ_8: $m_{q_6} > 86$ GeV.

Composite model example

Consider wakem-chrom [3] or haplon [4, 6] models, 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): α, β fermions, and ℓ and c_k ($k = r, g, b$) scalars.

Haplon	Spin [$\hbar$]	Q [$\|e\|$]	$SU(3)_c$	$SU(2)_h$
α	$1/2$	$+1/2$	1	2
β	$1/2$	$-1/2$	1	2
ℓ	0	$+1/2$	1	2
c_k	0	$-1/6$	3	2

Pairs of these preons can compose the SM particles as $\nu = (\alpha\bar{\ell})_1$, $d = (\beta\bar{c}_k)_3$, $W^- = (\bar{\alpha}\beta)_1, \ldots$, and the new composites, e.g., leptoquark $S^{2/3} = (\ell\bar{c}_k)$ and leptogluon $(\bar{\beta}\bar{\ell})_8$. Also multipreon states $(\alpha\bar{\ell}\beta\bar{c}_k\bar{\beta}c_k)$,...may exist in the analogy to the multiquark hadrons [7].

Notice that $SU(3)_c \times U(1)_{em}$ quantum numbers of haplons can be reproduced by the triples of scalar "prepreons" $\pi_k^{-1/6}$ and $\bar{\pi}_k^{+1/6}$, which are $SU(3)$ triplets, since the product decomposition $3 \times 3 \times 3 = 1 + 8 + 8 + 10$ contains singlet.

Leptomesons

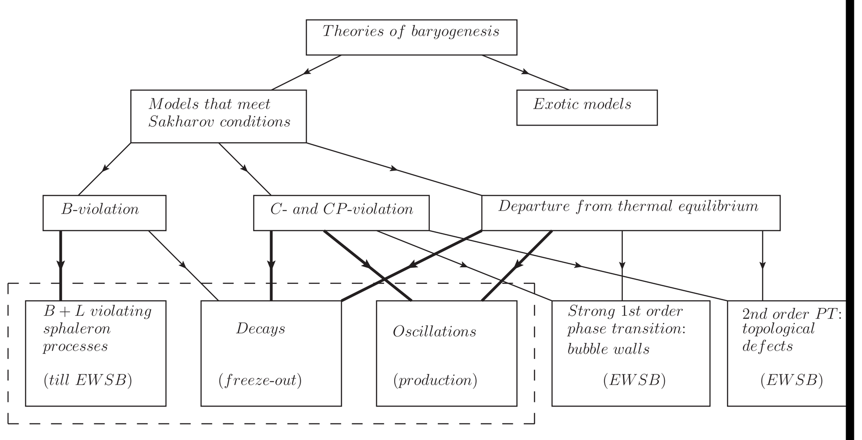
We define a leptomeson (LM) as an excited lepton ψ_ℓ^* that at relatively low energies of $\mathcal{O}(T_{\rm EW})$ interacts with the SM fermions f dominantly through the contact terms $\frac{2\pi\eta''}{\Lambda^2} \bar{f} f \bar{\psi}_\ell \psi_\ell^* + \ldots$, where $|\eta''| \leq 1$ is the new coupling, and the compositeness scale is typically bounded as $\Lambda \gtrsim \sqrt{|\eta''|} \times$ few TeV [8].

Baryogenesis

The observable universe is populated with baryonic matter rather than antimatter. The related baryon asymmetry $\eta_B \sim 10^{-10}$ [5] 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 [9] (scheme is below).

The SM does not provide a successful BG, though its economical extensions can generate η_B through the thermal leptogenesis (LG) [10] 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 to η_B.

However non-resonant LG in the supersymmetric generalizations of the SM suffers from the gravitino problem [11], which is related to the lower bound on the sterile neutrino mass.



Baryogenesis from Leptomesons

BG from LM oscillations

Once created (e.g., thermally from the primordial plasma) in the early universe neutral long-lived LMs oscillate and interact with ordinary matter. These processes do not violate the total lepton number $L^{\rm tot}$ (for Dirac LMs). However the oscillations violate CP and therefore do not conserve individual lepton numbers L_i for LMs. Hence the initial state with all zero lepton numbers evolves into a state with $L^{\rm tot} = L_0 + \sum_i L_i = 0$ but $L_i \neq 0$, where L_0 is the lepton number of other particles [12].

At temperatures $T \ll \Lambda$ the LMs communicate their lepton asymmetry to neutrinos ν_ℓ and charged leptons ℓ through the effective interactions, e.g., B-conserving (and L-conserving for Dirac LMs) vector couplings

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

where $\psi_\ell = \ell, \nu_\ell$ ($\ell = e, \mu, \tau$), the constants $\overset{(\sim)}{\epsilon} = 4\pi\eta''$ can be real, f and f' denote either quarks or leptons with $Q_{f_\alpha} + Q_{f'^c_\alpha} + Q_{\psi_{\ell\beta}} = 0$ and N_ℓ is the neutral LM flavor state related to the mass eigenstates N_i as $N_{\ell\alpha} = \sum_{i=1}^n U^\alpha_{\ell i} N_i$.

Suppose that LMs of at least one type N_i remain in thermal equilibrium till the electroweak symmetry breaking time $t_{\rm EW}$ at which sphalerons become ineffective, and those of at least one other type N_j come out-of-equilibrium by $t_{\rm EW}$. Hence L_i of the former (later) affects (has no effect on) BG. In result, the final η_B is nonzero. At the time $t \gg t_{\rm EW}$ all LMs decay into the SM fermions. Hence they do not contribute to the DM, 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 kinetic equation for $n \times n$ density matrix $\rho(t)$

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

where Γ (Γ^p) is the destruction (production) rate, and $\hat{H}(t, k)$ is the effective Hamiltonian.

One of the main features of the discussed BG from LMs is that the 4-particle interaction cross section that contributes to Γ is proportional to the total energy of the process s instead of the inverse proportionality that takes place in the BG from sterile ν_R oscillations [12]. This cross section can be written as

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

where a, b, c, d denote the interacting particles (f, f', ψ_ℓ and N_ℓ), and $C = \mathcal{O}(1)$ is the constant that includes the color factor in case of the interaction with quarks. For the respective interaction rate that equilibrates LMs we have

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

The conditions that LMs of type N_i remain in thermal equilibrium till $t_{\rm EW}$, while N_j do not:

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

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_{ν_R} the couplings ϵ can be significantly larger than the Yukawa couplings h_{ν_R} of ν_R. In particular, for $\Lambda \gtrsim 10$ TeV we have $\boldsymbol{\epsilon \gtrsim 10^{-4}}$ [$h_{\nu_R} \gtrsim 10^{-7}$]. 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 [12]

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

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

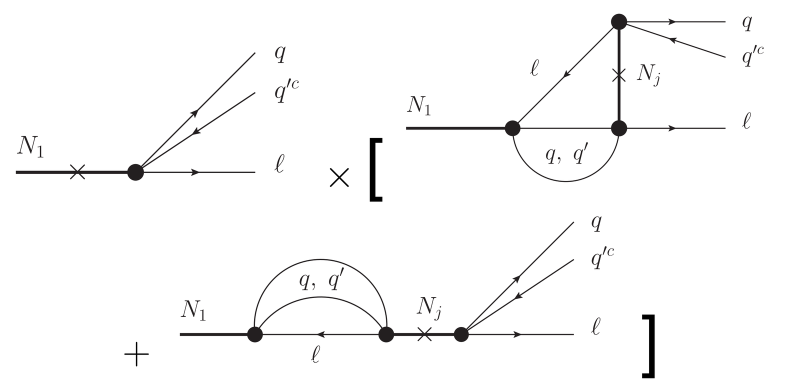
Suppose that the neutral LMs are Majorana particles ($N = N^c$). Then an analog of usual LG may take place due to their out-of-equilibrium, CP and L-violating decays. The relevant interactions can be written as

$$\frac{\epsilon^{\alpha R}_{ff'\psi_\ell}}{\Lambda^2}(\bar{f}_\alpha \gamma^\mu f'_\alpha)(\bar{\psi}_{\ell R}\gamma_\mu N_{\ell R}) + \frac{\epsilon^S_{ff'\psi_\ell}}{\Lambda^2}(\bar{f}_R f'_L)(\bar{\psi}_{\ell L} N_{\ell R}) + \frac{\epsilon^T_{ff'\psi_\ell}}{\Lambda^2}(\bar{f}\sigma^{\mu\nu} f')(\bar{\psi}_{\ell L}\sigma_{\mu\nu} N_{\ell R}) + \text{H.c.} \quad (2)$$

To be more specific we will discuss the term

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

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



(Same 2-loop self-energy graph was discussed also in the resonant BG from $qqq\nu_R$ interactions [13, 14], where η_B is directly produced in the three-body ν_R decays.)

Final CP asymmetry produced in N_1 decays

$$\varepsilon_1 = \frac{1}{\Gamma_1}\sum_\ell [\Gamma(N_1 \to \ell_R q_\alpha q'^c_\alpha) - \Gamma(N_1 \to \ell^c_R q^c_\alpha q'_\alpha)],$$

can be non-zero if $\text{Im}[(\lambda^\dagger\lambda)^2_{1j}] \neq 0$. Using

$$\Gamma_1 = \sum_\ell [\Gamma(N_1 \to \ell_R q_\alpha q'^c_\alpha) + \Gamma(N_1 \to \ell^c_R q^c_\alpha q'_\alpha)] \simeq \frac{1}{128\pi^3}(\lambda^\dagger\lambda)_{11}\frac{M_1^5}{\Lambda^4},$$

the condition for the decay parameter $K \equiv \Gamma_1/H(M_1) > 3$ (strong washout regime) translates into the limit of

$$(\lambda^\dagger\lambda)_{11} \gtrsim 4 \times 10^{-7}\left(\frac{\Lambda}{10\ \text{TeV}}\right)^4 \left(\frac{1\ \text{TeV}}{M_1}\right)^3. \quad (3)$$

The final baryon asymmetry can be written as

$$\frac{n_B - n_{\bar{B}}}{s} = \left(-\frac{28}{79}\right) \times \frac{n_L - n_{\bar{L}}}{s} = \left(-\frac{28}{79}\right) \times \frac{\varepsilon_1 \kappa}{g_*},$$

where n_B (n_L) is the baryon (lepton) number density, s is the entropy density, $-28/79$ is the sphaleron lepton-to-baryon factor, and $\kappa \leq 1$ is the washout coefficient to be determined by solving the Boltzmann equations.

Self-energy dominant case

The observed baryon asymmetry [5]

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 7.04 \times \frac{n_B - n_{\bar{B}}}{s} \simeq 6 \times 10^{-10}$$

can be produced, e.g., for $K \sim 100$ with the degeneracy factor of

$$\mu \equiv \frac{M_2 - M_1}{M_1} \lesssim 10^{-6}\left(\frac{M_1}{1\ \text{TeV}}\right)$$

needed to get large enough CP asymmetry

$$\varepsilon_i \sim \frac{\text{Im}\{[(\lambda^\dagger\lambda)_{ij}]^2\}}{(\lambda^\dagger\lambda)_{ii}(\lambda^\dagger\lambda)_{jj}} \frac{\Gamma_j}{M_j} \frac{M_i M_j}{M_i^2 - M_j^2} \sim \mu^{-1}\frac{\Gamma_1}{M_1}$$

that is strongly suppressed by small Γ_1/M_1.

Generic case: Larger parameter space can be opened. Degeneracy may be not needed.

LQ example: The discussed N_ℓ-q-$\bar{q}$-ψ_ℓ vertices can be realized, e.g., by exchange of the $SU(2)_L$ singlet scalar leptoquark (LQ) S_{0R} with the weak hypercharge of $Y_W = 1/3$. The relevant interaction terms can be written as

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

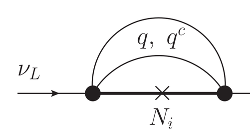
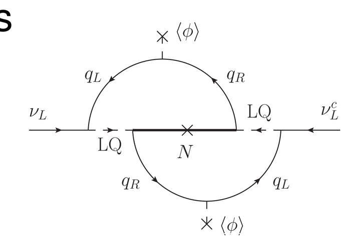
Then the above expressions are valid with the replacements $\lambda \to g f^*$ and $\Lambda \to M_{S_{0R}}$. Hence Eq. (3) can be satisfied for relatively large values of the new couplings, e.g., $|g| \sim |f| \sim 0.01 - 0.1$, which can be interesting for the LHC.

Neutrino mass

Among the terms in Eq. (2) the interactions

$$\frac{\epsilon^S_{ff\nu_\ell}}{\Lambda^2}\bar{f}_R f_L \bar{\nu}_{\ell L} N_{\ell R} + \frac{\epsilon^T_{ff\nu_\ell}}{\Lambda^2}\bar{f}\sigma^{\mu\nu} f \bar{\nu}_{\ell L}\sigma_{\mu\nu} N_{\ell R} + \text{H.c.}$$

can generate the two-loop contributions δm_{ν_ℓ} to the observable light neutrino masses that for $f = q$ can be illustrated generically and in a particular LQ model as

 and ,

respectively (arrows show L and B flows). A simple estimate of this contribution is

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

where m_q is the quark mass. 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 parameters.

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

Acknowledgments

The author thanks Marek Zrałek, Henryk Czyż, Bhupal Dev and Yue Zhang for useful discussions. This work was supported in part by the Polish National Science Centre, grant number DEC-2012/07/B/ST2/03867.

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International Workshop on e^+e^- collisions from Phi to Psi 2017, 26-29 June 2017, Mainz, Germany