Resurrection of Grand Unified Theory Baryogenesis

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A "new" scenario is proposed for baryogenesis. We show that the delayed decay of colored Higgs particles in grand unified theories may generate an excess baryon number of the empirically desired amount, if the mass of the heaviest neutrino is in the range $0.02\ \mathrm{eV} < m_{\nu_3} < 0.8\ \mathrm{eV}$, provided that neutrinos are of the Majorana type. The scenario accommodates the case of degenerate neutrino masses, in contrast to the usual leptogenesis scenario, which does not work when three neutrino masses are degenerate.

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After the advent of grand unified theory (GUT) the most popular idea for baryon asymmetry in the universe was to ascribe its origin to baryon number violating delayed decay of heavy colored Higgs particles [1–4]. It was later found, however, that standard electroweak theory contains baryon number violation, and this process efficiently erases all baryon numbers that are produced before the epoch of the electroweak phase transition, insofar as the baryon excess is produced respecting the $B - L$ conservation [5]. This is the case not only with SU(5) grand unification (and its supersymmetric extension) but also with any grand unification with higher symmetries that has been considered to date. This is because symmetry higher than SU(5) contains $U(1)_{B-L}$ as a subgroup, which is unbroken above the grand unification scale. Even if it is broken at a low energy, $\Delta B = \Delta L$ is satisfied for the excess baryon number insofar as it is generated in decay of $\phi \rightarrow qq$, $\bar{q}\ell$ and their conjugate. Multiparticle decays which would generate baryon numbers with $\Delta B \neq \Delta L$ require complicated diagrams and are generally too small. In this situation one usually invokes delayed decay of heavy Majorana particles with $\Delta L \neq 0$ ($\Delta B = 0$) to generate lepton number [6,7], and the sphaleron action [5] to transfer lepton number to baryon number. This mechanism does not particularly require unification of strong and electroweak interactions, and it is readily embedded into many classes of unified theories.

Experiment has now shown that neutrinos are massive. In particular, one neutrino that mixes with μ and τ neutrinos has a mass $m_{\nu_3} > 0.04\ \mathrm{eV}$ [8]. In this circumstance we can show that the GUT scenario using delayed decay of leptoquark Higgs particles is revived as a possible mechanism of baryon number production, with the proviso that neutrinos are of the Majorana type.

We first give a sketch of the idea of a new baryogenesis scenario. The simplest effective interaction that gives the neutrino the Majorana mass is

$$\frac{1}{2M_i}\ell_i\phi\ell_i\phi, \tag{1}$$

where ϕ is the standard Higgs doublet and the effective mass scale M_i is $<10^{15}$ GeV for $i = 3$ from $m_{\nu_3} > 0.04$ eV. With this effective interaction the lepton number violating interaction $\ell_i + \phi \rightarrow \bar{\ell}_i + \phi^\dagger$ is in thermal equilibrium above the temperature of $T \sim 10^{14}$ GeV. At this high temperature ($T > 10^{12}$ GeV) the action of sphaleron effects is not effective [9,10]. Hence, if delayed decay of the colored Higgs particles produces baryon and lepton number excess while conserving $B - L$, the lepton number excess is erased by the Majorana interaction, whereas the baryon number excess is intact. When the universe cools to $T < 10^{12}$ GeV, the sphaleron action becomes effective, while the lepton number violating interaction already decoupled. This leads to baryon number partly converted into lepton number, conserving $B - L$; 0.35 times the original baryon number, however, survives the sphaleron action. The crucial observation here is that the experimentally indicated neutrino mass points towards lepton number violation efficiently taking place at very high temperatures where sphaleron actions are not yet effective, rather than both baryon and lepton violations undergo at the same temperature, which would result in vanishing baryon excess [11]. We remark that what matters to our argument is the mass of the heaviest neutrino; all other neutrinos are irrelevant.

We now discuss a specific model. We consider for simplicity SU(5) GUT, but the model applies straightforwardly to SO(10) or other GUT without or with supersymmetry. We assume the presence of an SU(5) singlet (**1**) fermion in addition to the standard **5*** and **10** fermions for each family. This **1** may naturally be included in **16** of SO(10). We consider the Lagrangian,

$$\mathcal{L}_{\mathrm{Yukawa}} = h_{ij}^{(k)}\psi(\mathbf{10}_i)\psi(\mathbf{10}_i)H^{(k)} + f_{ij}^{(k)}\psi(\mathbf{5}_i^*)\psi(\mathbf{10}_j)H^{(k)\dagger} + g_{ij}^{(k)}\psi(\mathbf{1}_i)\psi(\mathbf{5}_j^*)H^{(k)}, \tag{2}$$

where $i = 1 - 3$ and we assume two Higgs particles $k = 1, 2$ [4]. We suppose that all right-handed Majorana neutrinos, $N_i \equiv \psi(\mathbf{1}_i) + \psi^c(\mathbf{1}_i)$, are heavier than the color-triplet Higgs particles H_c, i.e., we have mass hierarchy

$$10^{12}\,\text{GeV} < m_{H_c} < m_N < 10^{16}\,\text{GeV}, \tag{3}$$

where the first inequality is the requirement from the limit on proton instability, and the third inequality is the condition discussed in what follows. Note that the condition against proton instability agrees with the energy scale that the sphaleron action becomes ineffective, i.e., colored Higgs decay takes place where sphaleron effects are not active.

The effective mass of (1) is given by $M_i = m_{N_i}/g_i^2$ with g_i the Yukawa coupling for the right-handed neutrino. The condition that the reaction rate of $\ell_i + \phi \to \bar{\ell}_i + \phi^\dagger$, $\Gamma \approx 0.12T^3/4\pi M_i^2$, be sufficiently faster than the expansion rate of the universe $\gamma_{\text{exp}} \approx 17T^2/m_{\text{pl}}$ at temperature T is written

$$M_i \lesssim 10^{15}\left(\frac{T}{10^{14}\text{GeV}}\right)^{1/2}\,\text{GeV}. \tag{4}$$

If this inequality is violated for $T \approx m_{N_i}$, the Majorana neutrino undergoes out-of-equilibrium decay, and lepton excess is generated, and the model reduces to the usual leptogenesis scenario. We require that this does not happen, which gives $m_{N_i} < 10^{16}$ GeV for $g_i \lesssim 1$.

We consider the traditional delayed-decay scenario of colored Higgs particles. The calculation for the baryon abundance in units of specific entropy is standard [4,12]. We have

$$\frac{kn_B}{s} \simeq 0.5 \times 10^{-2}\epsilon\frac{1}{1 + (3K)^{1.2}}, \tag{5}$$

where

$$K = \frac{1}{2}\frac{\Gamma_H}{\gamma_{\text{exp}}}\bigg|_{T=m_{H_c}} = 3.5 \times 10^{17}\,\text{GeV}\alpha_H\frac{1}{m_{H_c}}, \tag{6}$$

with $\Gamma_H \approx \alpha_H m_{H_c}$ and $\alpha_H = h^2/4\pi$ the Yukawa coupling constant square; the net baryon number ϵ produced by pair decay of H_c and $\overline{H_c}$ through the interference of one-loop and tree diagrams is given by

$$\epsilon \approx \frac{\eta}{8\pi}10^{-2}(F(x) + G(x) - F(1/x) - G(1/x)), \tag{7}$$

where $F(x) \simeq 1 - x\log[(1 + x)/x]$ and $G(x) \simeq 1/(x - 1)$ with $x = [m_{H^{(1)}}/m_{H^{(2)}}]^2$ the ratio of the mass squares of the two colored Higgs particles and $\eta = \sin(\arg[\text{tr}(f^{(1)\dagger}f^{(2)}h^{(1)\dagger}h^{(2)})])$ is the factor representing the CP-violation phase. These two factors represent the contribution from the interference of the one-loop vertex with the tree diagram [4] and that of the self-energy with the tree diagram [13]. For example, if we take $m_{H_c} \approx 10^{14}$ GeV, $x \approx 0.5$, and $\eta \approx -0.1$, we obtain $kn_B/s \approx 2 \times 10^{-10}$ nominally in agreement with the empirical baryon abundance. This process produces lepton number at the same time by the amount $\Delta L = \Delta B$.

Produced lepton number, however, is erased if the Majorana interaction is in the thermal equilibrium at $T \approx m_{H_c}$. If we take $m_{H_c} \lesssim 10^{15}$ GeV the condition for thermal equilibrium is read from Eq. (4), which leads to

$$m_{\nu_i} \gtrsim 2 \times 10^{-2}\text{ eV}, \tag{8}$$

using (1) with $\langle\phi\rangle \simeq 250$ GeV. This condition should be satisfied at least for one species of neutrinos.

The rate for the action of sphalerons is computed to be [9,10]

$$\Gamma_{\text{sph}} \approx 2 \times 10^2\alpha_W^5 T, \tag{9}$$

where $\alpha_W \approx 1/40$ is the weak coupling constant. $\Gamma_{\text{sph}} > \gamma_{\text{exp}}$ gives $T \lesssim 12\alpha_W^5 m_{\text{pl}} \approx 1.4 \times 10^{12}$ GeV for the temperature, below which the sphaleron action becomes effective. We must require that the Majorana interaction decouples by this temperature, or otherwise all existing baryon and lepton numbers are erased by the joint action of sphalerons and Majorana interactions [11]. The condition obtained from Eq. (4) with the aid of (1) and the value of $\langle\phi\rangle$ is

$$m_{\nu_j} < 0.8\text{ eV}. \tag{10}$$

This must be satisfied for all neutrinos. The action of sphalerons at lower temperatures then partially converts baryon number to lepton number, but baryon number remains by the amount of [14]

$$\Delta B_f = \frac{8N_f + 4N_H}{22N_f + 13N_H}\Delta B_i = 0.35\Delta B_i \tag{11}$$

for three generations of fermion families $N_f = 3$ and two Higgs doublets $N_H = 2$. Hence we expect $kn_B/s \approx 1 \times 10^{-10}$ with the parameters exemplified above.

Our central result is summarized as follows. If the two inequalities (8) and (10) are satisfied, i.e., if the mass of the heaviest neutrino satisfies $0.02 < m_{\nu_3} < 0.8$ eV, baryogenesis via colored Higgs decay works within the framework of GUT. This neutrino mass range nearly coincides with the limits derived empirically: atmospheric neutrino oscillation gives a lower limit on the τ neutrino mass, $m_{\nu_3} > 0.04$ eV [8], and the limit from neutrinoless double beta decay experiment is about $\langle m_{\nu_1}\rangle < 0.5$–$1.5$ eV [15], or $\sum_i m_{\nu_i} < 4$ eV from cosmology [16].

We emphasize that the present scenario is valid with neutrinos nearly degenerate in mass. This contrasts to the usual leptogenesis scenario of delayed heavy Majorana neutrino decay, for which

$$\mu_1 = \left(h_{11}\frac{1}{M_1}h_{11}^\dagger + h_{21}\frac{1}{M_2}h_{12}^\dagger + h_{31}\frac{1}{M_3}h_{13}^\dagger\right) \tag{12}$$

must satisfy $\mu_1 \lesssim 2 \times 10^{-3}$ eV. While this mass term is not directly related with the physical neutrino mass

$$m_{\nu_i} = \left(h_{i1} \frac{1}{M_1} h_{1i} + h_{i2} \frac{1}{M_2} h_{2i} + h_{i3} \frac{1}{M_3} h_{3i} \right), \qquad (13)$$

it is clear that one or two neutrinos must have small masses. Namely, the neutrino mass must be hierarchical.

The neutrino mass would give a diagnostics as to which baryogenesis scenario is to be realized. If a future neutrino mass experiment would prove that the mass of three neutrinos has some nonzero baseline value in excess of 0.01 eV, say, by a positive detection of neutrinoless double beta decay, the Higgs decay scenario given in this paper would be a more promising possibility for baryon number generation. If the hierarchical neutrino mass is favored for some reasons, either of the two baryogenesis scenarios is equally viable, unless external constraints (e.g., those from the reheating temperature of the universe) are imposed.

[1] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5**, 32 (1967) [JETP Lett. **5**, 24 (1967)].

[2] A. Yu. Ignatiev, N.V. Krasnikov, V. A. Kuzmin, and A. N. Tavkhelidze, Phys. Lett. **76B**, 436 (1978); M. Yoshimura, Phys. Rev. Lett. **41**, 281 (1978).

[3] D. Toussaint, S. B. Treiman, F. Wilczek, and A. Zee, Phys. Rev. D**19**, 1036 (1979); S. Weinberg, Phys. Rev. Lett. **42**, 850 (1979); M. Yoshimura, Phys. Lett. **88B**, 294 (1979).

[4] S. M. Barr, G. Segrè, and H. A. Weldon, Phys. Rev. D **20**, 2494 (1979); D.V. Nanopoulos and S. Weinberg, Phys. Rev. D**20**, 2484 (1979); A. Yildiz and P. Cox, Phys. Rev. D **21**, 906 (1980).

[5] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, Phys. Lett. **155B**, 36 (1985); see also G. 't Hooft, Phys. Rev. Lett. **37**, 8 (1976); Phys. Rev. D**14**, 3432 (1976).

[6] M. Fukugita and T. Yanagida, Phys. Lett. B **174**, 45 (1986).

[7] M. A. Luty, Phys. Rev. D **45**, 455 (1992); M. Plumacher, Nucl. Phys. **B530**, 207 (1998); for reviews of the recent development, see W. Buchmuller and M. Plumacher, Phys. Rep. **320**, 329 (1999); W. Buchmuller and M. Plumacher, hep-ph/0007176.

[8] Y. Fukuda *et al.*, Phys. Rev. Lett. **81**, 1562 (1998); J. Kameda, in *Proceedings of International Cosmic Ray Conference, Hamburg, 2001*, edited by K.-H. Kampert, G. Heinzelmann and C. Spiering (Copernicus Gesellschaft Katlenburg-Lindau, 2001), Vol. 3, p. 1057.

[9] P. Arnold, D. Son, and L. G. Yaffe, Phys. Rev. D **55**, 6264 (1997); see also P. Arnold and L. McLerran, Phys. Rev. D **36**, 581 (1987); A. Ringwald, Phys. Lett. B **201**, 510 (1988); D. Yu. Grigoriev and V. A. Rubakov, Nucl. Phys. **B299**, 67 (1988); S. Yu. Khlebnikov and M. E. Shaposhnikov, Nucl. Phys. **B308**, 885 (1988).

[10] D. Bödeker, G. D. Moore, and K. Rummukainen, Phys. Rev. D **61**, 056003 (2000); G. D. Moore, hep-ph/0009161; G. D. Moore and N. Turok, Phys. Rev. D **56**, 6533 (1997); J. Ambjørn and A. Krasnitz, Nucl. Phys. **B506**, 387 (1997).

[11] M. Fukugita and T. Yanagida, Phys. Rev. D **42**, 1285 (1990); B. A. Campbell, S. Davidson, J. Ellis, and K. A. Olive, Phys. Lett. B **256**, 457 (1991); Astropart. Phys. **1**, 77 (1992).

[12] J. N. Fry, K. A. Olive, and M. S. Turner, Phys. Rev. Lett. **45**, 2074 (1980); Phys. Rev. D **22**, 2977 (1980).

[13] A. Yu. Ignatev, V. A. Kuz'min, and M. E. Shaposhnikov, JETP Lett. **30**, 688 (1979); F. J. Botella and J. Roldan, Phys. Rev. **D44**, 966 (1991); J. Liu and G. Segrè, Phys. Rev. **D48**, 4609 (1993).

[14] S. Yu. Khlebnikov and M. E. Shaposhnikov, Nucl. Phys. **B308**, 885 (1988); J. A. Harvey and M. S. Turner, Phys. Rev. D **42**, 3344 (1990).

[15] L. Baudis *et al.*, Phys. Rev. Lett. **83**, 41 (1999).

[16] W. Hu, M. Fukugita, M. Zaldarriaga, and M. Tegmark, Astrophys. J. **549**, 669 (2001); see also R. A. C. Croft, W. Hu, and R. Davé, Phys. Rev. Lett. **83**, 1092 (1999); M. Fukugita, G.-C. Liu, and N. Sugiyama, Phys. Rev. Lett. **84**, 1082 (2000).