The origin of baryon asymmetry in the universe

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A mechanism for generation of the baryon asymmetry in the universe, which is based on nonconservation of the baryon number, on *CP* noninvariant decay of scalar particles, and on the violation of thermodynamic equilibrium, is developed in the framework of unified gauge theories. It is shown that in the *SO* (10) model the proposed mechanism can explain the observed asymmetry. A modification of the Georgi-Glashow *SU* (5) model, which also explains the asymmetry, is proposed.

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At present, there is no evidence for the existence of antimatter in the universe. The baryon asymmetry in the universe (BAU) is characterized by the quantity $\Delta = (N - \bar{N})/n_\gamma \approx 10^{-8}$–$10^{-10}$,[1] where N, $\bar{N}$, and n_γ are the concentrations of bar-

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yons, antibaryons, and relict photons, respectively. The question of the origin and magnitude of the BAU constitutes one of the key problems of modern cosmology and physics of elementary particles.[1]

In Refs. 2 and 3 an explanation was proposed for the first time for the of BAU as the effect of nonconservation of the baryon number and of *CP* parity on the thermodynamic nonequilibrium in the expansion stage. It should be emphasized that the conditions for nonconservation of *CP* and of the baryon number[2,3] and also the violation of thermodynamic equilibrium[4,5] are necessary for the existence of BAU.

The BAU was examined for the first time in Ref. 6 in the framework of gauge theories with a spontaneous violation of symmetry and at present is investigated comprehensively.[5,7-11]

In this paper work we examine, in terms of the approach in Ref. 6, the unified gauge theories (UGT) of strong, electromagnetic, and weak interactions (with fractionally charged quarks).

We show that the *CP*-noninvariant decays of heavy, scalar, lepton-quark bosons, which are denoted by χ in the thermodynamically nonequilibrium expansion stage, can be the source of BAU.

The BAU, which occurs as a result of the decay of χ particles is[3,6]

$$\Delta = \frac{n_\chi}{n}\,\delta\,, \tag{1}$$

where n_χ/n is the relative concentration of χ at the moment of quenching and δ is the asymmetry due to the *CP*-noninvariant decay of a single-particle state χ, which is described by the *CPT*-invariant density matrix (see Ref. 4).

In general, the amplitudes of the charge-conjugate processes for the decay of χ particles are written in the following way:

$$\begin{aligned} A(\chi \to a_i\, b_i \ldots) &= g_i + \sum_k g'_{ik} A_{ik}\,, \\ A(\bar{\chi} \to \bar{a}_i\, \bar{b}_i \ldots) &= g_i^* + \sum_k g'^{*}_{ik} A_{ik}\,, \end{aligned} \tag{2}$$

where g_{ik} are the values for the corresponding coupling constants and A_{ik} are the values of the radiation corrections for individual coupling constants. From Eq. (2) we obtain

$$\delta = \frac{2\sum\limits_{ik} \operatorname{Im} g_i^* g'_{ik} \operatorname{Im} A_{ik} B_i}{\sum\limits_i g_i g_i^*}\,, \tag{3}$$

where B_i is the total baryon number of the products of the ith channel.

Let us turn now to the occurrence of BAU within the framework of UGT for the $SU(5)$[12] and $SO(10)$[13] groups.

In the $SU(5)$ model for the usual choice of Higgs fields,[12] the effects of *CP* violation in the processes with nonconservation of the baryon number in the post-equilibrium expansion stage produce a rather small BAU. This is attributed to the fact that *CP* violation turns out to be of the eighth order with respect to the Yukawa

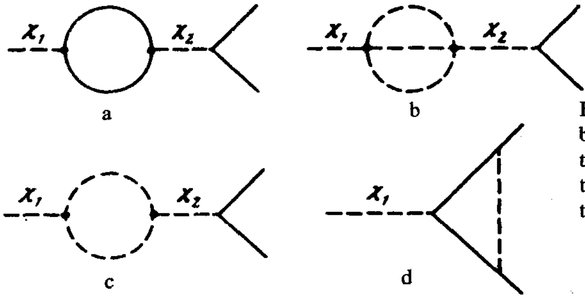

FIG. 1. Diagrams for the decay of scalar bosons into fermions, which contribute to the asymmetry. The broken line represents the scalar bosons and the solid line denotes the fermions.

coupling constant f,[8] so that for decays $\Delta \sim f^8 \sim 10^{-24}$, if $f \sim 10^{-3}$. Thus, the cosmological arguments apparently reject the $SU(5)$ combination with a minimum[12] set of Higgs fields.

We shall show that the expansion of the Higgs sector of the model can give the required value of δ. In fact, we shall examine the $SU(5)$ model with two scalar multiplets 5: χ_1 and χ_2. The Yukawa interaction in such model has the form

$$L = (f_{\alpha\beta}^{(1)} \chi_1^i + f_{\alpha\beta}^{(2)} \chi_2^i) \bar{\xi}_\alpha^{ij} \psi_\beta^j$$
$$+ (g_{\alpha\beta}^{(1)} \chi_1^i + g_{\alpha\beta}^{(2)} \chi_2^i) \epsilon_{ijklm} \bar{\xi}_\alpha^{jk(c)} \xi_\beta^{lm} + \mathrm{H.C.} \tag{4}$$

where ψ and ξ are the fermion multiplets $\underline{5}$ and $\underline{10}$, g and f are the coupling constants, the Latin letters pertain to the $SU(5)$ group, and the Greek letters denote the quark generations.

The contribution to A_{ik} in Eq. (3) comes from the diagrams such as those in Fig. 1. For brevity, we introduce the results for the case when the scalar boson masses are such that the decay of χ_1 and χ_2 to other scalar particles (say, $\underline{24}$) is forbidden. Thus, the imaginary part of the diagrams b and c vanishes, and they do not contribute to δ. Therefore, we have

$$\delta = \frac{1}{16\pi} \Gamma_1^{-1} [a_1 \mathrm{Im}\mathrm{Sp}(f_1^+ f_2) \mathrm{Sp}(g_1 g_2^+) + b_1 \mathrm{Im}\mathrm{Sp}(f_1^+ f_2 g_1 g_2^+)] + (1 \leftrightarrow 2), \tag{5}$$

where $\Gamma_{1,2}$ are the total widths of the χ_1 and χ_2 bosons, respectively, and a and b are certain mass functions of the order of unity.

We shall now turn to the $SO(10)$ model. The structure of the Higgs sector of the $SO(10)$ model is as follows: one or several representations $\underline{10}$, $\underline{120}$, $\underline{126}$ that gives mass to fermions, representation 16 this is responsible for $SU(2)_R$-violation, and also representation $\underline{45}$[16] or $\underline{54}$, that accounts for the mass of the lepton-quark bosons.

The generation of BAU in the $SO(10)$ model can occur in the decays of color bosons that have a Yukawa coupling with fermions ($\underline{10}$, $\underline{120}$, $\underline{126}$) only if the theory contains at least two such representations. In fact, in the opposite case the spur for the generations of fermions for any permissible product of the matrix Yukawa constants turns out to be real. A similar requirement apparently arises in examining the mass equations for fermions.[14]

It can be shown that to obtain a noticeable BAU, super strong violation of $SU(2)_R$ symmetry is necessary. Assuming that the average vacuum of the neutral component of the 16-multiplet is of the order of $v \sim 10^{15}$ GeV, we obtain for the BAU in $SO(10)$ an equation analogous to Eq. (5). We assume that the left-handed neutrino is massless and the right-handed one has a mass $O(v)$ (see, for example, Ref. 16).

Assuming that all the Yukawa coupling constants are of the same order of magnitude for δ in both the $SU(5)$ and $SO(10)$ models, we obtain (for maximum CP violation in the Yukawa interaction):

$$\delta \approx f^2/16\pi. \tag{6}$$

An estimate of the χ concentration at the moment of quenching gives

$$\frac{n_\chi}{n} \sim \frac{N_\chi}{N} \sim 10^{-2},$$

where N_χ is the number of scalar lepton-quarks contributing to the asymmetry and N is the total number of the degree of freedom of all the particles. Finally, we obtain

$$\Delta \approx \frac{f^2}{16\pi} 10^{-2} \sim 10^{-8} \quad \text{for} \quad \frac{f^2}{16\pi} \sim 10^{-6}. \tag{7}$$

Although this is only a rough estimate, the closeness of Eq. (7) to the observed BAU compels us to believe that the proposed picture of the occurrence of baryon charge in the universe generally corresponds to reality.

We note that the value of δ in the decay of vector lepton-quarks in both models turns out to be of the fourth order with respect to the coupling constant f.

Thus, we showed that in terms of UGT using the $SU(5)$ and $SO(10)$ both the existence of BAU and its value can be accounted for. The sign of BAU in such models cannot be predicted, since CP violation in the lepton-quark sector generally is not related to the experimentally observed nonconservation of CP in the decay of neutral kaons. We emphasize that the examined mechanism is valid for the case of symmetry reconstruction at high temperatures.

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