Baryon asymmetry of the universe and violation of the thermodynamic equilibrium

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A possible explanation of the observed abundance of baryons in comparison with antibaryons due to nonconservation of the baryon charge in the elementary-particle interactions is discussed. It is shown that the primary plasma goes out of the equilibrium state, in which the particle density is equal to the antiparticle density, at a much later time, as a result of which the number obtained for the current concentration of baryons in the universe is too small.

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Modern astronomy asserts[1] that the number of baryons in the visible part of the universe is $10^{-9} - 10^{-10}$ that of the relict photons and the antimatter content is negligible. If the baryon charge (B) is strictly conserved, then the abundance of baryons can be attributed either to the "initial" baryon charge of the universe, which is esthetically not very attractive for the hot model, or to the asymmetric absorption of baryons and antibaryons by black holes.[2] In the latter case, which can occur only when the (CP) charge invariance in violated, the black holes have a negative baryon charge which compensates for the observed surplus of baryons.

Below we discuss the alternative possibility of baryon generation in the model of

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the hot universe due to the processes in which conservation of the baryon charge and symmetry are violated relative to the replacement of particles and antiparticles. The hypothesis initially proposed by Sakharov[3] received support in recent years in view of an attempt to formulate a unified theory of strong and weak-electromagnetic interactions.[4] Since in every such scheme of general unification the leptons and quarks are placed in the same multiplet of one symmetry group or another, the baryon charge is not necessarily conserved.

In the papers[5] published recently, the different schemes for baryon generation in the hot universe were discussed. Below we show that in the ideal-gas approximation the generation of the baryon charge starts relatively late when the density of the primary plasma is already too small to yield the observed number of baryons $r = n_B/n_\gamma \approx 10^{-9} - 10^{-10}$.

As is well known,[6] if the initial conditions were sufficiently symmetric, then the equilibrium system should have a zero baryon charge, irrespective of the C and T invariance and conservation of the baryon charge.[1)] Because of this, at the early equilibrium stage of evolution the universe should have had an equal number of baryons and antibaryons. As the universe expanded, the density of the initial plasma n decreased $n \sim t^{-3/2}T^3$, where T is the temperature and t is the time measured from the moment of singularity. Since the rate of the elementary processes is proportional to σn (σ is the cross section of the process) and the rate of expansion of the universe is $\dot{R}/R \sim t^{-1}$, the universe appears to have gone into a nonequilibrium state with increasing time and theoretically can have a nonzero baryon charge. Below we estimate in the ideal-gas approximation the magnitude of the baryon asymmetry. The corrections due to nonideal conditions, which depend on the specific model, will be examined in a more detailed study. We note that in the gauge models the deviation from the ideal condition is $E_{\rm pot}/E_{\rm kin} \sim a < 1$.

First, we examine how the unitarity of the S matrix accounts for the ordinary statistical distributions, independent of the T invariance and the principle of detailed balancing. We assume that there is a gas for simplicity of spinless particles and that there are processes of mutual transformation

$$a_i + b_i + \dots \to a_k + b_k + c_k + \dots \quad (1)$$

Let us examine the time variation of the total number of particles a_i:

$$\dot{N}(a_i) \equiv \frac{d}{dt} \int n(a_i) d^3p = \text{const} \sum_k \int d^4\mathcal{P} d\tau_i \, d\tau_k (\Pi n_k |A_{ki}|^2 - \Pi n_i |A_{ik}|^2), \quad (2)$$

where $\Pi n_k = n(a_k)n(b_k)n(c_k)\dots$; $n(a_k)$ is the momentum distribution function of the particles a_k, $\mathcal{P} = p_a + p_b + \dots$ is the total momentum, $d\tau_i = \delta^4(\mathcal{P} - \Sigma p)\,\Pi(d^3p/2E \times 8\pi^3)$ is an element of the phase volume, and A_{ik} is the amplitude of transition from the i state to the k state. We assume that the Boltzmann momentum distribution is valid, i.e., $n(a_i) = n_0(a_i)\exp\{(\mu_{ai} - E_{ai})/T\}$. The quantum corrections introduce only small technical complications. We can easily see that this distribution is indeed a uniform distribution, i.e., the condition $\dot{N} = 0$ can be fulfilled by substitution in Eq.

(2). In fact, because of conservation of energy and of the chemical potential $\Pi n_i = \Pi n_k$ and equality (2) can be rewritten as follows:

$$\dot{N}(a_i) = \mathrm{const} \int d^4 \mathcal{P} d\tau_i \, \Pi n_i \sum_k \int d\tau_k (|A_{ki}|^2 - |A_{ik}|^2). \tag{3}$$

In the T invariant theory $|A_{ik}|^2 = |A_{ki}|^2$ (principle of detailed balancing) and $\dot{N}(a_i) = 0$. If, however, the T invariance does not hold, then the more general condition is valid:

$$\sum_k \int d\tau_k (|A_{ki}|^2 - |A_{ik}|^2) = 0, \tag{4}$$

which we call the cyclic equilibrium condition and which also ensures the equality $\dot{N}(a_i) = 0$.

In the equilibrium state the chemical potential of the baryons, which is equal to that of the antibaryons, is equal to zero. This is attributable to "balancing" of the chemical potentials in reactions with nonconservation of B. Since the uniform distributions are determined, apart from the temperature, by the mass and the chemical potential of the given particles, as noted above, there is no surplus of baryons above the antibaryons. Let us examine the nonequilibrium case. Let us assume that nonconservation of the baryon charge is due to the reaction.

$$qq \to \bar{q} l, \tag{5}$$

where q are the quarks and l is the lepton. As the universe expands, the first to lose equilibrium are the slowest processes; therefore, when reaction (5) becomes a nonequilibrium reaction, the other reactions produced by the usual strong and weak interactions, in which q and l participate, are still in the equilibrium state. Because of this, the distribution function of the quarks, for example, has the form:

$$n(q) \sim \exp\{[\mu_q(t) - E]/T\} \tag{6}$$

and analogously for $\bar{q}$ and l. The nonequilibrium reaction (5) now can render the equality $2\mu_q = \mu_{\bar{q}} + \mu_e$ invalid. If, however, at zero time the condition $\mu_q = \mu_{\bar{q}} = 0$, which provides an equal number of quarks and antiquarks, exists, then the equality will be valid even after reaction (5) goes out of equilibrium. This condition remains valid as long as faster processes than (5), which ensure the canonical distribution (6), are in equilibrium. In fact, if $\mu_q(t=0) = 0$, then, according to Eq. (3) at small t's [and hence small $\mu(t)$'s], the time derivative of the total number of quarks is $\dot{N}(q) \sim \mu$. On the other hand, $\Delta N = N(q) - N(\bar{q}) \sim \mu$. It follows from this that $\Delta \dot{N} \sim \Delta N$. The unique solution of this equation is such that $\Delta N(t=0) = 0$ is $\Delta N \equiv 0$. Thus, the generation of the baryon charge due to reaction (5), rather than starting at the time this reaction goes out of equilibrium, starts much later when all of the processes, in which at least one type of the particles for reaction (5) participates, go out of equilibrium. In our example, the generation of the baryon charge starts when the temperature of the quarks is different from that of the leptons. At this time, however, the concentration of leptons[7] and/or quarks[8] in the universe is too small to account for the ratio

$r(B) = 10^{-9} - 10^{-10}$ observed today. The generation of the baryon charge starts sufficiently early when the concentrations of the particles participating in the reaction are still high, provided that at least one of the particles is almost sterile, i.e., it does not participate neither in the strong nor in the electromagnetic-weak interaction, as a result of which all the processes involving it go out of equilibrium early.

We obtained the following estimate for $r(B)$:

$$r(B) = r_H \, \Delta\sigma / \sigma_{min} \,, \qquad (7)$$

where $\Delta\sigma - C(CP)$ is the odd part of the reaction cross section with non-conservation of B, $\sigma_{\min}$ is the smallest *total* interaction cross section of the particles that participate in this reaction, and r_H is the concentration of the heavy particles (i.e., those particles for which $m_H > T$), if they participate in the reaction. It is important to note that all the processes of the right-hand side of the equation (7) are determined at the time the processes with the cross section $\sigma_{\min}$ go out of equilibrium, i.e., $\sigma_{\min} nt \approx 1$. Since $\sigma_{\min}$ is the typical weak cross section for reaction (5), the generation of the baryon charge begins at $T \leqslant m_e/20$,[7] which yields a very small value of $r(B)$. In conclusion, we note that, in virtue of the assumptions made above, the estimates of Ref. 5 must be much smaller than those quoted. In particular, this apparently rules out the $SU(5)$ group as the group that unites the strong and weak-electromagnetic interactions.

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[1)]This is a corollary of such general principles as *CPT* invariance and *S*-matrix unitarity.

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