Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

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Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

Literal translation: *Out of S. Okubo's effect*
At high temperature
A fur coat is sewed for the Universe
Shaped for its crooked figure.

The theory of the expanding universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the universe is asymmetrical with respect to the number of particles and antiparticles (*C* asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a nonzero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of *C* asymmetry in the hot model of the expanding universe (see Ref. 1) by making use of effects of *CP* invariance violation (see Ref. 2). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

We assume that the baryon and muon conservation laws are not absolute and should be unified into a "combined" baryon-muon charge $n_c = 3n_B - n_\mu$. We put

for antimuons μ_+ and $\nu_\mu = \mu_0 : n_\mu = -1,\ n_K = +1$.

for muons μ_- and $\nu_\mu = \mu_0 : n_\mu = +1,\ n_K = -1$.

for baryons P and N: $n_B = +1,\ n_K = +3$.

for antibaryons $\bar{P}$ and $\bar{N}$: $n_B = -1,\ n_K = -3$.

This form of notation is connected with the quark concept; we ascribe to the p, n, and λ quarks $n_c = +1$, and to antiquarks, $n_c = -1$. The theory proposes that under laboratory conditions processes involving violation of n_B and n_μ play a negligible role, but they were very important during the earlier stage of the expansion of the universe.

We assume that the universe is neutral with respect to the conserved charges (lepton, electric, and combined), but *C* asymmetrical during the given instant of its development (the positive lepton charge is concentrated in the electrons and the negative lepton charge in the excess of antineutrinos over the neutrinos; the positive electric charge is concentrated in the protons and the negative in the electrons; the positive combined charge is concentrated in the baryons, and the negative in the excess of μ neutrinos over μ antineutrinos).

According to our hypothesis, the occurrence of *C* asymmetry is the consequence of violation of *CP* invariance in the nonstationary expansion of the hot universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions. This effect has not yet been observed experimentally, but its existence is theoretically undisputed (the first concrete example, Σ_+ and $\bar{\Sigma}_-$ decay, was pointed out by S. Okubo as early as 1958) and should, in our opinion, have much cosmological significance.

We assume that the asymmetry has occurred in an earlier stage of the expansion, in which the particle, energy, and entropy densities, the Hubble constant, and the temperatures were of the order of unity in gravitational units (in conventional units the particle and energy densities were $n \sim 10^{98}\ \mathrm{cm}^{-3}$ and $\varepsilon \sim 10^{114}\ \mathrm{erg/cm}^3$).

M. A. Markov (see Ref. 3) proposed that during the early stages there existed particles with maximum mass of the order of one gravitational unit ($M_0 = 2\times 10^{-5}$ g in ordinary units), and called them maximons. The presence of such particles leads unavoidably to strong violation of thermodynamic equilibrium. We can visualize that neutral spinless maximons (or photons) are produced at $t < 0$ from contracting matter having an excess of antiquarks, that they pass "one through the other" at the instant $t = 0$ when the density is infinite, and decay with an excess of quarks when $t > 0$, realizing total *CPT* symmetry of the universe. All the phenomena at $t < 0$ are assumed in this hypothesis to be *CPT* reflections of the phenomena at $t > 0$. We note that in the cold model *CPT* reflection is impossible and only *T* and *TP* reflections are kinematically possible. *TP* reflection was considered by Milne, and *T* reflection by the author; according to modern notions, such a reflection is dynamically impossible because of violation of *TP* and *T* invariance.

We regard maximons as particles whose energy per particle ε/n depends implicitly on the average particle density n. If we assume that $\varepsilon/n \sim n^{-1/3}$, then ε/n is proportional to the interaction energy of two "neighboring" maximons $(\varepsilon/n)^2 n^{1/3}$ (cf. the arguments in Ref. 4). Then $\varepsilon \sim n^{2/3}$ and

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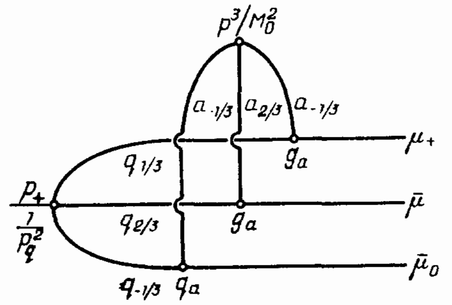

FIG. 1.

$R_0^0 \sim (\varepsilon + 3p) = 0$, i.e., the average distance between maximons is $n^{-1/3} \sim t$. Such dynamics are in good agreement with the concept of *CPT* reflection at the point $t = 0$.

We are unable at present to estimate theoretically the magnitude of the C asymmetry, which apparently (for the neutrino) amounts to about $(\bar{\nu} - \nu)/(\bar{\nu} + \nu) \sim 10^{-8} - 10^{-10}$.

The strong violation of the baryon charge during the superdense state and the fact that the baryons are stable in practice do not contradict each other. Let us consider a concrete model. We introduce interactions of two types.

1. An interaction between the quark-muon transformation current and the vector boson field $a_{i\alpha}$, to which we ascribe a fractional electric charge $\alpha = \pm 1/3$, $\pm 2/3$, $\pm 4/3$, and a mass $m_a \sim (10 - 10^3) m_p$. This interaction produces reactions $q \to a + \bar{\mu}$, $q + \mu \to a$, etc. The interaction of the first type conserves the fractional part of the electric charge and therefore the actual number of quarks minus the number of antiquarks ($= 3n_B$) is conserved in processes that include the a boson only virtually.

We estimate the constant of this interaction at $g_a = 137^{-3/2}$, from the following considerations: The vector interaction of the a boson with the μ neutrino leads to the presence of a certain rest mass in the latter. The upper bound of the mass μ_0 is estimated in Ref. 5 on the basis of cosmological considerations. If we assume a flat cosmological model of the universe and assume that the greater part of its density $\rho \sim 1.2 \times 10^{-29}$ g/cm^3 should be ascribed to μ_0, then the rest mass of μ_0 is close to 30 eV. The given value of g_a follows then from the hypothetical formula

$$\frac{m_{\mu_0}}{m_e} = \frac{g_a^2}{e^2} \sim (137)^{-2}.$$

We note that the presence in the universe of a large number of μ_0 with finite rest mass should lead to a number of very important cosmological consequences.

2. The baryon charge is violated if the interaction described in item 1 is supplemented with a three-boson interaction leading to virtual processes of the type $a_{\alpha_1} + a_{\alpha_2} + a_{\alpha_3} \to 0$. According to B. L. Ioffe, I. Yu. Kobzarev, and L. B. Okun', the Lagrangian of this interaction is assumed to be dependent on the derivatives of the a field, for example,

$$L_2 = g_2(\sum_a f_k^i f_j^k f_i^j + \text{h.c.}), \quad f_{ik} = \text{Rot}\, a_i.$$

Inasmuch as $\mathscr{L}_2$ vanishes when two tensors coincide, in this concrete form of the theory we should assume the presence of several types of a fields. Assuming $g_2 = 1/M_0^2$ and $M_0 = 2 \times 10^{-5}$ g, we have strong interaction at $n \sim 10^{98}$ cm^{-3} and very weak interaction under laboratory conditions. Figure 1 shows a proton-decay diagram including three vertices of the first type, one vertex of the second, and the vertex of proton decay into quarks, which we assume to contain the factor $1/p_q^2$ (due, for example, to the propagator of the "diquark" boson binding the quarks in the baryon). Cutting off the logarithmic divergence at $p_q = M_0$, we find the decay probability

$$\omega \sim \frac{m_p^5 g_a^6 [\ln(M_0/m_a)]^2}{M_0^4}.$$

The lifetime of the proton turns out to be very large (more than 10^{50} years), albeit finite.

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