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BARYON ASYMMETRY OF THE UNIVERSE

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Baryon asymmetry of the Universe

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A possible process of the appearance of baryon and anti-lepton excess at the early stage of the charge-neutral hot Universe expansion in the unified gauge theory of strong, weak and electromagnetic interactions is discussed. By the estimate presented here the baryon asymmetry $A = \frac{N_B}{N_\gamma}$ (the ratio of the mean baryon density to the relic radiation quantum density, to an accuracy of the numerical factor equal to the ratio of the number of baryons to the initial entropy of the hot Universe, in the same co-moving volume) is equal, in the order of magnitude to $A \sim \alpha^3 \eta^3 \delta_a$. The value $\alpha = g^2$ is the gauge field interaction constant, η is the quantity of the order of the Cabibbo angle, δ_a is the phase of complex quark mixing. The numerical coefficient in this formula may contain an additional small parameter. Some considerations are expressed concerning the many-sheet model of the Universe suggested before by the author.

1. Introduction. Estimation of the effect.

In 1966 the author expressed the supposition that the observed baryon (and supposed lepton) asymmetry of the Universe appears at the early stage of cosmological expansion from the initial neutral charge state. Such a process is possible due to the effects of CP-invariance violation in non-stationary conditions of expansion if the baryon and lepton charge conservation is supposed to be broken [1].

In 1978 an analogous idea was formulated independently by Yoshimura [2] who showed that in unified gauge-field theories of strong, weak and electromagnetic interactions (see ref.[3]) the baryon charge conservation is broken due to interactions in the presence of a "quark-lepton" boson and that in combination with CP-invariance breaking a residual baryon charge inevitably appears at early stages of hot Universe expansion. Yoshimura pointed out the possibility of quantitative calculation of this effect by perturbation theory methods. When working at the present paper the author also got acquainted with the paper by Dimopoulos and Susskind [4] devoted to the same question.

The estimate of the baryon asymmetry effect is presented below. It is close to the one suggested in ref.[4] but has been obtained from a more detailed consideration of the kinetics of mutual transformation of particles and has not used the assumption that the quark-lepton boson mass is equal by the order of magnitude to the Planck unit mass $M_0 = 10^{19}$ Gev. Some considerations concerning the "many-sheet Universe model" suggested before by the present author are expressed in Sec.5.

The other sections contain considerations concerning the estimate of baryon and lepton asymmetry. Let us briefly summarize the basic points of this considerations.

Deviations from symmetry between particles and antiparticles appear only due to the nonstationarity caused by the Universe expansion.

We designate the densities of different types particles by n_i . Equilibrium values of the densities are labeled by n_i^0 , then the deviation from the equilibrium state is characterized by the ratio $\frac{n_i'}{n_i^0}$, where $n_i' = n_i - n_i^0$.

The quantity $\frac{n_i'}{n_i^0}$ is equal to HT by the order of magnitude. T is the characteristic time of mutual particle transformation, and H is the "Hubble parameter" characterizing the dynamics of the Universe expansion; H is a logarithmic derivative of the "scale", the linear dimension of an arbitrary "co-moving" volume element

$$H = \frac{1}{a} \frac{da}{dt} = \left(\frac{8\pi}{3} G \rho \right)^{1/2}, \quad (1)$$

where ρ is the energy density, G is the gravitation constant. Here and below we assume $c = \hbar = k = 1$. $H \sim \frac{1}{t}$, where t is the "age of the Universe". Thus,

$$\frac{n_i'}{n_i^0} \sim \frac{T}{t} \quad (2)$$

(for the main processes of particle transformation) At the early stage of the Universe expansion $\sqrt{t} \sim \frac{1}{n_i^0} \sim a^2$, if $\rho \sim t^{-2}$

and $a \sim t^{1/2}$, i.e. relative deviations from the equilibrium state $\frac{n_i'}{n_i^0}$ are small and tend to zero at $t \rightarrow 0$. Essential for the appearance of asymmetry is the period Δt_c of the Universe expansion, when the temperature is of the order of the mass M_c of the quark-lepton vector boson W_c which plays a decisive role (Sec. 2, refs. [2,3]) in violation of the baryon and lepton numbers

$$T_c \sim M_c$$

This temperature corresponds to the characteristic particle

density $n_c^0 \sim M_c^3$, to the characteristic energy density $g_c \sim M_c^4$, and according to formula (1) to the characteristic age of the Universe $t_c \sim H_c^{-1} \sim G^{-1/2} M_c^{-2}$, as well as to the characteristic duration of the process under consideration

$$\Delta t_c \sim t_c$$

Breaking of CP- and T-symmetry leads to the fact the probabilities of mutual particle transformation are generally speaking different for direct and reverse reactions (even in a stationary state), and are also different when particles are replaced by antiparticles. We designate the probabilities of transitions between the states i and f by ω_{if} and for CP-conjugate states by $\omega_{\bar{i}\bar{f}}$, we designate

$$\omega_{if} = S_{if} + a_{if}; \quad \omega_{\bar{i}\bar{f}} = S_{if} - a_{if} \quad (3)$$

From CPT-invariance it follows that the sum over all finite states f for any initial state i is

$$\sum_f a_{if} = 0 \quad (4)$$

The condition (4) along with T-symmetry of the probabilities

S_{if} and equality between particle and antiparticle masses provides CP-symmetry of an equilibrium stationary state

($n_i^0 = \bar{n}_i^0$, $\frac{dn_i}{dt} = 0$). But in a nonstationary state $n_i \neq \bar{n}_i$. Designating $n' = n^{is} + n^{ia}$; $\bar{n}' = n^{is} - n^{ia}$ we have the estimate by the order of magnitude (Sec.3)

$$n^{ia} = \frac{a^*}{\lambda} n' \quad (5)$$

λ is the term in the probability of the reaction of mutual

particle transformation which does not depend on replacement of particles by antiparticles, and a^* is the asymmetric term of this probability (formula (3)). The sign $*$ at a^* is used not to mix it up with the scale a). The quantity τ in formula (2) $\sim \frac{1}{\lambda}$, i.e.

$$n^{1a} \sim \frac{a^* n^0}{\lambda^2 \Delta t} \quad (6)$$

In Sec. 4 for a simplified model of the theory the following estimations have been made; $\lambda \sim \alpha M_c$,

$d^* \sim \alpha^3 g^3 \delta_a M_c$, where $\alpha = g^2$ is the gauge field interaction constant, g is the quantity of the order of the Cabibbo angles. The quantity δ_a is the phase of complex mixing of quark states. Using $n_c^0 \sim M_c^3$, we obtain the estimate

$$n^{1a} \sim \frac{\alpha g^3 \delta_a M_c^2}{\Delta t} \quad (7)$$

The residual baryon and lepton charges appear as a result of reactions with the participation of a quark-lepton boson (four-boson reactions in Sec. 2 (13 R and R')). Their probability $\omega \sim \alpha^4 M_c$. Integrating over time (formula (15)) we find the residual baryon (or lepton) charges in the co-moving volume $[a(t)]^3$. The factor Δt appears under integration

$$N_B = a^3 n_B \sim \omega n^{1a} a^3 \Delta t \sim \alpha^3 g^3 \delta_a M_c^3 a^3 \quad (8)$$

The number of particles in the co-moving volume, which is equal by the order of magnitude to the number of quantat in relic radiation, is $n^0 a^3 \sim M_c^3 a^3$. The baryon asymmetry

is equal by the order of magnitude to

$$A = \frac{N_B}{N_f} \sim \alpha^3 v^3 \delta_a \quad (9)$$

The lepton asymmetry is to be of the same order of magnitude. Supposing the total number of leptons and quarks is conserved (see Sec.2), $N_{\bar{L}} - N_L = 3N_B$

There are no methods at present to verify this relation.

2. Violation of baryon and lepton charge conservation.

Unified theory of strong, weak and electromagnetic interactions postulates the existence of the so-called "quark-lepton" vector boson, the emission and absorption of which transforms quarks into leptons and vice versa.

Restricting ourselves to the theories in which an exact "coloured" symmetry and fractional electric charge for quarks are postulated, we ascribe a fractional electric charge to the quark-lepton boson too. The following designations are used below:

W_c is a quark-lepton boson with the charge $-1/3$ and also with any charge differing from it by an integral number (if electron is assumed to be a "particle", these charges are $2/3$ and $5/3$).

$\bar{W}_c$ is a quark-lepton boson with the charge $+1/3$ and also with the charge differing from it by an integral number.

W_c and $\bar{W}_c$ interact with quarks q and leptons l ($\bar{q}$ and $\bar{l}$ are antiquarks and antileptons) as follows

$$\begin{aligned} W_c &\leftrightarrow q + \bar{l} \\ \bar{W}_c &\leftrightarrow \bar{q} + l \end{aligned} \quad (10)$$

In the majority of unified theories there exist besides (10) three more types of reactions ("vertices") leading to the breaking of baryon charge conservation:

$$\begin{aligned} W_c &\leftrightarrow \bar{q} + \bar{q} \\ \bar{W}_c &\leftrightarrow q + q \end{aligned} \quad (11)$$

three-boson interaction (reaction off the mass shell)

$$\begin{aligned} W_c + W_c + W_c &\leftrightarrow \text{vacuum} \\ \bar{W}_c + \bar{W}_c + \bar{W}_c &\leftrightarrow \text{vacuum} \end{aligned} \quad (12)$$

and four-boson interaction with the participation of three W_c (admitting reaction on the mass shell)

$$\begin{aligned} \bar{W}_c + \bar{W}_c &\leftrightarrow W_c + R & (13R) \\ \bar{W}_c + R &\leftrightarrow W_c + W_c & (13R') \end{aligned} \quad (13)$$

Here R is a "usual" vector boson of weak interactions $W_{\pm}$ or another gauge boson with zero or integral charge.

Fig. 1 and Fig. 2 are diagrams of proton decay with the vertex (11) ($P \rightarrow \pi + \ell$) and the vertex (12) ($P \rightarrow 3\ell$). An analogous decay with the vertex (13) is $P \rightarrow 3\ell + W_{\pm}$. The three-boson vertex (12) was postulated in ref. [1]. In the gauge field theory with nonabelian gauge the three-boson and four-boson interactions (12) and (13) follow from the basic principles!

Models are possible where interactions of the type (11) are absent and there arises an additional exact conservation law for the summary number of quarks and leptons (combined charge N_0)

$$N_0 = N_q + N_\ell - N_{\bar{q}} - N_{\bar{\ell}} \quad (14)$$

Such models seem to be preferable. Even at not very large masses W_c the proton in such models has a long lifetime, which according to experiment exceeds 10^{30} years (see ref [5]). The estimate (omitting numerical coefficients which may be essential) for the process illustrated by Fig.1 makes up

$$\tau_1^{-1} = \left(\frac{\alpha}{\pi}\right)^2 \left(\frac{M_p}{M_c}\right)^4 M_p \quad \begin{array}{l} (M_p \text{ is the proton mass,} \\ M_c \text{ is the mass of the quark-lepton boson } W_c) \end{array}$$

and for the process shown in Fig.2 $\tau_2^{-1} = \left(\frac{\alpha}{\pi}\right)^4 \left(\frac{M_p}{M_c}\right)^{12} M_p$

The former formula requires $M_c > 10^{14} M_p$, and the latter one $M_c > 3 \cdot 10^4 M_p$.

Introduce an approximate quantum number

$$Z = \frac{1}{2} (N_q + N_{\bar{\ell}} - N_{\bar{q}} - N_\ell) + N_{W_c} - N_{W_{\bar{c}}}$$

It is easily seen that when (11) is assumed to be absent (and thus the lepton and baryon charges) is violated only by the reactions (12) and (13).

Under this assumption the following formula for the estimation of the residual baryon charge in the co-moving volume

$[a(t)]^3$ holds:

$$N_B = \int_0^\infty dt a^3 \left\{ \frac{1}{2} \sum_{ij} (\langle \dot{v} \rangle) (\bar{n}_i \bar{n}_j - n_i n_j) + \sum_i (\langle \dot{v} \rangle) (\bar{n}_i - n_i) n_R \right\} \quad (15)$$

Here n_i and $\bar{n}_i$ are the densities of W_i and $\bar{W}_i$ of three different types (with the charge $\mp \frac{1}{3}, \pm \frac{2}{3}, \pm \frac{5}{3}$); $(\langle \dot{v} \rangle)$, $(\langle \dot{v} \rangle)$ are the mean values of the product of the relative velocity of colliding particles to the cross-section of the reactions (13 R), (13 R'), n_R is the density of bosons other than W_i and $\bar{W}_i$. To find n_i it is necessary to solve kinetic equations.

3. Kinetic equations

At the early stage of Universe expansion the deviations from equilibrium are small

$$n_j^1 = n_j - n_j^0 \ll n_j^0$$

Let us write linearized kinetic equations in the following estimative form (a more exact set of integral equations can be written for spherically-symmetric functions of density $n_j^1(p)$ in the momentum space).

$$(S_{ij} + A_{ij}) n_j^1 = m_i; \quad m_i = \frac{1}{a^3} \frac{d}{dt} (a^3 n_i) \quad (16)$$

It is assumed that the matrix S_{ij} does not change under replacement of particles by antiparticles, and the matrix A_{ij} changes the sign. Neglecting in the expression for m_i the difference between n_i and n_i^0 we obtain for n_j^1 a set of linear algebraic equations (with the known right-hand side $m_i^0 = \frac{1}{a^3} \frac{d}{dt} (a^3 n_i^0)$). Note that (although it is essential only for more accurate

calculations than ours) that the matrices in A , S , $A+S$ are singular (their determinant is zero) since in the vector space there exists "specific" direction leaving the right-hand side of (16) equal to zero. This specific direction corresponds to the temperature variation of equilibrium

$$\delta n_j^1 = \frac{\partial n_j^0}{\partial T} \delta T$$

The unit vector of this direction is

$$e_j^0 \sim \delta n_j^1$$

Introduce a complete set of orthogonal unit vectors e_j^α $e_j^\alpha e_j^\beta = \delta_{\alpha\beta}$ and go over to a new co-ordinate system

$$n_\alpha = e_j^\alpha n_j^1$$

The coefficient η_0 is not determined by equation (16) but that is not essential since e^0 is invariant under replacement of particles by antiparticles. It is sufficient to find the component n_1 orthogonal to e^0 . The matrices in the space orthogonal to e^0

$$\tilde{S}_{\alpha\beta} + \tilde{A}_{\alpha\beta} = e_i^\alpha (S_{ik} + A_{ik}) e_k^\beta \quad (\alpha, \beta \neq 0) \quad (17)$$

are not singular. With the account taken of $A \ll S$ the inverse matrix is equal to

$$Q^{-1} = (\tilde{S} + \tilde{A})^{-1} = \tilde{S}^{-1} + P; \quad P = -\tilde{S}^{-1} \tilde{A} \tilde{S}^{-1} \quad (18)$$

Assuming $n^1 = n^{1s} + n^{1a}$; $\bar{n}^1 = n^{1s} - n^{1a}$ we have

$$n_j^{1a} = e_j^\alpha P_{\alpha\beta} e_k^\beta m_k^0 \quad (19)$$

The elements of the matrices S and A are estimated for a

simplified model of the theory.

4. A model of the theory

Let n_1, n_2, n_3 be the densities of three types of the quark-lepton bosons W_c with charges $-1/3, 2/3, 5/3$; $\bar{n}_1, \bar{n}_2, \bar{n}_3$ the densities of $\bar{W}_c$.

We take the masses of different types of bosons to be different with the mass difference $\sim M_c (\Delta M_c \sim M_c)$. A large mass difference of strange and charmed quarks $\Delta m_q \sim m_q$ will make such an assumption more probable by analogy. Bosons W_c of different types are mutually transformed in the course of reactions

Fig.3 a presents a typical diagram of this process. The symmetric part of the cross-section is of the order of

$$\sigma_{12}^s \sim \frac{\alpha^2}{M_c^2}$$

Taking into account that ~~the~~ the density of leptons, quarks (and any other particles) in the critical phase of the order of M_c^3 and the relative particle velocity ~ 1 , we find $S_{12} \sim \alpha^2 M_c$ ^{LS} To be more concrete the mechanism of CP-invariance breaking we follow the work by Kobayashi and Maskawa [6]. These authors have found that when the Cabibbo mixing schemes are extended to three or more mixing states in the presence of complex mixing matrices, there appear CP-invariance breaking effects. Consider mixing of three doublets of quarks. The states $\begin{pmatrix} p_1 & p_2 & p_3 \\ n_1 & n_2 & n_3 \end{pmatrix}$ by definition are diagonal for the mass operator.

The states $\begin{pmatrix} P_1 & P_2 & P_3 \\ N_1 & N_2 & N_3 \end{pmatrix}$ enter in the expression for quark and quark-lepton currents. The states P, N and p, n are connected by the unitary transformations $P = U_P$, $N = U_N n$. Lepton mixing may be described by analogous matrices, but we shall assume for definiteness that $U_e = U_{2e} = 1$. If quark-lepton currents are disregarded, U_1 and U_2 enter only in the combinations $U_1^{-1} U_2$. The asymmetric part of the cross-section is conditioned by the interference of contributions from the diagrams of the type (3a) and (3b) different in phase

$$\begin{array}{ll} \delta_S + \delta_a & \text{for particles} \\ \delta_S - \delta_a & \text{for antiparticles} \end{array}$$

The effect is proportional to

$$\cos(\delta_S - \delta_a) - \cos(\delta_S + \delta_a) = 2 \sin \delta_S \sin \delta_a$$

The phase $\delta_S = \frac{\pi}{2}$ according to the Feynman rules.

The phase δ_a is a parameter of the theory independent of the choice of quark and lepton state phases.

The estimate of the asymmetric part of the cross-section by the order of magnitude is as follows

$$\sigma_{12}^a \sim \sin \delta_a \frac{|M_a| |M_b|}{M_c^2}$$

M_a , M_b are the contributions to the amplitude from the diagrams of the type (3a) and (3b). $|M_a| \sim \alpha$, $|M_b| \sim \alpha^2 g^3$ (three vertices with change of type of particles). Taking into account that $A_{12} \sim g^0 \sigma_{12}^a$ we have $A_{12} \sim M_c \alpha^3 g^3$.

The mechanism proposed by Kobayashi and Maskawa is uneffective if the energies of quarks are ultra-relativistic. Consequently our estimate is correct only if quarks with the masses of the order M_c exist. For the known now light quarks an additional smallness parameter of the type $C' = \frac{M_a^2}{M_c^2}$ may appear.

. The probability of reactions $W_C \rightarrow q + \bar{l}$
 is of the order of $\propto M_C$.
 (S_{14}, S_{24}, S_{34})

The probability of four-boson reactions ($13R$) ($13R'$)
 is of the order $W_R \sim \alpha^2 M_C$.

In the general case if the masses, the probabilities of
 decays and reactions R for all the three types of W_C do
 not coincide, n^{1a} are determined by the order of mag-
 nitude by formulae (19), (18), (16)

$$n_{1,2,3}^{1a} \sim P m^0 \quad P \sim \frac{A_{12}}{(S_{14})^2} \quad m^0 \sim \frac{n_C}{\Delta t_C}$$

whence $n_{1,2,3}^{1a} \sim \frac{\alpha^3 \delta_a^3 M_C^2}{\Delta t_C}$

N_B is determined by the order of magnitude under the
 same assumptions by formula (15)

$$N_B \sim \alpha_C^3 n_{1,2,3}^{1a} W_R \Delta t_C \sim \alpha_C^3 n_C^0 \alpha^3 \delta_a^3 \quad (20)$$

i.e. $A = \frac{N_B}{N_f} \sim \alpha^3 \delta_a^3$

However if the mass difference for the bosons ΔM is
 less than the masses themselves, there appears a new small
 parameter $C(M_{C1}, M_{C2}, M_{C3})$. The quantity N_B vanishes
 when $\underbrace{\text{two}}_{\text{masses}}$ of the three types of quark-lepton bosons are equal.

Let, for example, $M_1 = M_2 \neq M_3$. We have automatically

$$m_1^0 = m_2^0 \neq m_3^0 \quad (\text{remember that } m_i^0 \sim \frac{1}{2M_C} (\alpha^3 n_i^0))$$

is the right-hand side of Eq. (16). The number of asymmetric
 transitions from state 1 into state 3 is equal to that from
 state 3 to state 2. The number of symmetric transitions
 from state 3 into states 2 and 1 are also equal, and the num-
 ber of symmetric transitions between states 2 and 1 is zero.

We have

$$n_1^{15} = n_2^{15} \neq n_3^{15}$$

$$n_1^{1a} = -n_2^{1a}; \quad n_3^{1a} = 0$$

Assume in addition that all probabilities of the transitions from states 1 and 2 to other states, including the cross-section of the reaction (13), which change the baryon and lepton charges, are equal.

We find $N_B = 0$ at $M_1 = M_2 \neq M_3$. An example of the C function, which possesses such properties and is $\neq$ symmetric with respect to its arguments, is

$$C = \frac{(M_1 - M_2)^2 (M_2 - M_3)^2 (M_3 - M_1)^2}{M_1^6 + M_2^6 + M_3^6} \quad (21)$$

Finally we get

$$A = \alpha^3 \nu^3 \delta_a C(M_1, M_2, M_3) \quad (22)$$

where C is a function of the type (21).

5. Many-sheet model of the Universe.

In 1969 the present author included an assumption of the Universe neutrality with respect to strictly conserved charges, for which he considered an electric and "combined" lepton-baryon charge (of the type of N_0 in formula (14) of the present paper), into his cosmological hypothesis of the "manysheet Universe" [7]. Another assumption of the hypothesis is plane spatial metric on the average in large scales, i.e. an

infinite radius of the Universe curvature. These two assumptions make possible an infinite repetition of cosmological cycles of expansion - contractions of a pulsing Universe with statistical characteristics repeated from cycle to cycle. Then entropy increases monotonously in any co-moving volume according to the second law of thermodynamics, but the entropy increase from cycle to cycle has no physical meaning, it can be eliminated by re-scaling on a singular hypersurface $t=t_0$, $\alpha(t_0) = 0$. Under this rescaling no changes in the density of exactly conserved charges (electric and combined baryon-lepton ones) as well as in the integral space curvature occur since these quantities are assumed to be zero.

Non-invariant charges (the numbers of baryons and leptons) change in any co-moving volume, but their ratio to the entropy and absolute values in rescaled co-moving volume are assumed to be the same at the corresponding moments of the age of the Universe in each cycle.

A dynamical reason for transition of the plane Universe from expansion to contraction may be, in particular, ^{the presence of} the cosmological constant of the corresponding sign ^{and} arbitrarily small in magnitude ($\xi < 0$, $p = |\xi| > 0$, $\xi + 3p > 0$). Black holes ^(in 14 [2]) formation was considered as a dynamical mechanism.

Note by the way that the repetition of statistical characteristics could be an important heuristic requirement determining initial inhomogeneities in the entropy density, in metric and in angular momentum density distribution, as well as other statistical parameters of the model.

6. Conclusions

So, for a certain model of the theory the following estimate of the baryon asymmetry

$$A = \frac{N_b}{N_r} \sim \mathcal{L}^3 \mathcal{D}^3 \delta_a \cdot C(M_1, M_2, M_3)$$

is obtained (the lepton asymmetry is of the same order magnitude). Our calculation contains too many uncertainties so we

can't speak of coincidence with the experiment which gives the value $A \sim 10^{-8} - 10^{-9}$ but it does not contradict it.

For example, setting $\mathcal{L} = 10^{-2}$, $\mathcal{D} = 0.5$, $\delta_a = 10^{-1}$, $C = 10^{-2}$, we obtain $A = 10^{-10}$.

This estimate is correct only if quarks with the masses $\sim M_c$ exist.

The result obtained in this paper does not depend on the dimensionless parameter $K = \frac{1}{M_c G^{1/2}}$ which determines the relation of the duration of the period $\Delta t \sim \frac{1}{G^{1/2} M_c^2}$ "essential" for the process under consideration to the characteristic time of reactions of mutual particle transformation $\tau \sim \frac{1}{\mathcal{L} M_c}$; $\Delta t / \tau \sim \mathcal{L} K$. In ref. 2 the formula other than ours was obtained according to which the baryon asymmetry

$A \sim K$, i.e. proportional to the duration of the essential period Δt . However, this result contradicts the absence of CP-symmetry breaking in stationary state. As shown in our paper (Sec.3) small deviations from equilibrium and thus from CP-symmetry are proportional to $\frac{1}{K}$. Integration over time leads to the disappearance of the K-dependence. In ref. [4] it is assumed from the very beginning that $K \sim 1$, and thus the dependence on this parameter is not established.

Sec.5 presents the considerations of the necessity to assume the neutrality of the Universe for the "many-sheet

model of the Universe" with statistical characteristics repeated from cycle to cycle.

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Fig 1

Fig 2

Fig 3a

Fig 3b

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