quency. We note that in the absence of a field the metric (40) describes a gravitational wave of zero frequency near a linear source with a definite mass density (43) and in vacuum (44), as proved in Ref. 5.

In the presence of a massless scalar field, the metric (40) takes the form

$$dS^2=-dx^2\pm\ln(x/a)x^{2p_1}dx_2^2-2x^{2p_1}dx_1dx_2-x^{2p_3}dy^2, \tag{45}$$

$$p_1=\frac{1\pm(1-3|\varphi_0|^2)^{1/2}}{3}, \quad p_3=\frac{1\mp2(1-3|\varphi_0|^2)^{1/2}}{3}, \quad \varphi=\varphi_0\ln x. \tag{46}$$

For a massive scalar field, Eqs. (45) and (46) are the asymptotic expressions for the metric at small x. At large x we have (45) with $(p_1, p_3)=(2/3, -1/3)$ or $(0, 1)$ and $\varphi\sim e^{-mx}x^{-1/2}$. That there are no singularities at finite x is proved in the same manner as in the preceding case.

In conclusion, the author would like to thank I. M. Khalatnkov for valuable discussions.

[1] I. M. Khalatnikov and S. L. Parnovsky, Phys. Lett. A **66**, 466 (1978).
[2] W. Israel, Phys. Rev. D 15 (1977); Ya. B. Zel'dovich and I. D. Novikov, Relyativistskaya astrofizika (Relativistic Astrophysics), Nauka, 1967.
[3] V. A. Belinskiĭ and I. M. Khalatnikov, Zh. Eksp. Teor. Fiz. **63**, 1121 (1972) [Sov. Phys. JETP **36**, 591 (1973)].
[4] L. D. Landau and E. M. Lifshitz, Teoriya polya Classical Theory of Fields, Nauka, 1974 [Pergamon, 1975].
[5] S. L. Parnovskiĭ, Zh. Eksp. Teor. Fiz. **76**, 385 (1979) [Sov. Phys. JETP **49**, 600 (1979)].

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The baryonic asymmetry of the Universe

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We discuss a possible process of appearance of an excess of baryons and antileptons during the early stage of expansion of a charge-symmetric hot universe in the framework of a unified gauge theory of strong, weak, and electromagnetic interactions. According to the estimates of the present paper, the baryon asymmetry $A = N_B/N_\gamma$ (the ratio of the mean baryon density to the density of quanta of the background radiation, which, up to a numerical factor, equals the ratio of the number of baryons to the initial entropy of the hot universe in the same comoving volume element) has the order of magnitude $A\sim\alpha^3\vartheta^3\delta_\alpha$ ($\alpha = g^2$ is the coupling constant of the gauge field, ϑ is a quantity of the order of the Cabibbo angle, δ_α is the phase of the complex quark mixing). The numerical coefficient in this formula may contain an additional small parameter. The paper presents some arguments relative to the "multifoliated" (many-sheeted) model of the universe previously proposed by the author.

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§1. INTRODUCTION. ESTIMATE OF THE EFFECT

In 1966 the author has proposed a hypothesis for the appearance of an observable baryon asymmetry of the Universe (and of a conjectured lepton asymmetry) during an early stage of the cosmological expansion out of a charge-symmetric initial state. Such a process is possible owing to effects of CP-violation under nonstationary expansion conditions, if one assumes nonconservation of the baryonic and leptonic charges.[1]

In 1978 an analogous idea has been formulated in a paper of Yoshimura.[2] Yoshimura indicates that in unified gauge theories of strong, weak, and electromagnetic interactions (cf. Ref. 3 and subsequent papers quoted in Ref. 2) baryon number is not conserved, due to interactions in which the "leptoquark" intermediate boson participates, and this together with the violation of CP-invariance leads unavoidably to an excess of baryonic charge (baryon number) during the early stages of the expansion of the hot Universe. Yoshimura indicates the possibility of a quantitative calculation of this effect by means of perturbation theory methods. While he was working on the present paper, the author also learned about the paper of Dimopoulos and Susskind[4] devoted to the same problem.

Below we obtain for the baryon asymmetry an estimate which is close to the one given by Dimopoulos and Susskind,[4] but was obtained from a more detailed consideration of the kinetics of mutual transformation of particles and does not make use of the assumption that the mass of the leptoquark boson has the order of magnitude of the Planck mass $M_0=10^{19}$ GeV. Section 5 contains some considerations related to the "multifoliated model of the Universe" ("many-sheeted model of the Universe") proposed earlier by the author.

The other sections contain the reasoning behind the estimate of the baryon and lepton asymmetry. Here we summarize briefly the main points of this reasoning.

Deviations from particle-antiparticle symmetry manifest themselves only on account of the nonstationarity caused by the expansion of the Universe. We denote the

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densities of different particle species by n_i. The equilibrium values of these densities will be denoted by n_i^0 and the deviations from the equilibrium situation will be characterized by the ratios

$$n_i'/n_i^0, \quad n_i'=n_i-n_i^0.$$

The order of magnitude of the ratio n'/n^0 is $H\tau$, where τ is the characteristic time of the reactions of mutual transformations of particles, and H is the "Hubble parameter" characterizing the dynamics of the expansion of the Universe. H is the logarithmic derivative of the "scale" a, the linear size of an arbitrary "comoving" volume element:

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

ρ is the energy density and G is the gravitational constant. Here and in the sequel we have set $c=\hbar=k=1$.

The quantity H is of the order of $1/t$, where t is the "age of the Universe." Thus

$$n'/n^0\sim\tau/t. \tag{2}$$

We assume that the most important processes of particle transformations are binary reactions with cross sections which tend to a constant in the high energy limit. With this assumption we have during the early stages of expansion of the Universe

$$\tau\sim1/n^0\sim a^3;$$

since $a\sim t^{1/2}$ the relative deviations from the equilibrium value n'/n^0 are small and tend to zero as $t\to0$.

For the appearance of an asymmetry it is essential that there exist a period of expansion of the Universe when the temperature is of the order of the mass M_c of the leptoquark vector boson W_c which plays (cf. § 2 and Refs. 2, 3) a decisive role in the violation of baryon and lepton number conservation:

$$T_c\sim M_c.$$

To this temperature corresponds a characteristic particle density $n_c^0\sim M_c^3$, a characteristic energy density $\rho\sim M_c^4$, and according to Eq. (1), a characteristic age of the Universe $t_c\sim H_c^{-1}\sim G^{-1/2}M_c^{-2}$, as well as a characteristic duration of the "decisive phase" (the length of the time interval which is most important for the processes we are interested in)

$$\Delta t_c\sim t_c.$$

The violation of CP-symmetry and T-symmetry has the consequence that the rates of mutual transformations of particles are in general different for the direct and inverse reactions (even in stationary states), and are also different when particles are replaced by the appropriate antiparticles. We denote the transition probabilities between the states i and f by ω_{if}, and the probabilities for the CP-conjuagte states by $\omega_{\bar{i}\bar{f}}$. We set

$$\omega_{if}=s_{if}+a_{if}, \quad \omega_{\bar{i}\bar{f}}=s_{if}-a_{if}. \tag{3}$$

The CPT-invariance implies the following relation: the sum over all final states f vanishes for any initial state i:

$$\sum_f a_{if}=0. \tag{4}$$

Together with the T-symmetry of the probabilities s_{if} and with the equality of particle and antiparticle masses, the condition (4) guarantees the CP-symmetry of the equilibrium stationary state ($n_i^0=\bar{n}_i^0, dn_i/dt=0$). But in a nonstationary state $n_i\neq\bar{n}_i$. Introducing the notation

$$n'=n'^s+n'^a, \quad \bar{n}'=n'^s-n'^a,$$

we obtain the order-of-magnitude estimate (§ 3)

$$n'^a\sim\frac{a^*}{s}n', \tag{5}$$

where s is the part of the probability of particle transformation which does not depend on replacing particles with antiparticles, and a^* is the antisymmetrical part of that probability (Eq. (3); the asterisk has been used in order not to confuse it with the scale a). In Eq. (2) $\tau\sim1/s$, i.e.,

$$n'^a\sim a^*n^0/s^2\Delta t. \tag{6}$$

In § 4 we obtain for a simplified model of the theory the estimate

$$s\sim\alpha M_c, \quad a^*\sim\alpha^3\vartheta^3\delta_a M_c,$$

where $\alpha=g^2$ is the coupling constant of the gauge field, ϑ is a quantity of the order of the Cabibbo angle, δ_a is the complex phase describing the mixing of quark states.

Making use of $n_c^0\sim M_c^2$ we obtain the estimate

$$n'^a=\frac{\alpha\vartheta^3\delta_a M_c^2}{\Delta t}. \tag{7}$$

The residual baryon and lepton numbers appear as a result of reactions with the participation of the leptoquark boson (four-boson reactions in § 2, Eqs. (13R) and (13R′)). Their probabilities are of the order $\omega\sim\alpha^2M_c$. Integrating with respect to time (Eq. (15)) we obtain the residual baryon (or lepton) number in the comoving volume $[a(t)]^3$. The factor Δt appears on account of the integration

$$N_B=a^3n_B\sim\omega n'^a a^3\Delta t\sim\alpha^3\vartheta^3\delta_a M_c^3a^3. \tag{8}$$

The particle number in the comoving volume has the same order of magnitude as the number of quanta of the background (relic) radiation, i.e., $n^0a^3\sim M_c^3a_c^3$. The baryon asymmetry has the order of magnitude

$$A=N_B/N_\gamma\sim\alpha^3\vartheta^3\delta_a. \tag{9}$$

The lepton asymmetry must be of the same order of magnitude. If one assumes conservation for the total number of leptons and quarks (cf. § 2) one obtains

$$N_{\bar{l}}-N_l=3N_B.$$

At present there exist no methods which would allow one to verify this relation.

§2. VIOLATION OF BARYON AND LEPTON NUMBER CONSERVATION

In unified theories of strong, weak and electromagnetic interactions one postulates the existence of a so-called leptoquark vector boson, which when emitted or absorbed converts quarks into leptons and vice versa.

Restricting ourselves to theories for which the quarks are postulated to obey exact "color" symmetry and to have fractional electric charges, we have to attribute a fractional charge also to the leptoquark boson. We shall use the following notations: W_c denotes a leptoquark with charge $-1/3$ or any charge differing from this by an integer (if one assumes that the electron is the "particle," these charges are 2/3 and 5/3); $\overline{W}_c$ denotes a leptoquark with charge $+1/3$, or a charge differing from 1/3 by an integer. The bosons W_c and $\overline{W}_c$ interact with the quarks q and leptons l according to the following b basic reactions ($\bar{q}$ and $\bar{l}$ denote antiquarks and antileptons):

$$W_c\leftrightarrow q+\bar{l},\quad W_c\leftrightarrow \bar{q}+l. \tag{10}$$

In addition to the reactions (10), in the majority of unified theories there are three more reactions ("vertices"), leading to baryon number nonconservation:

$$W_c\leftrightarrow \bar{q}+\bar{q},\quad \overline{W}_c\leftrightarrow q+q; \tag{11}$$

the three-boson interaction (an off-mass-shell reaction!):

$$W_c+W_c+W_c\leftrightarrow \text{vacuum},\quad \overline{W}_c+\overline{W}_c+\overline{W}_c\leftrightarrow \text{vacuum} \tag{12}$$

and the four-boson interaction with the participation of three W_c which allows for the on-shell reactions:

$$\overline{W}_c+\overline{W}_c\leftrightarrow W_c+R, \tag{13R}$$

$$\overline{W}_c+R\leftrightarrow W_c+W_c. \tag{13R$'$}$$

Here R is a "regular" vector boson responsible for the weak interactions, such as $W_\pm$ or another gauge boson of zero or integer charge.

Figures 1 and 2 are proton decay diagrams involving the vertex (11) ($p\to\pi+l$) and the vertex (12) ($p\to 3l$):

A similar decay for which the vertex (13) is responsible is: $p\to 3l+W_+$.

The three-boson vertex (12) was postulated in Ref. 1. In gauge field theories with nonabelian gauge group the three-boson and four-boson interactions (12) and (13) follow from first principles!

Models are possible in which interactions of the type (11) are absent, and which lead in addition to a strict conservation law of the total number of quarks and leptons (the combined charge N_0)

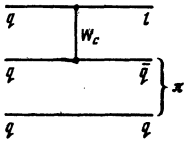

FIG. 1.

$$N_0=N_q+N_l-N_{\bar{q}}-N_{\bar{l}}=\text{const.} \tag{14}$$

Such models seem to be preferable. Even for masses M_c which are not too large the proton in such models has a long lifetime—a lifetime which according to experiments (cf. Ref. 5) exceeds 10^{30} years. An estimate (without essential numerical coefficients) for the process depicted in Fig. 1, yields

$$\tau_1^{-1}=\left(\frac{\alpha}{\pi}\right)^2\left(\frac{M_p}{M_c}\right)^4 M_p$$

(here M_p is the proton mass, M_c is the leptoquark boson (W_c) mass), and for the process depicted in Fig. 2:

$$\tau_2^{-1}=\left(\frac{\alpha}{\pi}\right)^4\left(\frac{M_p}{M_c}\right)^{12} M_p.$$

The first equation requires $M_c>10^{14}\,M_p$, and the second $M_c>3\times10^4\,M_p$.

We introduce the approximate quantum number

$$r={}^1/_2(N_q+N_{\bar{l}}-N_{\bar{q}}-N_l)+N_{W_c}-N_{\overline{W}_c}.$$

It is easy to verify that the conservation of r (and thus of the lepton and baryon numbers), in the absence of the interaction (11) is violated only by the reactions (12) and (13). With these assumptions the following estimate holds for the residual baryon number in a comoving volume $[a(t)]^3$:

$$N_B=\int_0^\infty dt\,a^3\left\{\frac{1}{2}\sum_{ij}(\sigma_{ij}v)(\bar{n}_i\bar{n}_j-n_in_j)+\sum_i(\sigma_iv)'n_R(\bar{n}_i-n_i)\right\}. \tag{15}$$

Here n_i and $\bar{n}_i$ are the densities of the W_c and $\overline{W}_c$ of the three different sorts (with charges $\mp1/3, \pm2/3, \pm5/3$); $(\sigma_{ij}v)$ and (σ_iv), are the average values of the products of relative velocities of colliding particles by the cross sections of the reactions (13R) and (13R$'$); n_R is the density of bosons different from W_c and $\overline{W}_c$. In order to determine n_i it is necessary to solve the kinetic equations.

§3. THE KINETIC EQUATIONS

During the early stage of the expansion of the Universe the deviations from the equilibrium state are small:

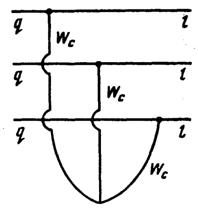

FIG. 2.

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

We write down the linearized kinetic equations in the following approximate form, for the purpose of obtaining estimates (one can write a more exact system of integral equations for spherically symmetric density functions $n_j^1(p)$ in momentum space):

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

It is assumed that the matrix S_{ij} does not change under particle-antiparticle conjugation, whereas the matrix A_{ij} changes sign under this substitution. Neglecting in the expression for m_i the deviation of n_i from n_i^0 we obtain for n_i^1 a system of linear algebraic equations with a known right-hand side m_i^0.

We note (although this is essential only for calculations which are more accurate than our estimates) that the matrices A, S, and $A+S$ are singular (have a vanishing determinant), since there is a "singular" direction in the vector space of the n_j^1, for which the right-hand side of (16) turns to zero. This singular direction corresponds to a variation of the temperature of the equilibrium state

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

We denote the unit vector of this direction by

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

We introduce a complete set of orthonormal vectors $e_j^\alpha e_j^\beta = \delta_{\alpha\beta}$ and the corresponding new coordinates $\eta_\alpha = e_j^\alpha n_j^1$. The coefficient η_0 is not determined by Eq. (16), but this is not essential, since e^0 is invariant with respect to particle-antiparticle conjugation. It suffices to find a component of n' orthogonal to e^0.

The matrices

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

defined in the space orthogonal to e^0, are nonsingular. Taking into account the fact that $A \ll S$, the inverse matrix becomes

$$(\tilde{S}+\tilde{A})^{-1} \approx \tilde{S}^{-1}+P, \quad P = -\tilde{S}^{-1}\tilde{A}\tilde{S}^{-1}. \tag{18}$$

Setting $n^1 = n^{1S} + n^{1A}$ and $\bar{n}^1 = n^{1S} - n^{1A}$, we obtain

$$n_j^{1A} = e_j^\alpha P_{\alpha\beta} e_k^\beta m_{0k}. \tag{19}$$

We estimate the elements of the matrices S, A for a simplified model of the theory.

§4. A MODEL OF THE THEORY

Let n_1, n_2, n_3 denote the densities of the three kinds of leptoquark bosons W_c with the charges $-1/3, 2/3, 5/3$, respectively, and let $\bar{n}_1, \bar{n}_2, \bar{n}_3$ denote the densities of the $\bar{W}_c$. We assume the masses of the different kinds of W_c to be different, with a mass difference of the order of M_c ($\Delta M_c \sim M_c$). The large mass difference between the strange and the charmed quark ($\Delta m_q \sim m_q$) makes this assumption a little more likely by analogy.

The W_c bosons of different kinds undergo transformations via the reactions

$$W_c^i + \bar{q} \to \bar{l} \to W_c^j + \bar{q}, \quad W_c^i + l \to q \to W_c^j + l.$$

Figure 3, a represents a typical diagram for this process:
The symmetric part of the cross sections is of the order

$$\sigma_{12}' \sim \alpha^2/M_c^2.$$

Taking into account that n^0, the density of quarks, leptons (and any other particles) in the critical phase, is of the order M_c^3, and the relative velocity of the particles is of the order of one, we obtain $S_{12} \sim \alpha^2 M_c$. In making the mechanism for CP-violation more concrete we follow the paper of Kobayashi and Maskawa.[6] These authors have found that if one generalizes the Cabibbo mixing model to three or more mixed states, then in the presence of complex mixing matrices there appear CP-violating effects.

Let us consider mixing among three quark doublets. The states

$$\begin{pmatrix} p_1 & p_2 & p_3 \\ n_1 & n_2 & n_3 \end{pmatrix}$$

are by definition diagonal for the mass operator. The states

$$\begin{pmatrix} P_1 & P_2 & P_3 \\ N_1 & N_2 & N_3 \end{pmatrix}$$

enter into the expressions of the quark and quark-lepton currents. The states P, N and p, n are unitarily related: $P = U_1 p, N = U_2 n$. The mixing of the leptons can be described by analogous matrices, but for definiteness we assume that $U_{1l} = U_{2l} = 1$. If one does not consider leptoquark currents, then U_1 and U_2 appear only in the combination $U_1^{-1} U_2$. The asymmetric part of the cross section is due to the interference between the contributions of the diagrams of the type of Fig. 3a and 3b, contributions which differ by the phases

$\delta_s + \delta_a$ for particle, $\delta_s - \delta_a$ for antiparticles.

The effect is proportional to

$$\cos(\delta_s - \delta_a) - \cos(\delta_s + \delta_a) = 2\sin\delta_s \sin\delta_a.$$

According to the Feynman rules $\delta_s = \pi/2$; the phase δ_a is the parameter of the theory and does not depend on the choice of phases for the quark and lepton states.

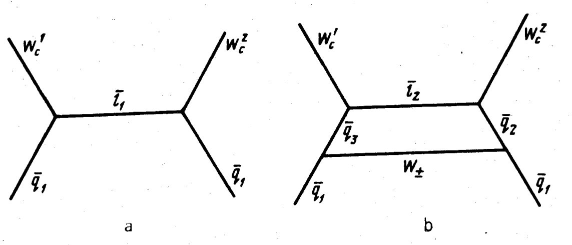

FIG. 3.

An estimate of the asymmetric part yields the order of magnitude

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

M_a and M_b are the respective contributions of diagrams of the type of Fig. 3, a and b, to the amplitude; $M_a \sim \alpha$, $M_b \sim \alpha^2\vartheta^3$ (three vertices with change of particle kind). Taking into account the fact that $A_{12}\sim n^0\sigma_{12}^a$, we obtain

$$A_{12}\sim\alpha^3\vartheta^3\delta_a M_c.$$

The Kobayashi-Maskawa mechanism is ineffective for extreme-relativistic quark energies. Therefore these estimates are valid only if there exist hypothetical quarks with masses of the order of M_c.

The probability of the reactions $W_c\to q+\bar{l}(S_{12}, S_{24}, S_{34})$ is of the order of αM_c. The probability of the four-boson reactions (13R), (13R′) is of the order

$$\omega_R\sim\alpha^2 M_c.$$

In the general case, if the masses, the decay probabilities, and the probabilities of the reactions R for the three kinds of W_c do not coincide, then the orders of magnitude of $n_{1,2,3}^{1a}$ are determined by the equations (19), (18), (16):

$$n_{1,2,3}^{1a}\sim Pm,\quad P\sim A_{12}/(S_{14})^2,\quad m\sim n_c/\Delta t_c,$$

whence

$$n_{1,2,3}^{1a}\sim\alpha\vartheta^3\delta_a M_c^2/\Delta t_c.$$

With the same assumptions, Eq. (15) yields the order of magnitude for N_B

$$N_B\sim a_c^3 n_{1,2,3}^{1a}\omega_R\Delta t_c\sim a_c^3 n_c^0\alpha^3\vartheta^3\delta_a,$$

i.e.,

$$A=N_B/N_\gamma\sim\alpha^3\vartheta^3\delta_a. \tag{20}$$

However, if the difference between the W_c boson masses is smaller than the masses themselves, there appears a new parameter of smallness $C(M_{1c}, M_{2c}, M_{3c})$. The quantity N_B vanishes if the masses of two of the three kinds of leptoquarks are equal. Assume, for instance, that $M_1=M_2\neq M_3$. We then automatically have $m_1^0=m_2^0\neq m_3^0$ (we recall that $m_i^0=a^{-3}\,d(a^3n_i^0)/dt$ is the right-hand side of Eq. (16)). The number of asymmetric transitions from state 1 into state 3 and from state 3 into state 2 are equal to one another. The numbers of symmetric transitions from state 3 into the states 1 and 2 are also equal, and the number of symmetric transitions between the states 1 and 2 is zero. We have

$$n_1^{1s}=n_2^{1s}\neq n_3^{1s},\quad n_1^{1a}=-n_2^{1a},\quad n_3^{1a}=0.$$

We assume in addition that all the transition probabilities from states 1 and 2 into other states are equal, including the equality of the reactions (13) which change baryon and lepton number. We obtain

$$N_B=0 \text{ for } M_1=M_2\neq M_3.$$

An example of a function C exhibiting such properties and which is symmetric in its arguments is:

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

We obtain finally

$$A=\alpha^3\vartheta^3\delta_a C(M_1, M_2, M_3), \tag{22}$$

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

§5. A MULTIFOLIATED MODEL OF THE UNIVERSE

In 1969 the author has included the assumption of neutrality of the Universe in the exactly conserved charges, which he considered to be the electric charge and the "combined" lepton-baryon charge (of the type of N_0 in Eq. (14) of the present paper) into the proposed cosmological hypothesis of a "multifoliated Universe" (many-sheeted-Universe).[7] Another assumption of this hypothesis was a flat spatial metric on the average on large scales, i.e., an infinite curvature radius of the Universe. These two assumptions make possible an infinte-fold repetition of cosmological expansion-contraction cycles of the pulsating Universe with repetition from cycle to cycle of its statitical characteristics. In any comoving volume the entropy increases in agreement with the second law of thermodynamics, but the increase of entropy from cycle to cycle has no physical meaning and can be removed by a change of scale on the singular hypersurface $t=t_0$, $a(t_0)=0$. With this redefinition there occurs no change of the densities of exactly conserved charges (electric charge and the combined baryon-lepton charge), as well as of the integral spatial curvature, since these quantities are assumed to vanish.

The noninvariant charges (the baryon number and the number of leptons in any comoving volume) change, but their ratio to the entropy and the absolute values in the redefined comoving volume are assumed the same at corresponding instants of age of the Universe in each cycle.

A dynamical reason for the transition of a flat Universe from expansion to contraction could be, in particular, an arbitrarily small (in absolute value) cosmological constant of the appropriate sign ($\varepsilon<0, p=|\varepsilon|>0, \varepsilon+3p>0$). In Ref. 7 the formation of black holes was considered as the dynamical mechanism.

We note, among other things, that the assumed repeatability of the statistical characteristics could be an important heuristic requirement which determines the initial inhomogeneities, the densities of entropy and metric, the density distribution of angular momentum and other statistical parameters of the model.

§6. CONCLUSION

Thus, for a model of the theory we have obtained an estimate of the baryon asymmetry of the Universe (the lepton asymmetry is of the same order):

$$A\sim N_B/a^3n^0\sim C\alpha^3\vartheta^3\delta_a.$$

Our calculations contain too many uncertainties in order to be able to talk about agreement with experiment, which yields a value of $A\sim 10^{-8}-10^{-9}$, however, our result is not in contradiction with experiment.

Thus, setting $\alpha=10^{-2}, \vartheta=0.5, \delta_a=10^{-1}, C=10^{-2}$ we obtain $A=10^{-10}$.

The estimate is valid only if there exist hypothetical quarks with masses of the order of M_c. The additional small parameter which appears for the presently known quarks seems to exclude a possibility of agreement with experiment for the concrete model considered in § 4.

The result obtained in the present paper does not depend on the dimensionless parameter $k=1/M_c G^{1/2}$, which determines the ratio of the duration of the "critical" phase for the process under consideration, $\Delta t\sim 1/G^{1/2}M_c^2$, to the characteristic reaction time for the mutual transformation of particles $\tau\sim 1/\alpha M_c$:

$$\Delta t/\tau\sim\alpha k.$$

Yoshimura[2] has obtained a formula which differs from ours, according to which the baryon asymmetry A is of the order of k, i.e., is proportional to the duration of the critical phase, Δt. This result is in contradiction with the absence of CP-violation in a stationary state. As was shown here (§ 3) small deviations from the equilibrium state, and thus from CP-symmetry, are proportional to $1/k$. An integration with respect to time leads to a cancellation of the k-dependence. In the paper of Dimopoulos and Susskind[4] it was assumed from the start that $k\sim 1$, and thus the dependence of the result on this parameter is not investigated.

In § 5 we have advanced arguments for the need of the assuming that the Universe is initially neutral, for the "multifoliated model of the Universe" with statistical characteristics which are repeated every cycle.

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[1]A. D. Sakharov, ZhETF Pis. Red. 5, 32 (1967) [JETP Lett. 5, 24 (1967)]
[2]M. Yoshimura, Phys. Rev. Lett. 41, 281 (1978).
[3]H. Georgi and S. L. Glashow, Phys. Rev. Lett. 32, 493 (1974).
[4]S. Dimopoulos and L. Susskind, SLAC-PUB-2126, June, 1978.
[5]F. Reines and M. F. Crouch, Phys. Rev. Lett. 32, 493 (1974).
[6]M. Kobayashi and T. Maskawa, Prog. Theor. Phys. (Kyoto) 49, 652 (1973).
[7]A. D. Sakharov, The multifoliated model of the Universe, Preprint of the Applied Mathematics Section of the V A. Steklov Mathematical Institute., 1969.

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Theory of depolarization of positive muons in antiferromagnetic chromium

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Expressions are obtained for the time dependence of muon polarization in chromium at temperatures below the Néel point. It is shown that the muon method can yield information on the magnetic anisotropy. At low magnetic anisotropy, the depolarization rates in longitudinal and magnetic fields should be different in the region above the spin-flip temperature.

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1. We show here, with chromium as an example, how the muon method can yield information on some subtle features of magnetic ordering.

Experiments on the depolarization of μ^+ mesons in the antiferromagnetic phases of chromium have recently been reported.[1,2] The magnetic structure of chromium is well known.[3] Below the Néel point T_N, magnetic ordering of delocalized d electrons of the spin-density wave (SDW) type occurs with a period equal to 27 periods of the crystal lattice, and with a wave vector directed along one of the edges of the cube. (We neglect hereafter the weak rhombicity of the crystal lattice and assume that chromium has a bcc structure.) Chromium has two magnetic sublattices, one over the corners of the cube, and the other over the centers. The directions of the magnetic moments are opposite at sites of different sublattices. At temperatures between

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