BARYON ASYMMETRY OF THE UNIVERSE VERSUS LEFT-RIGHT SYMMETRY

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The problem of generation of baryon asymmetry of the Universe is investigated in the framework of left-right symmetric grand unified models. We show that in a class of grand unified theories like SO(10) model the very existence of the baryon asymmetry of the Universe requires the right-handed weak gauge bosons to be almost as heavy as leptoquark bosons, $M_{W_R} > 10^{12}$ GeV.

Le problème de la génération de l'assymmetrie baryonique de l'Univers est investigué dans les cadres des grands modèles unifiés avec la symmetrie gauche-droite. Nous montrons, que dans la classe des grandes théories unifiées comme SO(10) modèle l'existence-même de l'assymmetrie de l'Univers exige, que les bosons de jauge avec l'helicité droite soivent extremement lourds, $M_{W_R} > 10^{12}$ GeV.

Lately there has been paid much attention to the problem of baryon asymmetry of the Universe (BAU) generation. It was shown in refs.[1-10] that the necessary conditions for BAU generation starting with charge symmetric initial state consist in baryon number violation, CP-nonconservation and deviation from thermal equilibrium at an early stage of the Universe expansion. In refs.[2,3;7-10] a mechanism for the BAU generation was proposed based on CP-noninvariant baryon number violating decays of heavy particles. In this note we show that in left-right (LR) symmetric grand unified theories like SO(10) the BAU may appear only provided right-handed weak gauge bosons are extremely massive in comparison with left-handed ones, i.e. the BAU argues strongly against LR-symmetry.

First of all let us introduce several definitions. We consider GUT's with gauge symmetry group $SU(2)_L \times SU(2)_R$ embedded in the unifying group G. Let (m,n) be the quantum numbers of a particle with respect to $SU(2)_L \times SU(2)_R$, m and n being $SU(2)_L$ and $SU(2)_R$ indices respectively. We shall call a theory LR-symmetric if:

1) the particle content of the theory is LR-symmetric, i.e. if $(m,n) \in A_i$ then also $(n,m) \in A_i$, A_i being a representation (fermion, scalar, vector) of G.
2) the operator P_{LR} defined by

$$P_{LR} \left|(m,n);\ \vec{p},\sigma\right\rangle = \eta \left|(m,n);\ -\vec{p},\sigma\right\rangle \qquad (1)$$

commutes with the Hamiltonian. Here $\vec{p}$ is the 3-momentum, σ is spin and η is the phase factor of a particle.

It is easy to see that operator P_{LR} defined in such a way can serve as a generalization of the parity operator P for the case of theories which are $SU(2)_L \times SU(2)_R$ symmetric. From 2) it follows immediately that masses and lifetimes of (m, n) and (n, m) states coincide. The same is true for partial decay rates into P_{LR} - conjugated channels (till now we had in mind unbroken $SU(2)_L \times SU(2)_R$):

$$A\big((m,n) \longrightarrow (k,l)\big) = A\big((n,m) \longrightarrow (l,k)\big) .$$

Besides LR-symmetric theories one may consider CP_{LR}, C_{LR} etc. symmetric theories. Definitions of such kind theories are similar to LR-symmetric ones except for in 2) instead of P_{LR} one should use the operator CPP_{LR} (CP_{LR}etc.) defined by

$$CPP_{LR} \left|(n,m),\ \vec{p},\sigma\right\rangle = \eta \left|(\overline{m,n});\ +\vec{p},\sigma\right\rangle \ . \qquad (2)$$

Here $(\overline{m,n})$ denotes the state which is charge-conjugated to (m,n).

We observe now that an overall charge asymmetry cannot arise in any C_{LR} or CP_{LR} symmetric theory.(Here charge means any CPT-odd operator. We discuss as usually the BAU generation due to charge non-conservation and CP-violation under non-equilibrium conditions from charge symmetric equilibrium initial state.) Indeed, both density matrix of the system $\rho(t)$ and the CP_{LR} conjugated matrix

$\rho'=(CP_{LR})^{+}\rho(CP_{LR})$ obey the same Liouville equation and same initial conditions because CP_{LR} commutes with the Hamiltonian. Hence always $\rho'(t)=\rho(t)$. Consequently the average value of CPT-odd charge B is equal to zero during the evolution of the system:

$$\langle B \rangle = \mathrm{Sp}\,\rho B = \mathrm{Sp}(CP_{LR})^{+}\rho(CP_{LR})B = -\mathrm{Sp}\,B\rho = 0 \, .$$

The physical reason consists in the fact that the charge arising in processes with (m,n) particles is completely compensated by the charge arising in processes with $(\overline{n,m})$ particles though due to CP-noninvariance amplitudes of the processes $(m,n) \longrightarrow (k,l)$ and $(k,l) \longrightarrow (m,n)$ may not coincide. The following equality holds

$$A\left((m,n)^{a} \longrightarrow (k,l)^{b}\right) = A\left((\overline{n,m})^{-a} \longrightarrow (\overline{l,k})^{-b}\right), \qquad (3)$$

where a and b are the values of initial and final charges respectively.

It is worth noting the following.

1. We have nowhere used the specific structure of the group $SU(2)_L \times SU(2)_R$. Our statement on the overall asymmetry is obviously true also in the case when Lagrangian is invariant under group $G' \times G''$ and under the transformation Cg, g transforming G' into G", G being any group.

2. The definition of CP_{LR} (or CPP_{LR}) transformation can be somewhat extended. Let the Hamiltonian be invariant under $\widetilde{CP}_{LR}$ transformation such that it coincides with "old" CP_{LR} transformation on the states (m,n) with $m \neq n$. On some states with $m = n$ the $\widetilde{CP}_{LR}$ acts as

$$\widetilde{CP}_{LR}\left|(k,k),\ \vec{p}, \sigma\right\rangle = \eta\left|(k,k),\ -\vec{p}, \sigma\right\rangle ,$$

i.e. in the usual way, $\widetilde{CP}_{LR} = CP_{LR}$, while on the other states it acts as

$$\widetilde{CP}_{LR}\left|(l,l),\ \vec{p}, \sigma\right\rangle = \eta\left|(l,l),\ -\vec{p}, \sigma\right\rangle ,$$

i.e. coincides with P_{LR}. In this case our statement on the overall asymmetry remains true for those charges B which are CP_{LR} antisymmetric, $(CP_{LR})^{+}B(CP_{LR}) = -B$. In particular it holds true for B being the baryon number only in the case when there do not exist exotic quarks transforming as (3, 2, 2), (3, 1, 1) etc. under $SU(3)^c \times SU(2)_L \times SU(2)_R$.

As an example of CPP_{LR} symmetric unified theory one may consider the SO(10) model[11)*]. It can be shown that CPP_{LR} transformation in SO(10) coincides with the proper rotation generated by an operator V:

$$(CPP_{LR})^+ A_i (CPP_{LR}) = VA_i \ . \tag{4}$$

If, for example, fermions are placed in the 16 representation of SO(10) as follows

$$\psi^T = (q_A^1\ q_A^2\ q_A^3\ q_C^1\ q_C^2\ q_C^3\ l_A\ l_C\ \bar{q}_A'^1\ \bar{q}_A'^2\ \bar{q}_A'^3\ \bar{q}_C'^1\ \bar{q}_C'^2\ \bar{q}_C'^3\ \bar{l}_A'\ \bar{l}_C')_L$$

(where indices A and C denote ano- and catho-fermions respectively) then the operator V may be written in the form:

$$V = \exp i\pi(\sigma_{810} - \sigma_{26})/2, \tag{5}$$

σ_{ij} being SO(10) generators. Under V, just as is required by CPP_{LR} transformation, q_A becomes $\bar{q}_A$ etc.

$SU(2)_L \times SU(2)_R$ symmetry in realistic models is usually spontaneously broken. We turn now to the question on how large should be the violation of $SU(2)_R$ symmetry in order that the BAU were close to the observational data. Denote by V_R the vacuum expectation value of the field which violates $SU(2)_R$; the mass of the particle which gives rise to the BAU is M_{mn}, m, n being $SU(2)_L \times SU(2)_R$ quantum numbers.

For the amplitude of the particle decay we have

$$T_{mn}(V_R) = T_{mn}(0)(1 + O(V_R/M_{mn})) \ . \tag{6}$$

At $V_R/M_{mn} \ll 1$ there occurs effective restoration of the broken $SU(2)_R$ symmetry (see, e.g.[12)]).Asymmetry resulting from decays of

*It was found in ref.[9)] that there are particles in SO(10) contributing much to the BAU generation. Here we stress that it is important to sum contributions over the SO(10) ensemble thus revealing the V_R dependence of the overall asymmetry. Our present results show that the value of the BAU found in ref. [9)] is correct provided the $SU(2)_R$ violation takes place on the first stage of SO(10) breaking.

(m,n) state is

$$\delta_{mn}(V_R) = \delta_{mn}(0)(1 + O(V_R/M_{mn})) \ . \tag{7}$$

According to Eq.(3) $\delta_{mn}(0)=-\delta_{\overline{nm}}(0)$, therefore the overall asymmetry at $V_R < M_{mn}$ is at most

$$\delta \sim \sum_{(mn)} \delta_{mn}(0)O(V_R/M_{mn}) \ . \tag{8}$$

Now we turn to the consideration of constraints on V_R analizing the contributions of different particles to the BAU. Consider first the case when the BAU is due to decays of leptoquark bosons (scalar or vector) which are directly coupled to fermions. The difference of partial decay widths arises due to the interference of tree and loop diagrams. The lowest order radiative corrections of interest are shown in Fig.1. Diagrams of the type d behave smoothly under variation of masses of the theory, therefore

$$\delta_{(d)} \sim \delta_{mn}(0) \ V_R/M_{mn} \sim h^2 V_R/M_{mn} \tag{9}$$

where h is the absolute value of Yukawa or Higgs coupling constant[**]. Diagrams of the type a,b,c depend on masses as follows (we take into account both the mixing through fermion and boson loops)

$$\delta_{(a)}(0) \sim h^2 (M_{mn}^{(1)})^2 / \left\{ (M_{mn}^{(1)})^2 - (M_{mn}^{(2)})^2 \right\}. \tag{10}$$

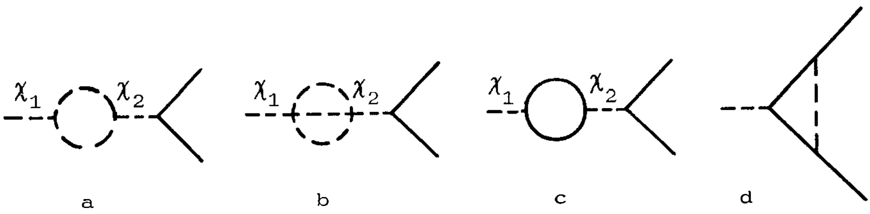

Fig.1.
Examples of radiative corrections to leptoquark decay into fermions.

[**]Here we assume that the CP-violation is maximum but this is not essential for our considerations.

On diagrams of the type a,b,c the mixing takes place between different particles χ_1 and χ_2 carrying the same $SU(3)^c \times SU(2)_L \times SU(2)_R$ quantum numbers. If $|M_{mn}^{(1)2} - M_{mn}^{(2)}| \approx M_{mn}^{(1)}$ then the total macroscopic asymmetry Δ (experimentally $\Delta \sim 10^{-8}$) is of the order[2,3;7-10)

$$\Delta \sim \frac{1}{N} \sum_{(mn)} \delta_{mn}(0) \frac{V_R}{M_{mn}} \sim \frac{N_\chi}{N} h^2 \frac{V_R}{M} \quad , \tag{11}$$

where N is the number of leptoquarks contributing to the BAU, M is their generic mass, N is the total number of the particle degrees of freedom. Having in mind the constraint on the masses of leptoquarks contributing to the BAU[8)

$$M \gtrsim \alpha_\chi M_0, \; M_0 = M_{Pl}/1.66 \quad N^{1/2} \approx 10^{18} \text{ GeV} \; ,$$

where α_χ is the χ decay constant, we obtain the lower bound on the magnitude of $SU(2)_R$ violation:

$$V_R \gtrsim \frac{N^{1/2}}{N_\chi} M_{Pl} \frac{\alpha_\chi}{h^2} \Delta \quad . \tag{12}$$

If the BAU is due to the decays of Higgs bosons, then $\alpha_\chi \sim h^2$, i.e. $V_R \gtrsim \Delta N^{1/2} N_\chi^{-1} M_{Pl} \sim 10^{12}$ GeV. If the vector particles contribute to the BAU, then $\alpha_\chi \sim \alpha_{GUT} \sim 10^{-2}$, i.e. $V_R \gtrsim 10^{12} h^{-2} \alpha_{GUT} \sim 10^{14}$ GeV, $h \sim 10^{-3}$ is the generic Yukawa coupling. Therefore we arrive to an exciting conclusion that the magnitude of $SU(2)_R$ violation should be almost as large as the violation of the unifying group G.

If the mixing occurs on mass shell (similarly to the $K^0 - \bar{K}^0$ system) $|M_{mn}^{(1)} - M_{mn}^{(2)}| \leqslant \Gamma_{mn}$, Γ_{mn} being the largest of the widths of (m,n) then the magnitude of δ_{mn} is no longer given by Eq.(10). It is independent of absolute values of coupling constants depending only upon phase relations between them. In this case δ_{mn} may be of the order of 1. Note that oscillations $\chi_1 \longleftrightarrow \chi_2$ in the χ_1, χ_2 system may occur. Now the dependence of δ_{mn} on (χ_1, χ_2) mass difference has "resonance" behaviour shown in Fig.2. One can see that the magnitude of δ is then

$$\delta \sim V_R/\Gamma \quad . \tag{13}$$

Taking $\Gamma \sim 10^{-6} M$, we obtain $V_R \sim 100$ GeV. Thus if the mixing takes place near the mass shell then the violation of $SU(2)_R$ symmetry should not necessarily be extremely large. In order that the mixing of χ_1 and χ_2 occured on the mass shell χ_1 and χ_2 should have the same conserved quantum numbers. Coincidence of χ_1 and χ_2 masses seems natural only if they belong to one and the same or to the conjugated representations of the unifying group G.

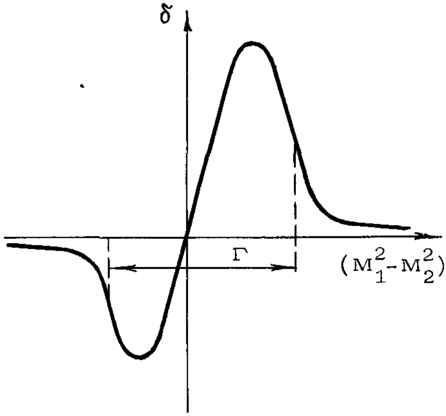

Fig.2.
Dependence of asymmetry on mass difference of mixing particles. The total "resonance" width is of the order of total χ_1 and χ_2 decay width.

If the BAU has originated from decays of Higgs bosons which do not couple directly to the fermions then the main conclusions will be as follows. If there are no mixing near the mass shell then the inequality $V_R \gtrsim \alpha_\chi M_0$ should hold. The V_R may be relatively small only when the χ-boson width is extremely small (as χ's do not couple directly to the fermions, decays may occur only in higher orders of perturbation theory). Say, with $V_R \sim 10^3$ GeV (experimental lower bound on M_{W_R} is $M_{W_R} \gtrsim 3M_{W_L}$ [13]) we obtain $\alpha_\chi \lesssim V_R/M_{Pl} \sim 10^{-16}$. If the mixing takes place on the mass shell then just as above $SU(2)_R$ violation should not be necessarily large.

Very strong constraint on magnitude of V_R can be derived in a somewhat different way. At high temperatures there may occur symmetry restoration[14]. The temperature of phase transition from the unbroken to the broken $SU(2)_R$ is apparently of the order $T_c \sim M_{W_R}/g \sim V_R$. If the phase transition really takes place then it is necessarily for the BAU generation that the temperature at which nonequilibrium decays begin should be less than T_c. Therefore

$$M_{W_R}/g \sim T_c \gtrsim T(t_{expan} = \Gamma^{-1}) \gtrsim \alpha_\chi M_0 \quad , \tag{14}$$

$$t^{-1}_{expan} = T^2/M_0 \quad .$$

Consequently if the widths of all the particles in the theory which contribute to the BAU generation are not extremely small then the $SU(2)_R$ symmetry should be broken just on the first stage of superstrong violation of the unifying group G.

Now we turn to the question of masses of the right-handed gauge bosons in the particular case of the SO(10) grand unified model. The BAU generation[9,10] through decays of gauge and scalar bosons interacting directly with fermions ($\underline{10}$, $\underline{120}$, $\underline{126}$[15])) requires W_R to be superheavy. Indeed, decay constant for Higgs particles from these multiplets is $\alpha_\chi \sim (m_q/M_{W_L})^2 \sim 10^{-6}$. Therefore, in accordance with Eq.(14) $M_{W_R} \gtrsim 10^{12}$ GeV if the BAU originated from scalar decays and even larger if gauge bosons contribute to the BAU.

In representations responsible for superstrong violation of SO(10)($\underline{16}$, $\underline{45}$ or $\underline{54}$[9,16])) there are no particles with almost equal masses and the same quantum numbers with respect to $SU(3)^c \times SU(2)_L \times SU(2)_R$, therefore the mixing on the mass shell here does not take place***. Therefore we have to put $V_{R} \sim M_{16,45,54}$, to obtain the overall macroscopic asymmetry $\Delta \sim 10^{-8}$ (see Eq.(11)). We now can derive the cosmological constaints on the masses of particles in $\underline{16}$, $\underline{45}$, $\underline{54}$, assuming that they contribute to the BAU. The masses of these particles should be larger than 10^{12} GeV if they participate in strong and/or electroweak interactions, because in other case their concentration at freezing moment will be rather small due to annihilation into light gauge bosons. Indeed, it may be shown that the relative concentration of χ's at the freezing moment (i.e. when $t_{expan} = t_{anni}$, t_{anni}^{-1} being the rate of the annihilation) is

$$N_\chi = (1/24)(M/T)^{3/2}\exp(-M/T) . \tag{15}$$

In order to obtain the observed value of the BAU we have to put $T \sim M$ when using $h \sim 10^{-3}$. Then we arrive to the constraint

$$M \gtrsim \alpha_\chi^2 \, M_{Pl}/24 \, N^{1/2} \simeq 10^{12} \text{ GeV} , \tag{16}$$

***In fact since $SU(2)_L \times SU(2)_R$ is broken, the transitions like $(3,2,2) \longleftrightarrow (3,1,1)$ can occur. However, their amplitude is proportional to the magnitude of $SU(2)_L \times SU(2)_R$ breaking and therefore δ_{mm} does not behave resonantly.

i.e. $V_R \gtrsim 10^{12}$ GeV. If we take the value $h \sim 10^{-2}$ we get $T/M \sim 1/7$ and $V_R \gtrsim 10^{10}$ GeV. We note by the way that the value of microscopic asymmetry $\delta > 10^{-4}$ seems unplausible.

As to the neutral particles from 16, 45, 54, they can decay into light bosons from 10, 120, 126 due to the Higgs coupling of the form $\xi^+\xi\phi^2$, h Tr $\eta^2\phi^2$, ξ belonging to 16, η - to 45 or 54, and ϕ - to 10, 120, 126. Their widths are of the order of $\Gamma \sim h^2 M$ which gives, using Eq.(14), $V_R \gtrsim h^2 M_0$. If we do not artificially choose h to be extremely small then we obtain again that V_R is of order of the largest mass parameter of the theory.

Thus we conclude that in SO(10) model and apparently in any other GUT with unifying group SO(2N), $N \geqslant 5$, it follows from the fact of the BAU existence the extreme massiveness of right-handed gauge bosons. In other words we arrive to the interesting connection between the BAU and the absence of the right-handed currents in experiment. It is worth emphasizing that if nevertheless the right-handed currents were discovered then the GUT based on SO(10) would be ruled out.

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References

1. A.D.Sakharov, Pis'ma Zh.Eksp.Teor.Fiz.5,32(1967).
2. V.A.Kuzmin, Pis'ma Zh.Eksp.Teor.Fiz. 13, 335 (1970).
3. A.Yu.Ignatiev, N.V.Krasnikov, V.A.Kuzmin, A.N.Tavkhelidze, Phys. Lett. B 76, 436(1978); Proc. Int. Conf. "Neutrino-77", Moscow, v.2, p.293 (1978).
4. S.Dimopoulos, L.Susskind, Phys. Rev. D 18 (1978) 4500.
5. A.Yu.Ignatiev, V.A.Kuzmin, M.E.Shaposhnikov, Preprint IYaI P-0102 (1978)
6. A.D.Dolgov, Pis'ma Zh. Eksp. Teor. Fiz. 29 (1979) 254.
7. D.Toussaint, S.B.Treiman, F.W. Wilczek, A.Zee, Phys. Rev. D 19 (1979) 1036.
8. S.Weinberg, Phys.Rev.Lett. 42, (1979) 850.
9. A.Yu.Ignatiev, V.A.Kuzmin, M.E.Shaposhnikov, Phys. Lett. B 87 (1979) 114.
10. A.Yu.Ignatiev, V.A.Kuzmin, M.E.Shaposhnikov, Pis'ma Zh. Eksp. Teor. Fiz. 30 (1979) 726.
11. H.Fritzsch, P.Minkovski, Ann. of Phys. 93 (1975) 193.
12. J.M.Cornwall, D.N.Levin, G.Tiktopoulos, Phys. Rev. D 10 (1974) 1145.
13. M.A.B.Bèg, R.Budny, R.N.Mohapatra, A.Sirlin, Phys. Rev. Lett. 38 (1977) 1252.
14. D.A.Kirzhnitz, A.D.Linde, Phys.Lett. B 42 (1972) 471.
15. M.S.Chanowitz, J.Ellis, M.K.Gaillard, Nucl. Phys. B 128 (1977) 506.
16. H.Georgi, D.V.Nanopoulos, Preprint HUTP-79/A001 (1979).