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CP VIOLATION AND THE DEVELOPMENT OF COSMOLOGICAL BARYON ASYMMETRY

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ABSTRACT

A discussion of the origin of the observed matter-antimatter asymmetry of the universe is presented in the context of the standard cosmological model. Except in the case of the minimal SU(5) theory, it is possible that grandunified theories predict the right order of magnitude for the ratio of baryon to photon number. The question of CP violation is addressed in detail and it is shown that, tied up with symmetry nonrestoration at high temperature, the soft CP violation does remain at $T \simeq 10^{15}$ GeV as to lead to the creation of baryon asymmetry in the very early universe.

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The standard cosmological model seems to provide a rather successful picture for the evolution of the universe[1], at least up to the times of order of a second or so. We have been able to observe a very important relic of the early universe: a 2.7°K microwave, isotropic, blackbody radiation. However, the observed amount of matter in the universe and the lack of antimatter[3] (up to the cluster of galaxies) has been an outstanding puzzle for a long time. Recently, a resolution has been suggested[4] which attributes the baryon number of the universe $n_B/S \approx 10^{-9} - 10^{-11}$ (S is the entropy) to baryon number and CP nonconserving decays of superheavy bosons (X) of grandunified theories during the very early stages of the universe. According to this picture at temperatures below the Planck mass and above the X boson masses the universe went through the epoch at thermal equilibrium during which time any previous matter-antimatter asymmetry would have been wiped out. When the temperature dropped below the superheavy boson masses and the inverse decay was blocked by $e^{-M/kT}$, the decays of these bosons into the channels with different baryon numbers presumably created a slight excess of particles over antiparticles. And finally, at much later times, when the baryons and antibaryons annihilated only matter was left, as the observations indicate. Quantitative analysis shows that for a large class of grandunified theories, the predicted baryon number does not disagree with the measurements.

The suggested scheme requires the extrapolation of the standard model, both of particle interactions and of cosmology, up to energies (temperatures) of order 10^{15} GeV or times up to the 10^{-35} sec. This, as outrageous as it seems, may not be totally unreasonable. Grandunified theories have offered us a long awaited explanation of why proton is so stable ($\tau_p \gtrsim 10^{30}$ years) and they also predict that we should, in near future, witness its decay. Their merits have been discussed at length[5] and they have become a respectable candidate for the old dream of unification of particle forces. On the other hand, we have no reason to suspect that the standard cosmological model will cease to be a valid description of the phenomena in the very early stages of the universe, as long as the temperature is below the Planck mass so that we can neglect the quantum gravitational effects. Of course, the whole picture may be totally wrong, but its simplicity and naturalness are highly suggestive. In this talk I will try to make the case for its validity.

For a baryon asymmetry to arise dynamically, independently of initial conditions, in addition to baryon number violation and the departure from the thermal equilibrium, CP cannot be a good symmetry. Otherwise, the X boson decays create an equal number of particles and antiparticles. More precisely, CP violation has to remain operative at $T \approx 10^{15}$ GeV. It is important to see what constraints does that requirement imply on our present understanding of the origin of CP nonconservation. Now, in the context of gauge theories we have two basically different mechanisms[6] of CP violation, hard and soft, depending on the canonical dimension of the CP nonconserving piece of the Lagrangian $d(L^-)$. For $d(L^-) = 4$ CP violation is hard, whereas for $d(L^-) \leq 3$ CP violation is called soft. The most popular example of the first kind is the so called Kobayashi-Maskawa extension[7] of the standard model with complex Yukawa couplings. By soft CP violation we will, in what follows, assume CP to be spontaneously broken.

Hard CP violation, since it is characterized by complex couplings in the basic weak Lagrangian, will remain at all temperature. The case with soft CP violation is more subtle and it is tied up with the nature of symmetry breaking at high temperature. On the basis of the anology with ferromagnets and as confirmed[8] in the simplest, single Higgs model one would expect symmetry to be restored above the temperature of order of the scale of weak interactions ($\simeq$ 300 GeV). But then soft CP violation would not present at $T \simeq 10^{15}$ GeV, as is required from the considerations of baryon asymmetry. However, the symmetry is not always restored at high temperature. Increased complexity of the Higgs sector allows (at least for some) vacuum expectation values to remain broken at high T.[9,10] Mohapatra and the author[9] have constructed a series of models in which soft CP violation is present at high T. As we shall see, the resulting baryon asymmetry is in accord with observations.[11] We should add that the main motivation for soft CP violation is not just aesthetic or philosophical, but rather the fact that it seems mandatory in order to understand the smallness of strong CP violation.

In this talk I will discuss above issues in some detail. The rest of the material is organized in the following manner: In section II we give a brief discussion of the standard cosmological model with the aim to obtain the expression for the expansion rate of the early universe. That will serve for the comparison with decay rates given in section III, which will determine when the universe went through the equilibrium epoch. There we also present a plausible scenario for the development of matter-antimatter asymmetry. In section IV we discuss the theories of CP nonconservation and the nature of high temperature behavior of gauge theories. We also present some rough, qualitative estimates of induced baryon number. Finally, in section V we offer some comments and summarize the basic contents of this paper.

II. Standard cosmological model and the very early universe

The assumptions of isotropy and homogeneity, encouraged by observations, lead to a unique form[1] for the metric of the space time (Robertson-Walker metric)

$$ds^2 = dt^2 - a^2(t) \left[\frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2\theta \, d\phi^2)\right] \tag{2.1}$$

where r, θ, ϕ are dimensionless parameters and a(t) is the scale factor. By simple rescaling $r \to (|k|)^{-\frac{1}{2}} r$, $a \to (|k|)^{\frac{1}{2}} a$ it is obvious that k takes only three different values: k = 0, + 1, - 1. The distance between material points, one at the origin and other at (r,0,0) is given by

$$R(t) = \int_1^2 \sqrt{-ds^2} = a(t) \int_0^2 \frac{dr}{(1 - kr^2)^{\frac{1}{2}}} \tag{2.2}$$

We then obtain the following results:

a) $k = 0 \Rightarrow R(t) = a(t)r$. The three-dimensional space is flat and infinite. Such universe is called Eucledian.

b) $k = -1 \Rightarrow R(t) = a(t) \sin^{-1} r$. This is called an open universe, since for $r \to \infty$ R(t) becomes infinite (infinite three dimensional space).

c) $k = 1 \Rightarrow R(t) = a(t) \sin^{-1} r$. Such models are called closed, since $0 \le r \le 1$ and $0 \le R \le \pi/2a$. It is still debated as to which is our universe.

The standard, or Friedmann model of the universe is obtained when Robertson-Walker metric (2.1) is combined with Einstein equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} \tag{2.3}$$

where the energy momentum tensor $T_{\mu\nu}$ has the form of the ideal fluid (which is forced by the dynamics)

$$T_{\mu\nu} = p g_{\mu\nu} - U_\mu U_\nu (p + \rho) \tag{2.4}$$

In the above p and ρ are the pressure and density. From (2.1), (2.3) and (2.4) one derives

$$\frac{1}{2} \left(\frac{da}{dt}\right)^2 - G\left(\frac{4\pi}{3} a^3 \rho\right) \frac{1}{a} = -\frac{k}{2} \tag{2.5}$$

which has a form of energy conservation, and

$$\frac{d\rho}{\rho} + 3(1 + p/\rho) \frac{da}{a} = 0 \tag{2.6}$$

which shows that the expansion of the universe is adiabatic.

The very early universe was radiation dominated, so that the, in addition needed, equation of state was $p = 1/3\rho$. Now, what we are after is the expansion rate of the universe, called Hubble constant

$$H \equiv \frac{1}{a}\frac{da}{dt} \tag{2.7}$$

which is a function of time, or temperature. For a radiation dominated universe $\rho \simeq NT^4$, and since the term in the right hand size of (2.6) is negligible[13], one obtains

$$H \simeq \sqrt{N}\,\frac{T^2}{M_p} \quad \text{and} \quad t \simeq \frac{M_p}{\sqrt{N}\,T^2} \tag{2.8}$$

What we will be discussing in this paper is the very early universe when the temperatures were between 10^{14} GeV and the Planck mass (10^{13} GeV). In terms of the age and the size of the universe

$$\begin{array}{lll} T_p = 10^{19}\ \text{GeV} \Rightarrow t_p = 10^{-43}\ \text{sec} & r_p = 10^{-33}\ \text{cm} \\ T = 10^{15}\ \text{GeV} \Rightarrow t = 10^{-35}\ \text{sec} & r = 10^{-25}\ \text{cm} \end{array} \tag{2.9}$$

etc. For the sake of completeness, I have included a table of some, somewhat randomly chosen, important moments in the history of the universe.

$t = 10^{10}$ years	$T = 3°K$	PRESENT
$t = 10^{6}$ years	$T = 1$ eV	ATOMS
$t = 4$ minutes	$T \simeq 10$ keV	NUCLEO SYNTHESIS
$t = 10$ sec	$T = .5$ MeV	e^+e^- ANNIHILATION
$t = 1$ sec	$T = 1$ MeV	NEUTRINOS DECOUPLE
$t = 10^{-10}$ sec	$T = 100$ GeV	$SU(2) \times U(1)$ BREAKING
$t = 10^{-35}$ sec	$T = 10^{15}$ GeV	SU(5) BREAKING; n_B CREATION; MONOPOLE -11-
$t = 10^{-43}$ sec	$T_p = 10^{19}$ GeV	QUANTUM GRAVITY

TABLE 1.

SOME IMPORTANT DATES IN THE HISTORY OF THE UNIVERSE

III. DEVELOPMENT OF BARYON ASYMMETRY

At enormously high temperature, much above all the known and conjectured particle masses it is natural to expect an equilibrium situation and therefore an equal number of particles and antiparticles. How did the universe then evolve into an asymmetric state, with mainly matter? Clearly, the answer could be that there are domains of matter and antimatter, large enough so that our observations are misleading. This picture still needs the explanation of the domain growth and of their separation. In any case, the magic number $n_B/S \approx 10^{-9} - 10^{-11}$ would have to be postulated ad hoc, as an initial condition.

It was relaized,[14] a long time ago, that in order to have baryon number dynamically generated, we need baryon number nonconservation at some level, or otherwise the baryon number of the universe would be a fixed quantity, throughout a history of the universe. Now, grandunified theories, as a rule, predict baryon number violation and therefore provide a natural theoretical scheme that could explain, on the basis of fundamental, microscopic laws such a global property of the universe as its material content. In the last two years a scenario for the origin of matter-antimatter asymmetry has been developed. It, as we have mentioned, incorporates the basic and general aspects of grandunification and the standard cosmological model and provides a simple, and logically consistent picture. It is our task to show that. As we shall see, it requires, at this point, a lot of faith, but future tests (of the proton decay) will hopefully justify it.

We start by briefly recalling some of the basic features of grandunified theories.[15] Let us imagine the simplest possibility according to which a unifying group G is broken down to $SU(3)_C \times SU(2)_L \times U(1)$ at a single energy scale M_X. Following Georgi, Quinn and Weinberg,[16] we can trace the momentum dependence of coupling constants and derive the well known relations for the low energy parameters of weak and strong interactions

$$\sin^2\theta_W(M_W) = \frac{3}{8}\left[1 - \frac{55}{9}\ \frac{\alpha(M_W)}{\pi}\ \ln\frac{M_X}{M_W}\right]$$

$$1 - \frac{8}{3}\ \frac{\alpha(M_W)}{\alpha_S(M_W)} = 11\ \frac{\alpha(M_W)}{\pi}\ \ln\frac{M_X}{M_W} \qquad (3.1)$$

Consistency of (3.1) predicts[17] then $M_X = 10^{14} - 10^{15}$ GeV. M_X corresponds roughly to the masses of superheavy or X bosons, which do not carry a fixed baryon number and whose enchange leads to baryon number violation. For example, one species of such bosons carry fractional charge $\pm$ 4/3 and have interactions

$$L_{int} = g_X/\sqrt{2}\ X_{\mu i}\left[\varepsilon_{ijk}\ \overline{u^C_{Lj}}\ \gamma^\mu\ u_{Lk} + d_i\ \gamma^\mu\ e^+\right] \qquad (3.2)$$

where C denotes charge conjugation and i, j, k stand for color. A tree level process in which X is exchanged leads to proton decay $p \to \pi^0 + e^+$ (see Fig. 1). From the prediction for $M_X \simeq 10^{14} - 10^{15}$ GeV, we can estimate $\tau_p \simeq 10^{31\pm2}$ years, which is within reach of experiments now in progress.

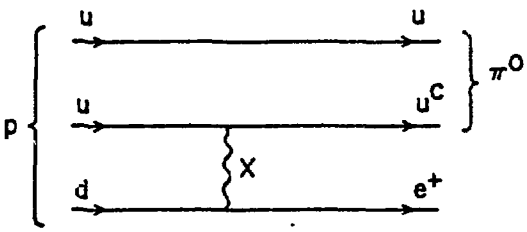

Fig. 1. Proton decay $p \to \pi^0 e^+$ as induced by exchange of X boson.

At very high temperature $T \gtrsim M_X$ the decays of X bosons should have played an important role, presumably being responsible for the observed baryon asymmetry. Namely, these bosons can decay into the channels with different baryon numbers

$$X \to \begin{cases} qq & B_1 = 2/3 \quad \text{branching ratio } r \\ \bar{q}\bar{l} & B_2 = -1/3 \quad \text{branching ratio } 1 - r \end{cases}$$

and

$$\bar{X} \to \begin{cases} \bar{q}\bar{q} & -B_1 = -2/3 \quad \text{branching ratio } \bar{r} \\ ql & -B_L = 1/3 \quad \text{branching ratio } 1 - \bar{r} \end{cases} \qquad (3.3)$$

If the branching ratios r and $\bar{r}$ are different, then when the temperature dropped below M_X, we would expect that a small asymmetry should have developed. As the temperature dropped even further, much below M_X, the baryon violating processes gradually stopped playing an important role (for being very slow) and so the induced small baryon excess should roughly correspond to the amount of matter in the present universe.[18]

Let us discuss the above picture in some detail. First, the key (necessary) ingredients for the explanation of n_B/S are

(i) microscopic baryon number violation

(ii) departure from thermal equilibrium

(iii) CP violation.

The condition (i) is automatically satisfied in most grandunified theories. Its necessity is obvious, unless we accept a baryon number of the universe as a mysterious initial condition.

The condition (ii) is also easy to understand.[19] If the baryon violating interactions are always in equilibrium, then the numbers of particles and antiparticles would be given by $e^{-m/kT}$ and $e^{-\bar{m}/kT}$ ($\bar{m}$ is the antiparticle mass), which are equal by CPT invariance: $m = \bar{m}$.

Finally, the condition (iii) comes about for the following reason. CP invariance implies the following equality between the amplitudes

$$M(i \rightarrow j) = M(\bar{i} \rightarrow \bar{j}) = M(j \rightarrow i) \tag{3.4}$$

where bars indicate, as before, CP conjugate states. Clearly, no asymmetry can be established.

We should make an important remark regarding the condition (iii). Namely, if we write for the amplitudes in the perturbation theory

$$\begin{aligned} M(i \rightarrow j) &= g_0 + g_1 F \\ M(\bar{i} \rightarrow \bar{j}) &= g_0^* + g_1^* F \end{aligned} \tag{3.5}$$

where g_0 denotes the tree level contribution and F denotes the Feynman amplitude, then[4]

$$|M(i \rightarrow j)|^2 - |M(\bar{i} \rightarrow \bar{j})|^2 = \mathrm{Im}\, g_0 g_1^* \times \mathrm{Im} F \ . \tag{3.6}$$

Therefore, an absorptive part of the amplitude has to be nonvanishing (i.e., physical intermediate states) and also we need the interference between the lowest and higher orders. The latter is a very useful result, since it tells us that n_B/S is expected small, in some sense. How small precisely, will depend on the amount of CP violation at high temperature. Furthermore, one can also derive the following result:[20]

$$\sum_{j=B} |M(i \rightarrow j)|^2 = \sum_{j=-B} |M(\bar{i} \rightarrow \bar{j})|^2 \tag{3.7}$$

which holds true to all orders in baryon conserving interactions and to the first order in baryon violating interactions. Therefore, $n_B/S \neq 0$ requires higher orders in baryon nonconserving forces.

Let us now follow the history of the universe from the earliest moments and present the scenario which meets all the necessary conditions (i), (ii), and (iii). We shall need to compare the expansion rate of the universe

$$H \simeq \sqrt{N}\ \frac{T^2}{M_p} \tag{3.8}$$

and the decay rate of X bosons[21]

$$\Gamma_X \simeq \alpha_X N \frac{m_X^{\ 2}}{\sqrt{T^2 + m_X^{\ 2}}} \tag{3.9}$$

where $\alpha_X \simeq 10^{-2}$ for gauge mesons and $\alpha_X \simeq 10^{-5} - 10^{-6}$ for Higgs boson interactions. In what follows we shall ignore the baryon violating collisions of light particles, since it can be shown that such processes cannot lead to baryon asymmetry.[4]

(1) $T \leq M_p$

Obviously, $\Gamma_X << H$ which means that the expansion rate of the universe is so fast that the decays do not occur. The baryon number is given now by the initial condition at $T = M_p$. Its value, as we shall see is irrelevant for future asymmetry.

(2) $T \simeq 10\ m_X$

The main change that has occurred is that the expansion rate has showed down and $\Gamma_X \simeq H$. Therefore, X decays and inverse decays establish an equilibrium an so $n_B(T = 10\ m_X) \simeq 0$. That's a very important result and it means that irrespectively of the initial condition the universe is bound to go through an epoch of equilibrium during which any preexisting baryon number has to vanish. At these temperatures, we start naturally with a symmetric universe.

(3) $T < m_X$

Now, $\Gamma_X > H$. Decays are very important. However, inverse decays become more and more rare, due to Boltzmann suppression $e^{-m_X/kT}$. The needed departure from the equilibrium gets created. If X and $\bar{X}$ bosons do not decay equally fast, an excess of matter over antimatter will be created. What is required is CP violation.

(4) $T << m_X$

As the temperature drops down, X bosons will all decay. Created baryon excess should survive today. Of course, baryons and antibaryons will annihilate when temperatures is of order of their masses much later in the evolution of the universe, leaving only matter behind.

Now, in order to estimate the induced baryon to entropy ratio we need to know the density of X bosons n_X and the total entropy at $T \simeq m_X$. At such high temperature

$$n_X \simeq N_X T^3$$

$$s \simeq NT^3 \qquad (3.10)$$

where N_X is the number of X spin states and N is the number of all spin states, the assumption being that the baryon conserving collisions were in equilibrium so that (3.10) applies. But then[21]

$$\frac{n_B}{s} = \frac{N_X}{N} \Delta B \qquad (3.11)$$

with ΔB the net baryon number produced for the decay of X bosons. From (3.3) we evaluate ΔB

$$\Delta B = [rB_1 + (1 - r) B_2 - \bar{r}B_1 - (1 - \bar{r})B_2] = (r - \bar{r}) (B_1 - B_2). \qquad (3.12)$$

Since $B_1 - B_2 \simeq 1$, we get

$$\frac{n_B}{s} \cong \frac{N_X}{N} (r - \bar{r}) \simeq 10^{-2}(r - \bar{r}) \qquad (3.13)$$

In order to predict the correct amount of matter in the universe, we need $r - \bar{r} \simeq 10^{-7} - 10^{-9}$. In the next section we discuss the theories of CP violation and their predictions for $r - \bar{r}$. We shall, of course, need to discuss the high temperature behavior of gauge theories, in particular the theories of CP non-conservation.

IV. HIGH TEMPERATURE BEHAVIOR OF GAUGE THEORIES AND CP VIOLATION IN THE EARLY UNIVERSE

For the purpose of discussing phenomena which supposedly took place at $t \simeq 10^{-35}$ sec ($T \simeq 10^{15}$ GeV) we need to know the nature of baryon number and CP violating interactions at high temperature. That question is closely tied up to the origin of such interactions, namely whether they are intrinsic (that is, present in the basic symmetric Lagrangian) or the product of symmetry breaking.

If the interactions are intrinsic, then they will remain operative at any temperature, since the form of the Lagrangian is temperature independent. If they, however, result from symmetry breaking of the originally symmetric theory then the question of the form of such interactions depends on the nature of symmetry breaking at high temperature.

Now, baryon number violation is intrinsic in the minimal schemes, such as SU(5) or O(10), whereas in the Pati-Salam theory baryon number is spontaneously broken. For the sake of simplicity we assume intrinsic baryon number nonconservation, since there is no other reason, besides aesthetical and philosophical one, to assume otherwise.

In the case of CP nonconservation, we have similarly theories of intrinsic (hard) and spontaneously broken[22] (soft) CP violation. We describe first the minimal $SU(2)_L \times U(1)$ hard CP theory with 6 quarks, known as KM model.[7] One assumes a single Higgs doublet ϕ, which implies that $\langle\phi\rangle$ can be made real by the use of gauge symmetry. In this case one <u>requires</u> complex Yukawa couplings in order to generate CP violation. The Yukawa interactions have the form

$$Ly = \bar{\psi}_{iL}\, h_{ij}\, \phi\, n_{jR} + \bar{\psi}_{iL}\, \tilde{h}_{ij}\, \tilde{\phi}\, p_{jR} + h.c. \qquad (4.1)$$

where $\tilde{\phi} \equiv i\tau_2\, \phi^*$, n_i and p_i stand for three up and down quarks and ψ_{iL} stands for left-handed doublets $\psi_{iL} = \binom{p_i}{n_i}_L$ $(h, \tilde{h}\varepsilon C)$. It turns out then, that when the quark mass matrices

$$M^n_{ij} = h_{ij} \langle\phi\rangle$$
$$M^p_{ij} = \tilde{h}_{ij} \langle\phi\rangle \qquad (4.2)$$

are diagonalized, so are the interactions of neutral, physical Higgs scalar with quarks. <u>The source of CP violation in this model is complex Cabbibo rotation</u>, which results from complex unitary matrices that diagonalize quark mass matrices. The CP violation resides completely in the gauge meson interactions with quarks.

When this model is extended to SU(5) gauge theory, the doublet of SU(2) × U(1), gets replaced by a <u>5</u> dimensional Higgs multiplet

$$\phi_5 = \begin{pmatrix} H_1 \\ H_2 \\ H_3 \\ \phi^+ \\ \phi^0 \end{pmatrix} \qquad (4.3)$$

where H_i $(i = 1,2,3)$ is a color triplet of fractionally charged, superheavy Higgs bosons. Due to the complex Yukawa couplings, their interactions with quarks will be CP nonconserving, and so their decays will not respect CP.

In the case of soft CP violation, one assumes all the couplings in the basic Lagrangian real, so that CP is a good symmetry prior to symmetry breaking. The motivation for these theories, besides the philosophical or aesthetical preference, is that they offer a natural resolution of the strong CP problem, as I will discuss below.

Let me first describe the simplest scheme, based on the two Higgs doublet $SU(2)_L \times U(1)$ model.[22] It turns that, consistent with a minimization of the potencial, one can achieve, in a range of the free parameters of the potential that

$$\langle\phi_1\rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle\phi_2\rangle = \begin{pmatrix} 0 \\ e^{\pm i\alpha}\ v_2 \end{pmatrix} \qquad (4.4)$$

where v_1, v_2 and α are real numbers. Then the quark mass matrices, say for the down quarks

$$M^n_{ij} = h^1_{ij}\ v_1 + h^2_{ij}\ e^{i\alpha}\ v_2 \qquad (4.5)$$

become complex and, similar to the kM case, the Cabbibo rotation will be complex. The minimal soft CP model completely mimics kM scheme in the gauge meson sector. The extra physical Higgs scalars, present in the model, have CP nonconserving interactions with quarks which, if nothing else, tend to alter the KM prediction for the electric dipole moment of the neutron. One predicts $d_n^e \approx (10^{-25} - 10^{-28})$ecm which serves as a distinguishing feature from the superweak[23] and kM model.

The question is, do we need soft CP violation? Since one measures only the resulting, physical effects why talk of sponanteous breaking of CP? The answer is: natural explanation of the smallness of strong CP violation seems to favor soft CP violation. Let us first review briefly what the strong CP problem is.

From the form of the QCD Lagrangain it was shown originally[24] that strong interactions conserve P and CP to order $G_F\alpha$ (and not only α). The result followed from the neglect of the allowed term (by the symmetry and renormalizability) $\varepsilon_{\mu\nu\alpha\beta} F^{i}_{\mu\nu} F^{i\alpha\beta}$, since such a term is a total divergence and was not expected to play a role in physical phenomena. However, from the work of 't Hooft and others[25] we have learned that such a term cannot be ignored: through the perturbative, instanton effects it leads to an effective interaction

$$L_{eff} = c[e^{i\theta} \det|\bar{q}^0_L q^0_R| + e^{-i\theta} \det|\bar{q}^0_R q^0_L|] \tag{4.6}$$

where $q^0_{L,R}$ denotes all the (weak eigenstates) quark flavors and c is a dimensional parameter. The interactions in (4.7) violate both P and CP. From the upper limit on the electric dipole moment of the neutron[26] $d_n^e \leq 10^{-24}$ ecm, one obtains a limit[27] $\theta \leq 10^{-9}$. The burning question then becomes as why is θ so small? A trivial answer could be: set $\theta = 0$ and it will always remain such, since it cannot be induced perturbatively. Unfortunately, it doesn't work. As is well known, the quark mass matrices are in general arbitrary and complex, so that in the process of diagonalization

$$q^0_{L,R} \equiv U_{L,R}\, q_{L,R}$$
$$U^+_L\ M\ U_R = D \equiv \begin{pmatrix} m_1 & & 0 \\ & m_2 & \\ 0 & & \ddots \end{pmatrix} \tag{4.7}$$

an additional complex phase in (4.6) will be induced, and the effective $\bar{\theta}$ parameter becomes

$$\bar{\theta} = \theta + i \ln \frac{\det M}{\det M^{+}} \tag{4.8}$$

Well, maybe we should instead set $\theta_{tree} = 0$ and hope that perturbation theory keeps it finite and small. In the absence of any symmetry that of course won't work. Weak and electromagnetic interactions will induce infinities, since there is no reason for them not to (we know that all counterterms allowed by asymmetry must be present to ensure the renormalizability of gauge theories). For example, in kM scheme infinities were explicitly isolated[28] (albeit in high orders in perturbation theory).

An interesting suggestion has been made by Peccei and Quinn[29], who postulate an existence of extra $U_A(1)$ axial symmetry, which effectively removes $\bar{\theta}$ from the theory. Such a symmetry, as was realized by Weinberg and Wilczek[30], gets broken and so results in a pseudogoldstone boson, axion, which gets a tiny mass due to instanton effects. Axion seems to be ruled out experimentally[31], at least in the context of the standard model.

Another simple possibility is that some quark, presumably up quark, is massless so that the chiral symmetry eliminates $\bar{\theta}$. It seems to be disfavored by current algebra. In any case, question then just becomes: why is $m_u = 0$?

Finally, it has been suggested[32] that if CP is broken spontaneously, then the symmetry of the original Lagrangian may be used to set $\theta_{tree} = 0$ and then, hopefully, the same symmetry would keep θ finite to all orders in perturbation theory. Of course, it is $\bar{\theta}$ that has to be calculable and small.

One particular program[33] utilizes left-right symmetric gauge theories, derived by Pati, Salam, Mohapatra and the author[34], in order to explain parity violation in weak interactions. According to these theories parity violation is a low energy phenomenon (result of spontaneous symmetry breaking) which ought to disappear at high energies. In the case of the so called manifest left-right symmetric models[35], characterized by hermetian mass matrices $M = M^{+}$ (and $U_L = U_R$) $\bar{\theta}_{tree} = 0$. Infinities do not appear and $\bar{\theta}$ is a calculable quantity. Estimates[33] show $\bar{\theta}$ (1 loop) = 0 and also $\bar{\theta}$ (2 loop) $\leq 10^{-10}$. The strong CP violation becomes naturally small.

We hope to have convinced the reader that soft CP violation is a highly desirable tool in understanding the smallness of strong CP nonconservation. To make the whole program fully viable we have to make sure that soft CP violation remains at $T \simeq 10^{15}$ GeV[36], when the baryon excess was created. That is tied up with the whole question of symmetry behavior of gauge theories at high temperature, which we now address.

By the analogy with ferromagnetic systems, one would intuitively expect a phase transition at $T_c \simeq \langle\phi\rangle$ as to lead to symmetry restriction for $T \gtrsim T_c$. This is exactly what the actual computations in the simple Higgs model demonstrated.[8] Let us take an example of the scalar model. The temperature dependent Higgs potential is[8]

$$V(T) - \left(- \frac{\mu^2}{2} + \frac{c}{2} T^2\right) \phi^+\phi + \frac{\lambda}{4} (\phi^+\phi)^2 \tag{4.9}$$

where

$$C = \frac{1}{8} \lambda \tag{4.10}$$

From the positi ty of the potential at $T = 0$, $\lambda > 0$ and so $C > 0$. Therefore, the phase transition occurs at

$$T_c \simeq \sqrt{\mu^2/c} \tag{4.11}$$

and so

$$T > T_c : \quad \langle\phi\rangle = 0$$

$$T \leq T_c : \quad \langle\phi\rangle = \sqrt{\frac{-CT^2 + \mu^2}{\lambda}} = \sqrt{\frac{c}{\lambda}} \sqrt{T_c^{\,2} - T^2} \tag{4.12}$$

Figure 2 shows the form at the potential for the two phase.

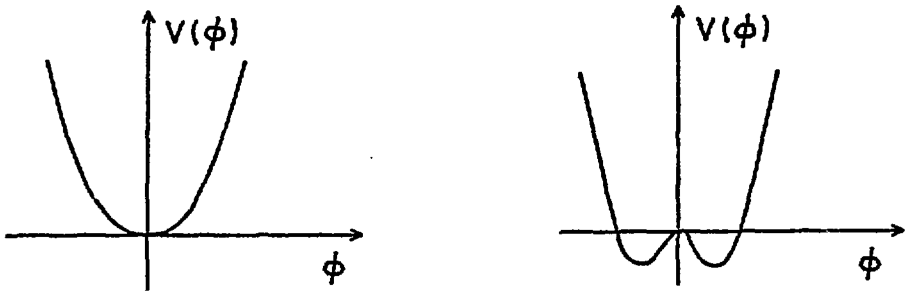

Fig. 2. The unbroken phase for $T > T_c$ in (a) and the broken phase for $T \leq T_c$ in (b).

Actually, the picture (although essentially correct) is somewhat more subtle[37], when the one-loop terms for V(0) are included, which play a dominant role neat $T \approx T_c$, as Coleman and Weinberg[38] have taught us. The phase transition becomes first order and schematically the situation looks as in Fig. 3.

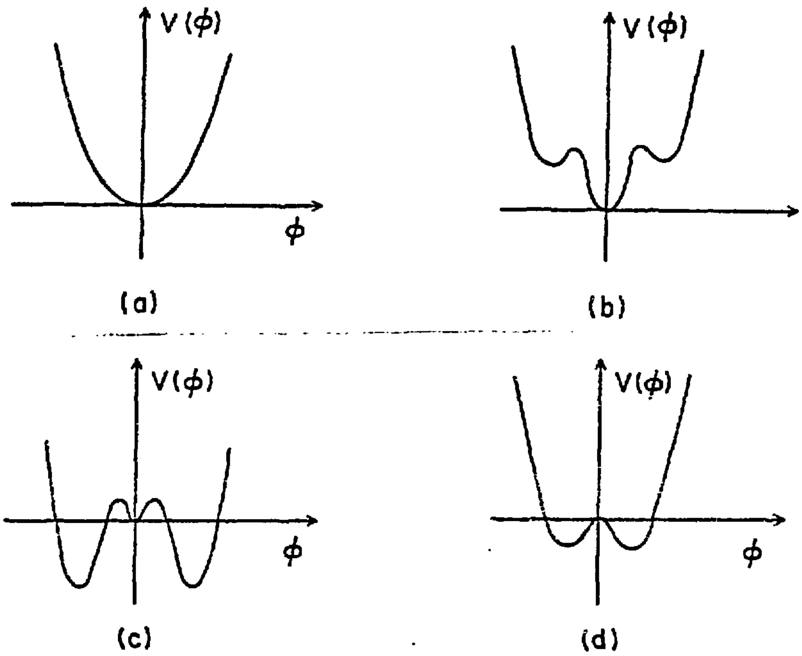

Fig. 3. Before going from unbroken phase a) to broken one d); the potential goes through phases b) and c) with broken and unbroken false vacua, respectively (in addition to true vacua).

We turn now to the implications of above analysis for the creation of baryon asymmetry in the early universe.

(i) <u>Hard CP violation: KM scheme</u>

As we have seen above $T_c \approx 300$ GeV, $\langle\phi\rangle$ vanishes. Therefore, for $T \geq T_c$, $M_q = 0$ and the Cabbibo rotation becomes identity: $U_c = 1$. At high temperature, gauge meson interactions conserve CP. Their interactions cannot, by themselves, induce a baryon asymmetry. Something else is needed and that, of course, are Higgs bosons. As we have seen in (4.3), the $\underline{5}$ dimensional Higgs of SU(5) consists of, besides the usual light Higgs particles, a color triplet of super-heavy Higgs scalars whose interactions with quarks and leptons violate baryon number. Due to complex Yukawa couplings, these interactions violate CP as well, at all temperatures. Their decays, it turns out, play a dominant role in the generation of matter-antimatter asymmetry.

Still, the minimal, single Higgs scheme does not pass the test of predicting the correct n_B/S Namely, nonvanishing $r - \bar{r}$ appears only at the three loop level[39] and for ordinary quarks one gets a hopelessly small baryon number $n_B/S \leq 10^{-18}$. A way out is to postulate the existence of a rather heavy quark Q ($m_Q \approx 100$ GeV), whose Yukawa couplings would not be small and so even the three-loop contribution would be nonnegligible.[40] Alternatively, one could imagine two $\underline{5}$'s of SU(5), in which case the one-loop diagram shown in Fig. 4 gives a nonvanishing contribution.[41]

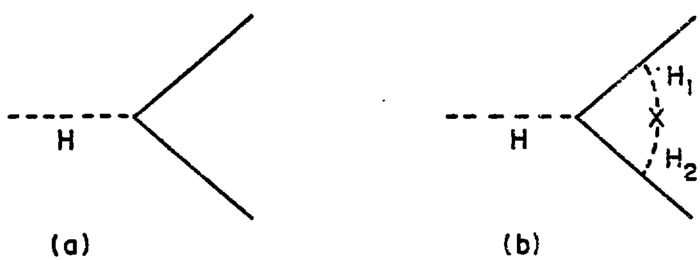

Fig. 4. Nonvanishing $r - \bar{r}$ which results from interference of the tree level graph a) and one-loop b).

Estimates give

$$r - \bar{r} \simeq \frac{1}{16\pi^2} h^2(m_X) \tag{4.14}$$

or

$$\frac{n_B}{S} \simeq (10^{-3} - 10^{-5})\ h^2(m_X)$$

where $h(m_X)$ are the Yukawa couplings at $T = m_X$, which can be determined from $h(0)$ by the use of renormalization group equations. Yukawa couplings in gauge theories are asymptotically free and so they get smaller at high T. Roughly, for $h(0) \simeq 10^{-2}$ (b,t quarks), we should use $h(m_X) \simeq 10^{-3} - 10^{-2}$. Therefore,

$$\left(\frac{n_B}{S}\right)_{th} \simeq 10^{-11} - 10^{-7} \tag{4.15}$$

a value which does not contradict observation.

(ii) Soft CP Violation

If, as in our example discussed before, the symmetry gets always restored for $T > T_c \simeq 300$ GeV, then at high T, CP would become a good symmetry, since the underlying Lagrangian is CP conserving. That in turn implies $n_B/S = 0$. Do the global observations of the universe rule out spontaneous symmetry breaking as a mechanism for generating CP nonconservation? The answer, as we shall readily demonstrate, is no!

The essential point is that symmetry is not necessarily restored.[42] About a year ago, Mohapatra and myself[9] have redone the analysis of high temperature behavior of gauge theories, motivated by the desire to have a realistic model of CP nonconservation at $T \simeq 10^{15}$ GeV. It turns out that in the models with more complex Higgs sector, not all the vacuum expectation values vanish for $T > T_c$. We present a simple example of a model with two Higgs scalars, with a potential invariant under $\phi_i \to -\phi_i$,

$$V(T) - \tfrac{1}{2}(-\mu_1^2 + c_1 T^2)\ \phi_1^2 + \tfrac{1}{2}(-\mu_2^2 + c_2 T^2)\ \phi_2^2 +$$

$$+ \frac{\lambda_1}{4} \phi_1^4 + \frac{\lambda_2}{4} \phi_2^4 + \frac{\lambda_3}{2} \phi_1^2 \phi_2^2 \tag{4.16}$$

where

$$C_1 = \frac{1}{24} (3\lambda_1 + \lambda_3)$$

$$C_2 = \frac{1}{24} (3\lambda_2 + \lambda_3) \tag{4.17}$$

The positivity conditions at zero temperature, for the case of symmetry breaking $\langle\phi_1\rangle \neq 0 \neq \langle\phi_2\rangle$ are

$$\lambda_1, \lambda_2 > 0 \qquad \lambda_1\lambda_2 - \lambda_3^2 > 0 \tag{4.18}$$

It is clear from (4.17) then, that in the range of parameters

$$3\lambda_2 + \lambda_3 < 0, \ \lambda_3 < 0$$

$$\lambda_1\lambda_2 - \lambda_3^2 > 0 \tag{4.19}$$

$C_1 > 0$ and $C_2 < 0$. Therefore, the temperature dependent mass term for the ϕ_2 field is negative and for the $T > T_c \approx \sqrt{\mu_1^2/c}$

$$\langle\phi_1\rangle = 0, \quad \langle\phi_2\rangle^2 = \frac{1}{\lambda_2} (CT^2 - \mu_2^2) \tag{4.20}$$

As we promised, the symmetry remains partially broken. Along the same lines, one can easily construct an $SU(2)_L \times U(1)$ model with the two Higgs doublets ϕ_1 and ϕ_2, so that at high T $\langle\phi_1\rangle = 0$, $\langle\phi_2\rangle \neq 0$ and so the $SU(2) \times U(1)$ symmetry does not get restored at all. Since the gauge meson contribution to C_i terms, defined in (4.16), is always positive, in the case of $SU(2) \times U(1)$ model we need some Higgs self-couplings to be not only negative, but also greater than g^2 in order to ensure that one of the C_i's is negative (see Ref. 9). We display below the two different phases, both which amount to the broken $SU(2) \times U(1)$ symmetry.

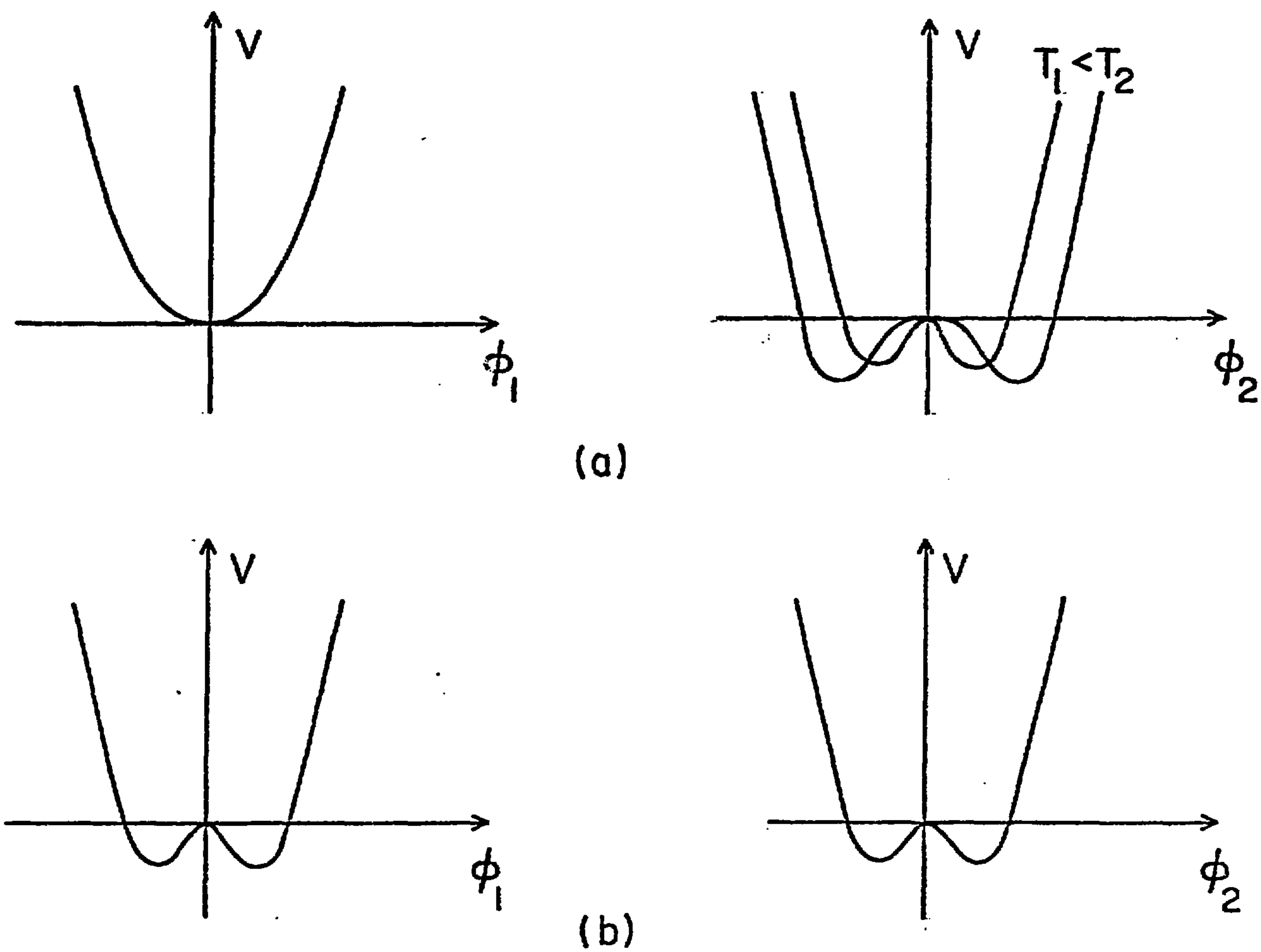

Fig. 5. High T (a) and low T (b) patterns of symmetry breaking in the model discussed above.

Of course, what we are after is CP breaking at high T. Then two Higgs doublets are not enough, since only one of vacuum expectation values remain broken and so by an $SU(2) \times U(1)$ rotation it can be made real. Hence the corollary: for soft CP broken at high T we need at least three Higgs doublets.

A realistic such grandunified theory in which CP is broken at $T \sim m_X$ is then easy to construct.[9] It is based on the SU(5) theory with the three sets of $\underline{5}$ dimensional Higgs multiplets. At $T >> T_c \simeq 300$ GeV one can achieve the following pattern of symmetry breaking

$$\langle\phi_1\rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ v_1 \end{pmatrix} , \qquad \langle\phi_2\rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ v_2 e^{i\alpha} \end{pmatrix} , \quad \langle\phi_3\rangle = 0 \tag{4.21}$$

where $v_i \alpha T$. As displayed in (4.5) quark mass matrices will be nonvanishing and complex, which induces complex Cabbibo rotation for six flavors. Similarly, the Higgs boson mass matrices will be complex, and as a result CP will be broken both in gauge meson and Higgs boson interactions with quarks and leptons. In principle, both the superheavy gauge meson and Higgs boson decays will be inducing the baryon asymmetry. But first, it is important to make sure that quarks and leptons, whose mass depends on temperature are light enough so that the decays are possible. From

$$m_f(T) \simeq h(T)\ v(T) \tag{4.22}$$

and using

$$v(T) \simeq \sqrt{c/\lambda}\ T \simeq T \tag{4.23}$$

we obtain

$$m_f(T) \simeq h(T)\ T \tag{4.24}$$

Now, the baryon asymmetry develops when T drops much below m_X so that the inverse decay is blocked, say at $T \approx \frac{m_X}{10}$. Then

$$m_f \left(\frac{1}{10} m_X \right) \approx 1/10\ h(T) m_X \lesssim (10^{-3} - 10^{-4}) m_X \qquad (4.25)$$

Clearly, the phase space is enormous and so the previous analysis[4,39,40,41] which assumes massless fermions applies. It was shown[43] that the leading graphs which induce the baryon asymmetry are the following

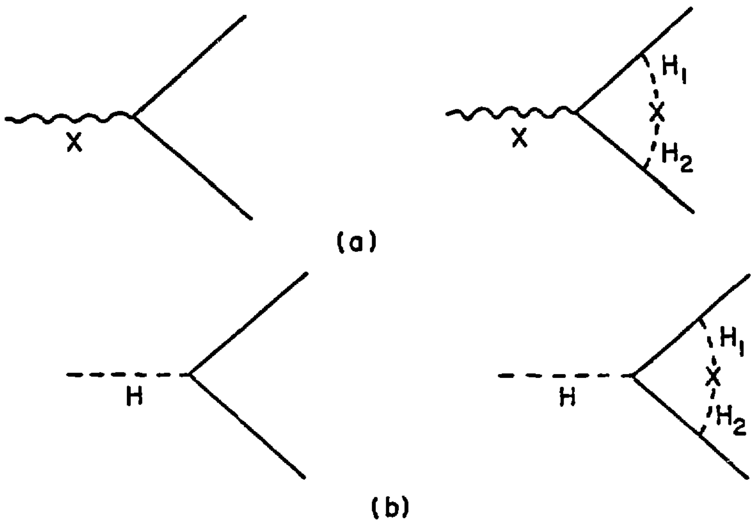

Fig. 6. Gauge meson (a) and Higgs boson (b) baryon number violating decays.

Except for a suppressed mixing between H_1 and H_2, which is of order $T^2/m_X^2 \approx (10^{-1} - 10^{-2})$, the rest of the computation follows the conventional two Higgs model with the results given in (4.14) and (4.15). Therefore, we predict

$$\left(\frac{n_B}{S} \right)_{\text{soft CP}} \approx 10^{-8} - 10^{-13} \qquad (4.26)$$

which is in agreement with observation.

In summary, due to increased symmetry breaking at high temperature soft CP violation in a large class of models doe remain at $T \approx m_X$ as to ensure the non-vanishing dynamically originated baryon number. In terms of actual quantative prediction, we can say the same as for the other models of CP violation discussed before: they do not obviously fail. We clearly need a specific theory at our hands to be able to discuss these questions more precisely. As far as the discrimination between the various mechanisms of CP nonconservation, i.e., hard and soft, we have to patiently await future and more precise, low energy measurements.

One can wonder, in the context of soft CP models, what happens when the temperature increases beyond 10^{15} GeV. Well, it turns out that we cannot give a definite answer. Namely, ϕ^4 couplings are not asymptotically free and so they increase with temperature. Since at T = 0, at least some $\lambda_i \geq g^2$, we expect $\lambda(T=m_X)/4\pi \approx 1$, so that perturbation theory breaks down. It is hard to estimate precisely at what T it happens, but roughly $T \approx 10^{17} - 10^{18}$ Gev. In other words we cannot say whether symmetry gets restored or remains broken. Of course, at $T = M_P$ quantum gravitational effects would start to play an important role, confusing the situation even more.

An amusing comment can be made assuming that the symmetry does get restored at $T >> m_X$. By the anology with ferromagnets one would expect domains with different signs of CP phase to be formed as the universe cools down through the phase transition. From (4.4) we see that both α and $-\alpha$ minimize the potential and since $(r-\bar{r})\alpha \pm \delta$, that would mean that universe consists of domains of matter and antimatter.[44] This picture, in order to work, has to solve the questions of domain sizes and their separation, which may not be impossible in the case of the first order phase transition. More work is called for. We should emphasize, however, that symmetry may not be restored in which case the universe should be solely filled with matter.

Before closing, we would like briefly to mention the question of what gets created in the early universe: matter or antimatter? At the first glance, this looks as a matter of semantics: whatever asymmetry develops, we can call it "matter". However, the situation is not completely arbitrary, and the "matter" is usually defined by the sign of CP violation in K meson decays, so what is needed is the relation between the signs of CP phases in X and K meson decays. Only if the signs are the same can we claim the fully successful understanding of the dynamical origin of the baryon number of the universe. At present the desired connection between the CP phases is still lacking.

Let me point out briefly what seems to be the problem in the case of the simplest grandunified theory, i.e., minimal SU(5) theory with a single $\underline{5}$ multiplet. At low energies, the only source of CP violation is the complex Cabbibo rotation, its complexity being the product of orginally complex Yukawa couplings. At high temperatures, Cabbibo rotation disappears since the quarks become massless and CP violation resides in Yukawa couplings only. In order to relate the CP phases in the light and the heavy section of the theory, one would need a one-to-one correspondence between the KM phase and the phases of Yukawa couplings, which, unfortunately, is obscured by the phase redefinitions used to simplify the form of KM matrix.

In my opinion, the hope of relating the phases in K and X meson decays lies in soft CP models. There, the symmetry will not be restored at high temperature, which by itself does not provide a solution. However, there is a class of models[45] where one forbids the flavor changing neutral Higgs current, which requires the existence of at least three $SU(2)_L \times U(1)$ doublets (or SU(5) $\underline{5}$'s) In such models the Cabbibo rotation becomes necessarily real[46], so that the only source of CP nonconservation, both at low and high T, are the complex Yukawa couplings. One has then to see what the connection between heavy and light Higgs couplings are. It should be done.

V. SUMMARY

Standard cosmological model and the grandunified theories offer plausible and logically consistent scenario for the dynamical development of matter-antimatter asymmetry of the universe. At the temperatures of order on 10^{16} GeV or so ($\approx 10\ m_X$), the universe has undergone through an epoch of equilibrium which erased any previous baryon number. The present baryon asymmetry becomes therefore a calculable quantity determined by the dynamics of the fundamental interactions present in grandunified theories. These baryon violating forces which are responsible for the equilibrium situation were forced to go out of equilibrium as the universe grew older. Namely, as the temperature dropped below m_X, the inverse decays of superheavy bosons became more and more rare and so eventually all these boson decayed away. Due to CP violation, naturally present in these theories, the rates for X and $\bar{X}$ bosons were not the same and so the baryon asymmetry was created. Originally, there was only a tiny excess of particles over antiparticles which, when the baryons and antibaryons annihilated much later in the history of the universe, remained what we today observe as matter.

Unless there are heavy quarks ($m \approx 100$ GeV), the analysis of the induced baryon number tells us that the minimal SU(5) theory cannot account for the observed asymmetry. We need at least two $\underline{5}$ Higgs multiplets. It is an interesting and amusing result, since our low energy phenomenology typically depends on the type of the scalar multiplets and not on their number.

Now, the predicted baryon number depends on whether the CP violation is of hard or soft origin, a question which has profound effect on our understanding of strong CP nonconservation. Hard CP violation, automatically present at high T, leads to $n_B/S \approx 10^{-11} - 10^{-7}$. On the other hand, soft CP nonconservation requires theoretically perfectly acceptable symmetry restoration at high temperature in order to remain at $T \simeq 10^{15}$ GeV and predicts $n_B/S \simeq 10^{-13} - 10^{-9}$. Both results do not disagree with observation. I should add that the computations are plagued by the uncertainties in the values of CP phases and of Yukawa couplings (or quark masses). At present, we just cannot make precise predictions, before all the quark masses are known.

The above picture appears appealing and plausible. However, clearly much more work remains to be done. In particular, in my opinion, there are two fundamental questions which need to be answered:

(i) What is the character of produced "matter", i.e., its sign?

(ii) Is the universe filled solely with matter or maybe there are large domains of matter and antimatter and we just happen to live in one of them? And if there are domains, how do we account for their size[47]?

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