Connection between Cosmological Matter-Antimatter Asymmetry and *CP* Nonconservation in *K* Decays

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We suggest a scenario according to which the *CP*-nonconserving interactions responsible for both the generation of matter-antimatter asymmetry in the universe and the microscopic process of $K_L \to 2\pi$ decay have a common origin at high energies. Consistency with the decoupling theorem is discussed. The general characteristics of gauge models that bring out this connection are outlined and a specific SO(10) model is discussed, where n_B/n_γ and ϵ are related.

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Grand-unified theories have raised the very interesting possibility that a microscopic theory of particles and fields can solve an old cosmological riddle—the origin of matter. The idea is based on the proposal of Sakharov,[1] suggested as early as 1967, that baryon-nonconserving interactions in conjunction with *CP* nonconservation can generate an asymmetry between baryons and antibaryons in an appropriate thermodynamical environment.[1] It should, therefore, in principle be possible to connect the baryon number of the universe with the strength of baryon-nonconserving interactions and the observed *CP*-nonconserving decay $K_L^0 \to 2\pi$. This question has been investigated in the past[2] within the framework of grand-unified gauge theories, which contain both *CP*-nonconserving interactions as well as baryon-nonconserving ones. It has been pointed out[2] that there exist several outstanding obstacles in the path of a concrete realization of this idea: (a) In models with hard *CP* nonconservation (*CP* nonconservation intrinsic in the coupling constants), the phases that appear in baryon-nonconserving interactions are different from those appearing in baryon-number–conserving, *CP*-nonconserving interactions, thus eliminating the possibility of any connection of the type we seek; (b) if *CP* nonconservation arises from spontaneous symmetry breaking (as phases in vacuum expectation values), then the existence of phase transitions corresponding to different symmetries complicates, in general, any search for a connection between *CP* nonconservation at high and low temperatures. In particular, the phases[2] at high and low temperature depend on different equations governing the minimum of the potential.

In this Letter, we wish to report on a class of models that we have discovered, where the *CP*-nonconserving phase responsible for a macroscopic quantity such as matter-antimatter asymmetry and for the microscopic process, e.g., $K_L \to 2\pi$ decay, is one and the same. This realizes the long cherished dream of connecting the only two manifestations of *CP*-nonconserving interactions, i.e, n_B/n_γ and $K_L \to 2\pi$ decay. In principle, this paves the way towards understanding why the universe is matter (rather than antimatter) dominated.

Let us now discuss the general characteristics of such models: (a) *CP* nonconservation is either spontaneous or present in soft terms of the potential. (b) It is associated with a superheavy scale. (c) The low-energy electroweak model is such that in the symmetry limit it can accommodate *CP*-nonconserving interactions. [This last condition is nontrivial, since it implies, for example, that if the low-energy gauge group is $\mathrm{SU}(2)_L \otimes \mathrm{U}(1) \otimes \mathrm{SU}(3)_C$, one must have at least three generations.] The important feature of our model is a nondecoupling of heavy-particle effects which transmit the *CP* nonconservation associated with the superheavy scale down to light-fermion mass matrices through quantum effects (see later). For models satisfying this requirement, we find that the baryon to entropy ratio n_B/n_γ and the $K_L \to 2\pi$ decay parameter ϵ obey the following relation:

$$n_B/n_\gamma = \epsilon f, \qquad (1)$$

where f does *not* involve any *CP*-nonconserving phase but depends instead on other coupling parameters of the theory.

In the first part of this paper, we illustrate our idea in the context of an $SU(2)_L \otimes U(1) \otimes SU(3)_C$ model extended to include baryon-nonconserving interactions coupled to superheavy Higgs fields, and in the second part, we present a grand-unified SO(10) realization of our idea.

It may appear to the reader that the suggestion that the observable *CP* nonconservation in *K*-meson decays originates at a superlarge energy scale is in obvious contradiction with the decoupling theorem.[3] If the "light sector" of the theory is characterized by gauge invariance, one may naively interpret the decoupling theorem as the statement that the effects of heavy particles at low energies are inversely proportional to their mass. However, *this is true only if one considers the most general gauge invariant "light" theory.* For example, the most general $SU(2) \otimes U(1)$ theory with only Higgs doublets automatically implies baryon-number conservation. Therefore, any $\Delta B \neq 0$ effect associated with heavy particles will be suppressed by their large masses.

On the other hand, in the scenario that we are suggesting we imagine spontaneous *CP* nonconservation, i.e., real Yukawa couplings. But that is not the most general form of the theory that the gauge invariance allows. Therefore, *the contribution of heavy particles to the imaginary part of Yukawa couplings will not be down by* $1/m_{\mathrm{H}}$. The heavy particles will induce nonnegligible effects at low energies, being actually responsible for the *CP* nonconservation in the kaon system. This is completely analogous to the usual renormalization of $\sin^2\theta_W$ through the heavy-particle effects. All this should be made even more clear when we discuss explicit examples below.

Let us consider an extension of the standard minimal $SU(2)_L \otimes U(1) \otimes SU(3)_C$ model by the inclusion of two superheavy ($m_{\mathrm{H}} \sim 10^{14}$ GeV or so) Higgs bosons ξ_1 and ξ_2 which are singlet under $SU(2)_L$ symmetry but are color triplets with $U(1)_Y$ quantum number $-\frac{2}{3}$. Denoting left-handed quark doublets by Q_i ($i = 1, 2, 3$ for color), leptonic doublet by L, right-handed $SU(2)_L$ singlet quarks by $U_{R,i}, D_{R,i}$, and leptons by E, we can write down the most general $SU(2)_L \otimes U(1) \otimes SU(3)_C$-invariant interaction of quarks and leptons involving ξ_m as follows:

$$\mathscr{L} = \sum_{m,ab} \{h_{ab}^{(m)} \xi_{m,i} Q_j^{a^T} C^{-1} \tau_2 Q_k^b \epsilon^{ijk} + h_{ab}^{(m)'} \xi_{mi} U_{R,j}^T C^{-1} D_{R,k} \epsilon_{ijk} + f_{ab}^{(m)} \xi_{m,j}^\dagger Q_j^{a^T} C^{-1} \tau_2 L^b + f_{ab}^{(m)'} \xi_{m,i}^\dagger U_{R,i}^{a^T} C^{-1} \tau_2 E^b + \mathrm{H.c.}\}, \tag{2}$$

where a and b are generation indices, C is the Dirac charge-conjugation matrix, and τ_2 is the Pauli matrix.

We impose *CP* symmetry on all dimension-4 terms in the Lagrangian so that h, f, and f' as well as the usual low-energy Yukawa couplings are all real. We introduce *CP* nonconservation into the theory via a soft-mass term of the superheavy Higgs bosons ξ_m as follows:

$$\mathscr{L}_m = \textstyle\sum_m M^2 \xi_m^\dagger \xi_m + \mu^2 \xi_1^\dagger \xi_2 e^{i\delta} + \mathrm{H.c.} \quad (\text{where } M, \mu \sim m_{\mathrm{H}}). \tag{3}$$

First, we show that in this model, one can generate cosmological baryon-antibaryon asymmetry starting with a symmetric "big-bang" model. The n_B/n_γ is then obviously proportional to $\sin\delta$. Then, we argue, that at the one-loop level, the light-fermion mass matrix becomes complex, thereby including *CP*-nonconserving $K_L \to 2\pi$ decays. Since δ is the only phase in the theory, we find that the ϵ parameter is also proportional to $\sin\delta$, and hence the desired connection emerges.

The baryon asymmetry arises from the interference between the tree and one-loop graphs, a typical one of which is shown in Fig. 1 and is given by

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} = (-\sin\delta) \textstyle\sum_m \{[\mathrm{Tr}(h^{(m)^\dagger} h^{(1)} f^{(m)^\dagger} f^{(2)}) - \mathrm{Tr}(h^{(m)^\dagger} h^{(2)} f^{(m)^\dagger} f^{(1)})] + \frac{1}{2}(f,h \to f',h')\} 8 \frac{\mathrm{Im} A_1^{(m)}}{\Gamma(\xi^m)}, \tag{4}$$

where $\mathrm{Im} A_1$ represents the absorptive part of Fig. 1(b). The conditions for equilibrium can be easily satisfied by an appropriate choice of h's and are not relevant in our discussion.[1]

To see the impact of *CP* nonconservation in the light-fermion sector, we look at the one-loop diagram (Fig. 2) involving the exchange of superheavy Higgs triplets. In the presence of these one-loop diagrams,

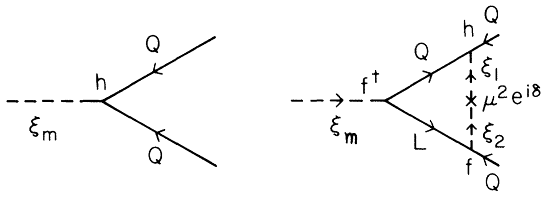

FIG. 1. Typical tree and one-loop graphs whose interference leads to the generation of cosmological baryon asymmetry.

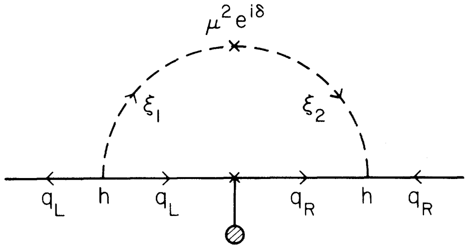

FIG. 2. One-loop graphs that induce *CP* nonconservation into the quark mass matrices.

the quark mass matrix can be written as

$$M_\pm = M_\pm^{(0)} + M_\pm^{(1)}, \tag{5}$$

where +,− stand for weak isospin $+\frac{1}{2}$ and $-\frac{1}{2}$ components, respectively. The important point is that the *CP*-nonconserving terms in the quark mass matrices do not decouple in the limit of $M, \mu \rightarrow \infty$ for reasons discussed before. To see this, let us calculate $M_\pm^{(1)}$:

$$(M_\pm^{(1)})_{ab} \simeq e^{i\delta}\left(\frac{\mu^2}{M^2}\right)\frac{1}{16\pi^2}\,(h^{(1)T}M_\mp^{(0)}h^{(2)\prime})_{ab} + e^{-i\delta}\left(\frac{\mu^2}{M^2}\right)\frac{1}{16\pi^2}(h^{(2)T}M_\mp^{(0)}h^{(1)\prime})_{ab}. \tag{6}$$

It is then clear that as $\mu^2, M^2 \rightarrow \infty$ the effect is nonzero and finite. Thus, the heavy-particle effects do not decouple and the high-energy *CP*-nonconserving phase "trickles" down to the light-particle sector.

The mass matrix in Eq. (5) can be diagonalized and the *CP*-nonconserving phase can be transferred to the currents as usual. This illustrates the main physics point of our paper. Let us briefly address the quantitative aspect of discussion. Since the *CP*-nonconserving phase in the mass matrix arises at the one-loop level, is it really big enough to be a useful source of low-energy *CP* nonconservation? Clearly if the low-energy sector is chosen to be minimal, i.e., one Higgs doublet only, we can easily estimate $M^{(1)}$ and we find that the *CP*-nonconserving terms in the mass matrix are multiplied by terms of order $G_F m_f^2/16\pi^2 \lesssim 10^{-5}$ and are negligible. On the other hand, if we work with two-Higgs models, the light-fermion–doublet-Higgs Yukawa couplings can be of order 1 without conflicting with phenomenology and the above coefficients can be big.

A second question is, can we predict the sign of the baryon asymmetry? Unfortunately, the answer to this question is negative as a result of the presence of several arbitrary parameters whose signs are *a priori* unknown.

We now turn to an SO(10) grand-unified model where this idea is realized. We consider the usual SO(10) models with an additional *CP* symmetry such that all couplings are real. Thus, the model is fully *CP* conserving prior to spontaneous symmetry breaking. We consider the following set of Higgs multiplets to implement symmetry breaking: Two {45}-dimensional Higgs multiplets denoted by $\phi_{\mu\nu}^a$, $a = 1, 2$, a {126}-dimensional representation, denoted by $\Sigma_{\mu\nu\lambda\rho\sigma}$, and two {10}-dimensional Higgs multiplets, $H_\mu^{(a)}$, $a = 1, 2$. The symmetry-breaking chain is as follows[4]:

$$\begin{tikzcd}
\mathrm{SO}(10) \arrow[r, "\{45\}", "M_X"'] & \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{SU}(3)_C \otimes \mathrm{U}(1)_{B-L} \arrow[d, "\{126\}", "M_R"'] \\
\mathrm{U}(1)_{\mathrm{em}} \otimes \mathrm{SU}(3)_C & \mathrm{SU}(2)_L \otimes \mathrm{U}(1) \otimes \mathrm{SU}(3)_C . \arrow[l, "\{10\}"', "M_W"]
\end{tikzcd}$$

It has been pointed out[5] that subsequent to spontaneous breakdown of SO(10) symmetry by {45}-dimensional Higgs multiplet, the color-triplet Higgs bosons in the {10}-dimensional Higgs multiplets H mix with a complex mass. Furthermore, if we choose one $\phi_{\mu\nu}$ to be odd under *CP* and another to be even, both the *CP* symmetry as well as the *D* symmetry (the analog of charge conjugation) present in the SO(10) model are broken.[6] Thus, regardless of the scale of the right-handed W_R bosons, an adequate baryon asymmetry can be generated. The model now becomes similar to the one discussed in the first part, except that we have $h = h'$, $f = f'$ and the rest of the discussion goes through.

In conclusion, we have developed a scenario for the unified gauge theories where the cosmological baryon asymmetry and the *CP* nonconservation in $K \rightarrow 2\pi$ decay owe their origin to a common phase,[7] thereby unifying the two very different manifestations of *CP* nonconservation. An SO(10) model that illustrates this idea has been presented.

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