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ABSTRACT

We consider scenarios for baryon production within the context of SU(5) and SO(10) grand unified theories where CP violation arises spontaneously. The spontaneous CP symmetry breaking then results in a matter-antimatter domain structure in the universe.

Recently, progress has been made in understanding the observed ratio of baryons to photons in the universe.[1] The picture which is emerging involves the creation of baryons (which later became galaxies) from initially thermal radiation having no net baryon number through baryon-number violating and CP violating decays of the superheavy bosons of the grand unified theories. With this scenario, the baryon-photon ratio of the universe becomes a calculable quantity, or at least a quantity which can be determined from other parameters of the theory such as the CP asymmetry, which may potentially be calculable.

Within the framework of this scenario, a new important question can be posed: Is the universe as a whole filled only with excess matter (no antimatter) or does the universe evolve large regions which separately contain either matter <u>or</u> antimatter excesses with the universe as a whole having no built in preference concerning baryon number? This question is intimately tied up with the nature of CP nonconservation.[2] The answer depends on whether the CP violation at the superheavy energy scale is hard or soft, i.e., whether it is built into the theory via complex Yukawa couplings or whether it originates from spontaneous symmetry breaking in an initially CP-conserving theory. In this paper, we discuss theories of soft CP violation, i.e., the theories in which all the couplings in the Lagrangian are real. Within these theories, for a given range of parameters and a sufficiently large Higgs sector, the real Higgs potential will generate complex vacuum expectation values leading to CP-violation.[3] We show that the CP violation will arise with random sign changes in causally independent regions and the universe will naturally evolve a baryon-antibaryon domain structure.[2]

As discussed previously, the theory of soft CP violation leads to a domain structure of the universe when horizon effects are taken into account.[2] It has been further pointed out that the gravitational effect of the vacuum energy of the Higgs fields on the evolution of the universe can lead to a dynamical mechanism for horizon growth to astronomically relevant sizes.[4] It has also been pointed out that one may require a theory in which CP invariance is broken softly in order to explain the small magnitude of the QCD induced strong CP-violating phase.[5]

We discuss two distinct classes of models, viz., those with only one source of CP violation independent of temperature and those in which the CP violation at the superheavy mass scale has nothing to do with the observed CP violation at "low temperatures" in the K^0-$\bar{K}^0$ system. These models are based on the SU(5) and the SO(10) grand unified theories, respectively. We conclude that independently of the particular model, the domain picture of the universe emerges naturally in theories of soft CP violation. Of course, the ultimate understanding of the baryon and antibaryon content of the universe will be provided by observation.

We first consider the SU(5) model.[6] In the minimal SU(5) model with only one Higgs 5, CP violation has to be put in "by hand" in the Lagrangian in the form of complex Yukawa couplings, since the vacuum expectation value of the Higgs 5 can always be redefined to be real by means of a gauge transformation. Choosing such a hard CP violation, aside from being unsatisfactorily ad hoc, yields a baryon-photon ratio which is unacceptably small compared to that determined by astrophysical observation.[7] It is therefore necessary for consistency to increase the number of 5 dimensional Higgs multiplets. Increasing this number to three results in a realistic grand unified theory based on SU(5) which allows for soft CP violation at high temperatures.[8] Two of the Higgs fields acquire vacuum expectation values with a relative phase which cannot be transformed away since they carry the same U(1) quantum number. We thus consider for the Higgs sector three 5 dimensional representations of SU(5) with the following pattern of symmetry breaking at the electroweak level ($T \sim 300$ GeV):

$$\langle\chi\rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \rho \end{pmatrix}, \quad \langle\phi_1\rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ v_1 \end{pmatrix}, \quad \langle\phi_2\rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ v_2 e^{i\theta} \end{pmatrix} \tag{1}$$

It can be shown[8] that at $T \gg 300$ GeV the symmetry will still be broken, with $\langle\chi\rangle = 0$ but with $\langle\phi_1\rangle$ and $\langle\phi_2\rangle$ nonvanishing in the model which has been called the "superconducting early universe".[9] Now it is easy to see that the potential as a function of θ can, in general, be written as

$$V(\theta) = A+B\cos\theta + C\cos 2\theta \tag{2}$$

where A, B, and C are independent of θ. Obviously, for an appropriate range of parameters, the minimum of the Higgs potential lies at $\theta_0 \neq 0$ with $\cos\theta_0 = -B/4C$, so that <u>we always have two solutions</u>, $\underline{\theta_0}$ and $\underline{-\theta_0}$. Keeping this in mind, let us now turn to the mechanism for the production of baryons.

One can show that the dominant graphs determining the baryon asymmetry (shown in Figure 1) involve the decay of superheavy gauge and Higgs bosons corrected at the one loop level by an exchange of Higgs scalars.[7,9] Through such decays, one obtains the following expression for the resulting baryon-photon ratio:[1]

$$n_B/n_\gamma = \frac{N_X}{N} \Delta B(r-\overline{r}) \tag{3}$$

Where N_X and N are the number of species of superheavy and light particles, respectively and r ($\overline{r}$) are the branching ratios for the production of baryons (antibaryons) in the decays of X's with $\Delta B \neq 0$ (net change in baryon number). The difference $r-\overline{r} \sim \mathrm{Im}\,(\mathrm{Tr}\, H_i H_j^\dagger)$ where H_i are the Yukawa couplings (in matrix form) associated with the i-type Higgs multiplets. It is our aim to show now that $r-\overline{r}$ is proportional to θ (the complex phase in the Higgs potential). The proof is very simple; except for the complex mixing between ϕ_1 and ϕ_2 in Figure 1, all other couplings are real. Namely, as we emphasized, ours is a model of spontaneous CP violation in which the complex phase θ originates from an otherwise completely real CP symmetric Lagrangian. It is a simple exercise to find the ϕ_1 $-\phi_2$ mixing. For that purpose, we display the Higgs potential (we need to discuss the piece containing ϕ_1 and ϕ_2 only):

$$V(\phi_1,\phi_2) = -\tfrac{1}{2}\mu_1^2\phi_1^\dagger\phi_1 - \tfrac{1}{2}\mu_2^2\phi_2^\dagger\phi_2 + \tfrac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \tfrac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 + \tfrac{1}{2}\lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2)$$
$$+\tfrac{1}{2}\lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \tfrac{1}{2}\lambda_5\{(\phi_1^\dagger\phi_2)^2 + (\phi_2^\dagger\phi_1)^2\} \tag{4}$$
$$+\tfrac{1}{2}(\lambda_6\phi_1^\dagger\phi_1 + \lambda_7\phi_2^\dagger\phi_2)(\phi_1^\dagger\phi_2 + \phi_2^\dagger\phi_1)$$

where all the coupling constants are real so that, as we mentioned before, CP is a good symmetry prior to symmetry breaking. For simplicity, we display only the mixing between the superheavy colored Higgs particles $\phi^\pm_{1i}$ and $\phi^\pm_{2i}$ ($i = 1,2,3$ is the color index) which carry charges $\pm$ 1/3. The mixing part of the potential is given by

$$V_{mix} = \tfrac{1}{2}\{ v_1 v_2(\lambda_4 e^{-i\theta} + \lambda_5 e^{i\theta}) + \lambda_6 v_1^2 + \lambda_7 v_2^2 \}\, \phi^-_{1i}\phi^+_{2i} + \text{h.c.}$$
$$\equiv z\, \phi^-_{1i}\, \phi^+_{2i} + z^*\, \phi^-_{2i}\phi^+_{1i} \tag{5}$$

The mixing is complex, and its phase is determined from equation (5) to be

$$\tan\delta = \frac{\text{Im } z}{\text{Re } z} = \frac{v_1 v_2(\lambda_5 - \lambda_4)\sin\theta}{\lambda_6 v_1^2 + \lambda_7 v_2^2 + v_1 v_2(\lambda_4 + \lambda_5)\cos\theta} \tag{6}$$

That prov; our claim: $r-\bar{r}$ is proportional to tan δ and therefore to sin θ. Now, since $\theta = \pm\,\theta_o$ (the solution of the minimization of the potential), one obtains

$$n_B/n_\gamma \propto \pm \sin\theta_o \tag{7}$$

The above is the main result of our paper. Now, it has been shown that the renormalization group analysis suggests the possibility (intuitively expected) that at even higher temperatures $T > m_X \simeq 10^{15}$ GeV, the symmetry was unbroken. Then as the temperature decreased below the mass scale of the superheavy gauge bosons, we expect separate domains were generated with θ_o and $-\theta_o$ phases (by the analogy with ferromagnetic systems.) Therefore from equation (7) it is obvious that one is bound to expect domains with matter and antimatter excesses in the universe. Thus our main result: a realistic theory of soft CP violation leads to the domain picture with matter and antimatter being randomly distributed throughout the universe.

To summarize, the model we discussed is a realistic SU(5) theory with CP violation being due to the breaking of $SU(2)_L \times U(1)$ symmetry. We then used the recent result that this symmetry can be broken at temperatures of the order of 10^{15} GeV, with the soft CP violation resulting in the creation of baryon domains of positive <u>and negative</u> asymmetry in the early universe.

We now show, that within a different class of models, one can have a conventional picture of CP symmetry at high temperature leading again to a domain picture of the universe. This is exemplified by a recently suggested model,[10] based on SO(10) grand unified theory.[11] The idea is the following: A 126 dimensional representation of SO(10) can be shown to be able to acquire a complex vacuum expectation value, for a range of parameters of the Higgs potential.[10] Therefore, one can have CP violation at the unification temperature scale completely independent of the nature of the light Higgs sector. (This situation is to be contrasted with the SU(5) theory, where the heavy Higgs is chosen to be a 24 dimensional, or adjoint representation, whose vacuum expectation value is always real.) Again, as in the previous example, one can show that $\pm\,\theta_0$ are solutions which minimize the potential (actually, $\theta_0 = \pi/4$ in this model). Now, even in the conventional picture, according to which the electroweak symmetry $SU_L(2) \times U(1)$ holds at a temperature on the order of the grand unification mass scale (m_X) at which the baryon symmetry is broken, this model still predicts creation of a baryon asymmetry, since the CP violation originates at the grand unification scale through the superheavy Higgs sector. Then, as in the previous example, the domains of matter and antimatter are bound to be formed. We should exphasize, that in the above picture, this conclusion is inevitable, since the symmetry was unbroken at $T > m_X$.

We now conclude: There are two possible, distinct types of theories of soft CP violation. The first type is the theory in which CP nonconservation originates only from the breaking of $SU(2)_L \times U(1)$ symmetry, and the second type being the theory in which even at the unification temperature scale, CP violation can emerge as a result of symmetry breaking by the vacuum expectation values of the superheavy Higgs sector scalars. In the first class of models, discussed within the context of SU(5) grand unified theory, the baryon domain picture of the universe emerges, providing symmetry breaking occurs at $T \sim m_W$ as is commonly assumed. This is a perfectly consistent possibility, leading us to believe in the likelihood of having domians of matter and antimatter in the universe. An example of the second class of model is an SO(10) theory in which CP violation in the early universe results from the breaking of a 126 dimensional Higgs representation so that it occurs at the superheavy scale. In this case, even if the $SU(2)_L \times U(1)$ symmetry breaking is absent above the electroweak energy scale, the CP is still broken by the superheavy Higgs fields at the grand unified energy scale ($T \sim 10^{15}$ GeV) so as to produce the baryon asymmetry. Therefore, the matter-antimatter domain picture again results. These models should be discussed, developed and tested in the context of the cosmological and astrophysical data as previously discussed.[2,12] Additional direct observational tests of the antimatter content of the universe using neutrino astronomy have been suggested[13] and are called for. Thus, observational cosmology could help to determine the nature of the CP violation (hard or soft) in unified gauge theories.

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REFERENCES

1. S. Weinberg, in Lectures on Particles and Field Theories (ed. S. Deser and K. Ford) Prentice Hall; Englewood Cliffs, N. J. 1964, p. 482; A. D. Sakharov, Zh. Eksp. Theor. Fiz. Pis'ma Red. 5, 32 (1967); V. A. Kuz'min, Pis'ma Zh. Eksp. Theor. Fiz. 13, 335 (1970); M. Yoshimura, Phys. Rev. Lett. 41, 381 (1978); A. Yu. Ignatiev, N. Y. Krasnikov, V. A. Kuz'min, and A. N. Tavkhelidze, Phys. Lett. B76, 436 (1978); S. Dimopoulos and L. Susskind, Phys. Rev. D18, 4300 (1978); D. Toussaint, S. Treiman, F. Wilczek and A. Zee, Phys. Rev. D19, 1036 (1979); S. Weinberg, Phys. Rev. Lett. 42, 850 (1979); J. Ellis, M. Gaillard, and D. V. Nanopoulos, Phys. Lett. 80B, 360 (1978); A. Yu. Ignatiev, V. A. Kuz'min and M. E. Shaposhnikov, Phys. Lett. B87, 114 (1979); Pis'ma Zh. Eksp. Theor. Fiz. 30, 726 (1979); A.D. Sakharov, Sov. Phys. JETP 49, 594 (1979); M.Yoshimura, Phys.Lett. B88,294 (1979); see also references 7 and 9.

2. R. W. Brown and F. W. Stecker, Phys. Rev. Lett. 43, 315 (1979); F. W. Stecker and R. W. Brown, Proc. Neutrino 79 International Symposium on Neutrinos, Weak Interactions and Cosmology (ed. A. Haatuft and C. Jarlskog) University of Bergen, Norway 1980, 2, 409.

3. T. D. Lee, Phys. Rev. D8, 1226 (1973); Phys. Rpts. 9, 143 (1974).

4. K. Sato, Nordita Preprint 1980.

5. M. A. B. Beg and H. S. Tsao, Phys. Rev. Lett. 41, 278 (1978); R. N. Mohapatra and G. Senjanović, Phys. Lett. 79B, 283 (1978); H. Georgi, Hadronic J. 1, 155 (1978), A. Segré and A. Weldon, Phys. Rev. Lett. 42, 1191 (1979); S. M. Barr and P. Langacker, Phys. Rev. Lett. 42, 1654 (1979).

6. H. Georgi and S.L. Glashow, Phys. Rev. Lett. 32, 43 (1974).

7. S. Barr, G. Segré and H. A. Weldon, Phys. Rev. D20, 2494 (1979); A. Yildiz and P. Cox, Phys. Rev. D21, 906 (1980); D. V. Nanopoulos and S. Weinberg, Phys. Rev. D20, 2484 (1979); T. Yanagida and M. Yoshimura, Tohuku Preprint (1979).

8. R. N. Mohapatra and G. Senjanović, Phys. Rev. Lett. 42, 1651 (1979); Phys. Rev. D20, 3390 (1979); Phys. Lett. 89B, 57 (1979).

9. R. N. Mohapatra and G. Senjanović, Phys. Rev. D, in press.

10. J. A. Harvey, P. Ramond and D. B. Reiss, Caltech Preprint 68-758 (1980).

11. H. Georgi, in Particles and Fields (ed. C.E.Carlson, A.I.P. Conf. No. 23, New York, 1975); H. Fritzsch and P. Minkowski, Ann. Phys. (N.Y.) 93, 193 (1975); M.S. Chanowitz, J. Ellis and M.K. Gaillard, Nuc. Phys. B128, 505 (1977); F. Hadjionnou, Univ.Athens preprint 1978, C.E. Vayonakis, Univ.Athens preprint 1978; H. Georgi and D.V. Nanopoulos, Phys. Lett. 82B, 392 (1979); Nuc.Phys. B155, 52 (1979); M. Gell-Mann, P. Ramond and R. Slansky (unpublished);

R. N. Mohapatra and B. Sakita, Phys. Rev. D, in press; E. Witten, Phys. Lett., in press; M. Machacek, Harvard preprint, 1979.

12. F. W. Stecker, Nature 273, 493 (1978); Phys. Rev. Lett. 44, 1237 (1980).

13. J. Learned and F. W. Stecker, Proc. Neutrino 79 International Symposium on Neutrinos, Weak Interactions and Cosmology (ed. A. Haatuft and C. Jarlskog) University of Bergen, Norway 1980, 2, 461; F. W. Stecker and R. W. Brown, Proc. 1980 International DUMAND Symposium, Honolulu, Hawaii, in preparation.

FIGURE CAPTION

Figure 1. Dominant diagrams at the one loop level contributing to the production of baryon asymmetry in the early universe by the decay of superheavy bosons into fermions. X stands for superheavy gauge bosons, and the ϕ's denote superheavy Higgs scalars. (The indices i, j count different sets of such multiplets needed in the models discussed).

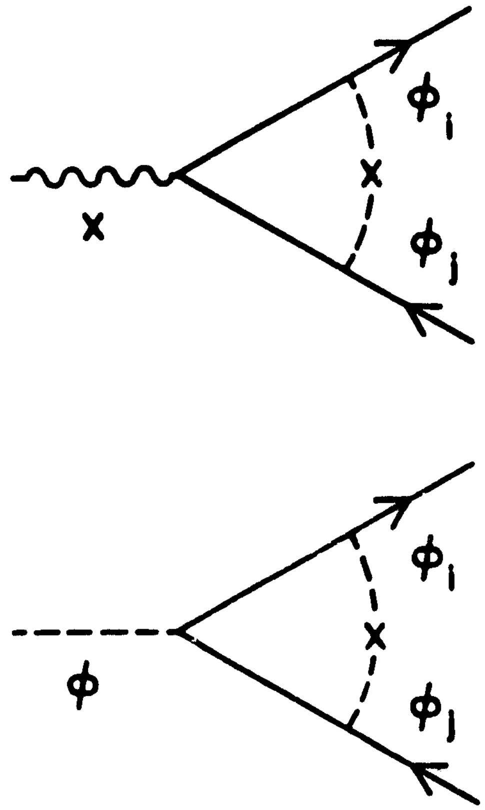

Figure 1.