Are there antimatter domains in the universe?

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A new mechanism for the formation of domains of matter and antimatter in the universe is proposed. In this mechanism there is no problem of the walls between vacuum domains with different *CP* signs.

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The synthesis of unified gauge theories with the theory of a hot universe leads to a qualitative and quantitative explanation[1] of the baryon asymmetry of the universe, which, as we now believe, may have arisen from nonconservation of baryon number in the early, nonequilibrium stages of the expansion of the universe, at temperatures $T \sim 10^{15}$ GeV.

In this approach, whether the universe is globally asymmetric or instead consists of domains of matter and antimatter depends on the nature of the *CP* violation at extremely high energies. If this violation is explicit or "hard," then the sign of the *CP* violation is the same at different points in space, so that the universe as a whole has excess matter (in contrast with antimatter). In the case of a spontaneous or "soft" *CP* violation, caused by a complex vacuum expectation value of some field, we would expect a domain structure of the vacuum with different *CP* signs in different spatial below the point of the corresponding phase transition. In the vacuum domains with different *CP* signs the baryon asymmetry is generated in different ways: In some domains, the decays of leptoquarks lead to an excess of baryons over antibaryons, while in others the opposite occurs.[2,3] For this reason, theories with spontaneous *CP* violation may lead to a globally symmetric universe of an island type.[2,3]

The development of a concept of a globally symmetric universe on the basis of a spontaneous *CP* violation, however, has thus far run into two unresolved problems. First, the domain structure of the vacuum implies massive walls between domains,[4] and these walls cause radical changes in the evolution of the universe, leading to consequences at odds with observations.[4] The second problem is that of how to obtain the necessary domain dimensions.

In this paper we attempt to resolve the first of these problems. We address the question of how it might be possible to reconcile the picture of a globally symmetric universe with the absence of vacuum *CP* domains and walls in the later stages of the expansion. One of the key points of this discussion is the requirement that there must be no spontaneous *CP* violation at zero temperature, while there must be such a violation at some stage in the expansion of the universe, as a result of finite-temperature effects.[5] An explicit *CP* violation, which contradicts neither the group structure nor the Hermitian nature of the Langrangian, is of course allowed.

Let us consider unified gauge theories for the SU(5) group,[6] which contains three 5-multiplets of scalar fields ϕ_1, ϕ_2, χ. At temperatures $T \ll 10^{15}$ GeV we can use an effective low-energy SU(2)× U(1) electroweak model with three Higgs doublets. Following Mohapatra and Senjanović,[7] we write their interaction potential as follows:

$$V(\phi_1,\phi_2,\chi) = -\mu_1^2(\phi_1^+\phi_1 + \phi_2^+\phi_2) + \lambda_1((\phi_1^*\phi_2)^2 + (\phi_2^+\phi_2)^2)$$

$$+ 2\lambda_3(\phi_1^+\phi_1)(\phi_2^+\phi_2) + 2\lambda_4(\phi_1^+\phi_2)(\phi_2^+\phi_1) + \lambda_5[(\phi_1^+\phi_2)^2 + \text{H.c.}]$$

$$+ \lambda_6(\phi_1^+\phi_1 + \phi_2^+\phi_2)(\phi_1^+\phi_2 + \phi_2^+\phi_1) - \mu_2^2\chi^+\chi + \delta(\chi^+\chi) + 2\alpha(\chi^+\chi)(\phi_1^+\phi_1$$

$$+ \phi_2^+\phi_2) + 2\beta[(\phi_1^+\chi)(\chi^+\phi_1) + (\phi_2^+\chi)(\chi^+\phi_2)]. \qquad (1)$$

The choice of the "bare" masses $\mu_1^2 < 0, \mu_2^2 > 0$, in contrast to the values $\mu_i^2 > 0$ used in Ref. 7 for all the fields, leads to radical changes in the behavior of the vacuum expectation values of the scalar fields. At zero temperature, the potential minimum is reached at fields

$$<\phi_i> = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \qquad \chi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}, \qquad (2)$$

whereas at high temperatures, $T > T_2 \approx 300$ GeV, the structure of the vacuum expectation values is

$$<\phi_1>^T = (0, \rho_1) \qquad <\phi_2>^T = (0, \rho_2 e^{i\theta}) \qquad <\chi>^T = (0, 0), \qquad (3)$$

where

$$\theta = \pm \arccos(-\lambda_6/2\lambda_5).$$

The ambiguity in the choice of the angle θ means that there are two vacuum fields, with the same energy but different *CP* signs. At temperatures $T \gtrsim 10^{15}$ GeV the effective potential of the scalar fields will also be affected by the superheavy particles of the complete gauge group, SU(5), so that the symmetry will be restored at some temperature T_1.

In this model, therefore, a *CP* domain structure of the vacuum may exist over the temperature range $T_2 < T < T_1$.

In a theory of this type, the chain of events in the expansion of the universe from a singularity would be as follows: At temperatures $T > T_1 > M$, where M is the leptoquark mass, there is only an explicit *CP* violation, but a baryon Asymmetry is not yet being generated.[1)] At T_1 the first phase transition occurs, resulting in the formation of domains with different *CP* violations, so that in the temperature range $T_2 < T < T_1$ there are two sources *CP* violation: both explicit and spontaneous. As the temperature falls further, $T_2 < T < M$, the baryon asymmetry is generated in the usual manner,[1] and we can write schematically,

$$n_B/n_\gamma \equiv \Delta = \Delta_{\text{exp}} + \Delta_{\text{spont}} + (\text{interference}), \qquad (4)$$

where n_B and n_γ are the number densities of baryons and antibaryons, respectively;

Δ_{exp} is determined by the complex nature of the coupling constants; and the source $\Delta_{spont} \sim \theta$ is a spontaneous *CP* violation.[3] We note that Δ_{exp} does not depend on the spatial position, while Δ_{spont} is a random quantity which changes sign when we go from one domain to another. Depending on the relative values of Δ_{exp} and Δ_{spont}, we can have, in general, three cases. The first, with $\Delta_{exp} \ll \Delta_{spont}$, leads to a globally symmetric universe with a domain structure of matter and antimatter. The case $\Delta_{exp} \gg \Delta_{spont}$ corresponds to the usual picture[1] of a globally asymmetric universe. Finally, the case $\Delta_{exp} \sim \Delta_{spont}$ corresponds to a strong interference between these two sources of *CP* violation, with the result that inhomogeneities arise in the early stage of the expansion of a universe which is globally asymmetric on the average.

Of particular interest here is the question of the walls between the domains. At a temperature $T \sim T_2$ the domain walls become very thick; in the limit of a zero vacuum expectation value, $\rho = 0$, they become infinitely thick, and we find a translationally invariant vacuum. The matter, of course, retains its island structure if the domains grow in a suitable manner.

Further study will be required to resolve the questions of the size of the domains and whether the island structure of the universe can survive. At this point, we simply note that in the model considered here the SU(5) symmetry is initially disrupted to SU(4) and then to SU(3) × U(1) by a vacuum expectation value of the 24-multiplet upon spontaneous *CP* violation as a result of the 5-multiplet, if the Higgs coupling constants are chosen appropriately. Supercooling in the SU(4) stage leads to an exponential growth of the *CP* domains,[8] followed by the generation of a baryon (or antibaryon) asymmetry in each domain after the evolution of latent heat.

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[1)] A baryon asymmetry of the universe can arise only at $T < M$ (Ref. 1).

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