Cosmological consequences of $E_8 \times E_8$ superstring models

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Possible sources of baryon asymmetry are discussed in $E_8 \times E_8$ superstring models. It is shown that because of the dominance of supermassive shadow particles (shadow hadrons) in the early universe one can conclude that the observed value of the baryon asymmetry is compatible only with an unbroken shadow E_8, provided that the baryosynthesis is determined by decays of heavy particles.

Recently there has been much interest in models of grand unification including gravitation which are based on the superstring model.[1] It turns out that the corresponding field theory does not have internal gauge and gravitational anomalies in the case of the groups SO (32) and $E_8 \times E_8$,[2,3] so the string theory in these groups is finite in one loop.[4,5] For the actual finiteness this would imply not only the creation of quantum gravitation but also the choice of symmetry group from first principles. For the construction of realistic four-dimensional theories it is necessary to consider spontaneous compactification of the original ten-dimensional space. In Ref. 6 a scheme of compactification on a Ricci-flat space of Calabi-Yau was proposed. In the field theory approach the requirement or Ricci-flatness arose from an analysis of the consequences of the condition of invariance under $N = 1$ supersymmetry in a four-dimensional theory. It was shown[6] that this requirement is singled out also in the original string formalism in that only in the case of a Ricci-flat background can conformal invariance be preserved in the two-dimensional theory (σ-model), which describes the string, and this is necessary for a self-consistent formulation of a theory of interacting strings. This allows one to justify the choice of the compact manifold even in the case where the field description is unsuitable for compactification.[7]

The mechanism of compactification of Ref. 6 is based on the formation of a condensate of a gauge field which transforms according to the adjoint representation of the group $SU(3)$. This requirement arises from the condition for topological consistency of compactification: $\mathrm{Tr}F^2_{mn} = \mathrm{Tr}R^2_{mn}$, where R_{mn} and F_{mn} are the Riemann tensor and the gauge field strength, which are written in matrix form. Moreover, the requirement of the existence of zero modes on the compact manifold is imposed. As a result of compactification the symmetry groups are broken to SO(28) and $E_8 \times E_8$. The models with the symmetry group SO(28) are phenomenologically acceptable only in the case of reflection symmetry since the group SO(28) has only real representations. We will consider further only the case of $E_8 \times E_8$.
Ne/H$_2$ From the analysis which was carried out in Ref. 6, it is easy to see that in an effective four-dimensional theory light scalars which transform nontrivially under the "shadow" E_8 (E'_8 in what follows) do not arise, and a condensate of SU(3) fields does not precipitate out from E'_8. This is related to the fact that scalar fields in a four-dimensional theory are components of the ten-dimensional vectors with indices which correspond to the compactified dimensions. For these vectors the equations for the zero modes have the form

$$D^n D_n A_m = 0,\ D^n \partial_n A_\mu = 0,\ \mu = 1, \ldots, 4;\ m, n = 5, \ldots, 10,$$

and admit solutions only for 4-vectors A_μ which do not depend on compact coordinates; the scalars A_m do not have zero modes, since the curvature of the Calibi-Yau manifold acts on them. In the case of "our" group E_8 (or E_6) the massless scalars arise from compensation of curvature effects by the condensates of the SU(3) gauge field A^c_n:

$$D^n(D_n A_m + [A_n{}^c A_m]) = 0, \quad [D_n A_m{}^c] = R_{mn}.$$

For the fields of E'_8 there are no corresponding condensates, which leads to the absence of zero modes. This means that we are left with supersymmetric gluodynamics either with the symmetry group E_8 or a smaller one in the case of the formation of Hosotani's condensate[8]:

$$U = P \exp\left(i \int_c A_m\, dx^m \right)$$

(see also Ref. 6).

The "shadow" world consists of shadow hadrons which arise in the presence of the confinement of gluodynamics. Since in this theory there are no spontaneously broken, conserved, colorless currents, light shadow hadrons do not arise; the masses of the very lightest particles are of order Λ, which is the scale at which the gauge interaction becomes strong. This scale is easy to find on the basis of the renormalization group. In case E_8 is not broken, it is of order $10^{-1} m_P$, where m_P is the Planck mass. This is related to the large value of the Casimir operator $C_2(G)$ for the group E_8: $C_2(G) = 30$. In the case of smaller symmetries this scale is sharply reduced; for example, for E_7 it is of order 10^{14} GeV (for more details see Refs. 9 and 10). Shadow hadrons can decay only gravitationally (naturally, the lightest ones), so their lifetime is quite large; the widths of the two-particle decays are of order (the gravitational coupling constant is $1/m_P$)

$$\Gamma \sim \Lambda^5 / m_P{}^4. \tag{1}$$

Depending on the quantum numbers of the shadow hadrons, one can have both purely gravitational decays into gravitons G and gravitinos $\tilde{G}$ and also decays into the "usu-

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al" particles going through an intermediate graviton or gravitino and having the same small factor $1/m_P^2$ in the amplitude as in decays of the first type, so formula (1) gives the answer in all cases. In the latter case the generation of baryon asymmetry is possible as the result of the effects of CP breaking in four-particle decays of shadow hadrons $T(\tilde{T})$ with the breaking of baryon number:

$$T \to G \to q\bar{q} \to qqql, \quad \tilde{T} \to \tilde{G} \to q_s\bar{q} \to q_s qql.$$

These decays are supressed relative to the fundamental two particle decays

$$T \to G \to q\bar{q}(l\bar{l}), \quad \tilde{T} \to \tilde{G} \to q_s\bar{q}(l_s\bar{l})$$

by the additional factor $(\Lambda/m_p)^4$ in the width. An analogous supression factor arises also for baryon-number-nonconserving decays of the gravitino, the mass of which is $\sim \Lambda^3/m_P^2$ in these models; here the supression factor is larger since $(m_{\tilde{G}}/m_P)^4 = (\Lambda/m_P)^{12}$.

Let us consider the cosmological consequences of the existence of a "shadow" world, assuming that in the process of compactification the gravitational creation of particles guarantees equal distribution of all degrees of freedom, both "usual" and "shadow" particles, from which in particular it follows that there is an absence of an original excess of baryon charge.

After the emergence of confinement, nonrelativistic shadow hadrons form with mass of order $\Lambda \gg 10^2$ GeV, which dominate in the universe beginning at $t_\Lambda \sim m_P/\Lambda^2$ and ending at the time of their decay $t_D \sim m_P^4/\Lambda^5$ [see Eq. (1)]. Generally speaking, for an amplitude of the initial perturbations of the density $\delta\rho/\rho = \delta_0 > (t_\Lambda/t_D)^{2/3}$, inhomogeneities of the shadow hadrons develop which are distinct from the cosmological expansion[11]; in these inhomogeneities there could be gravitational pair annihilation at the rate $\sigma v \sim \Lambda^2/m_P^4$. Because the characteristic density in the inhomogeneities is of order $n \sim \Lambda^3\delta^3$, the characteristic time of such an annihilation is

$$t_{an} \sim (n\sigma v)^{-1} \sim \left[\Lambda^3\delta^3 \frac{\Lambda^2}{m_P{}^4}\right]^{-1} \sim \delta^{-3} t_D \gg t_D,$$

since $\delta \ll 1$. This means that the dominance of shadow hadrons ends just at $t \sim t_D$ and not earlier.

"Our" particles, the masses of which are negligibly small compared with the masses of the shadow hadrons, are ultrarelativistic during this period; their contribution to the cosmological density decreases as a^{-1} (a is the scale factor), and by the end of the era of the shadow hadrons this contribution amounts to $1/a^4 \sim (\Lambda/m_P)^2$ of the original. As a consequence of this suppression, the products of the decay of the shadow hadrons dominate in the universe for $t > t_D$. Here, for the ratio of the number of baryons to the number of photons there is the relation

$$\frac{\Delta n_B}{n_\gamma} \sim \chi\left(\frac{\Lambda}{m_P}\right)^4 \frac{n_T}{n_\gamma} \sim \chi\left(\frac{\Lambda}{m_P}\right)^{11/2}, \qquad (2)$$

where χ characterizes CP breaking and the factor $(\Lambda/m_p)^4$ is related to the suppression of four-particle decays, which generate baryon asymmetry, relative to two-particle decays, which generate entropy. For the ratio of the number of photons n_γ to the number of shadow hadrons n_T it is possible to obtain the estimate (the derivation will be presented in a detailed article) $n_T/n_\gamma \sim (\Lambda/m_P)^{3/2}$. For $\Lambda < 10^{-2} m_P$ it follows from Eq. (2) that $\Delta n_B/n_\gamma < 10^{-11}$, which is unacceptable since the phenomenological value of $\Delta n_B/n_\gamma$ is of order 10^{-10}. For the unbroken E_8' we obtain ($\Lambda \sim 0.1 m_P$) $\Delta n_B/n_\gamma \sim \chi \cdot 10^{-5.5}$, which allows one to find the observed value with the reasonable magnitude $\chi \sim 10^{-5}$–10^{-6}.

Thus, from cosmological considerations one can conclude the E_8' is not broken under compactification, the gravitino has a large mass, and observable matter arose from the decay of shadow hadrons. If it is assumed that E_8' is broken so strongly that in general the epoch of the dominance of shadow hadrons is absent, then in the considered scenario difficulties arise with the ultralight gravitino and, moreover, the mechanism for generating baryon asymmetry is absent in the four-dimensional world.

The scenario which was considered above did not invoke the mechanisms of baryosynthesis which were proposed in Ref. 12. The realization of these mechanisms within the framework of the theory of superstrings requires special study.

Let us note in conclusion that a delayed transition to the confinement phase of shadow hadrons could realize the inflationary stage of the expansion of the universe. Another mechanism of inflation could be related to compactification through the appearance of three-dimensional solitons under a vacuum phase transition of the $(1+9)$-dimensional theory, which are analogous to filaments, walls, and monopoles of the $(1+3)$-dimensional theory. Also of interest is an analysis of the cosmological situation in the SO (32) model with reflection symmetry. These questions will be considered in subsequent papers.

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