

HARMFUL AXIONS IN SUPERSTRING MODELS

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We show in this paper that the existing superstring models, $E_8 \times E_8$ and $O(32)$, have the axion decay constant problem. It is either 300 GeV or 10^{16} GeV, which are outside the cosmologically allowed region. It is also pointed out that the invisible axion with $10^8 \text{ GeV} \leq v_{\text{PQ}} \leq 10^{12} \text{ GeV}$ is a necessity for all theories which have an effective interaction $(\phi_n/M_{\text{Pl}})F\tilde{F}$ below the Planck scale.

The type I superstring theories with $O(32)$ or $E_8 \times E_8$ Yang–Mills groups have attracted a great deal of attention recently [1–4] because of the absence of the Yang–Mills and gravitational anomalies. One clear prediction of these theories is the existence of the axion [5,6].

On the other hand, there exists an upper bound [7] on the invisible axion scale v where the Peccei–Quinn symmetry is broken. Since the energy density of the coherent axion field is proportional to v , $v > 10^{12} \text{ GeV}$ is not acceptable in the standard big bang cosmology.

In superstring theories, there appear [2] two types of axions, the model independent one ($\equiv$ MI axion) and the Peccei–Quinn type one ($\equiv$ PQ axion). The MI axion scale is near the Planck scale because the nonrenormalizable interaction of the MI axion arises as a result of the compactification. The PQ axion scale is not determined by the compactification, but determined by the process of spontaneous symmetry breaking. Because the MI axion scale violates the aforementioned cosmological bound, which we will show later, the su-

perstring theories at a first glance seem to be ruled out in the standard big bang cosmology. However, this is not necessarily so. This is because there can in principle exist an invisible axion of the Peccei–Quinn type.

For the canonically defined MI axion field ϕ_n and the canonically defined PQ axion field ϕ_a , the lagrangian is

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu \phi_n)^2 - \frac{1}{2}(\partial_\mu \phi_a)^2 + (1/32\pi^2)(\phi_n/M_a + \phi_a/v_{\text{PQ}})F_{\mu\nu}^i \tilde{F}^{i\mu\nu}, \quad (1)$$

where $F_{\mu\nu}^i$ is the gluon field strength and $\tilde{F}^{i\mu\nu}$ is its dual. It is trivial to notice from eq. (1) that only one combination couples to $F\tilde{F}$. This component can be properly called the “axion” a . The a field is

$$a \equiv \cos \alpha \phi_a + \sin \alpha \phi_n, \quad (2)$$

where

$$\begin{aligned} \cos \alpha &= M_a(M_a^2 + v_{\text{PQ}}^2)^{-1/2}, \\ \sin \alpha &= v_{\text{PQ}}(M_a^2 + v_{\text{PQ}}^2)^{-1/2}. \end{aligned} \quad (3)$$

The other orthogonal field, $-\sin \alpha \phi_a + \cos \alpha \phi_n$, is truly massless. The interaction term of eq. (1) now reads

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$$\mathcal{L}_{\text{int}} = \frac{1}{32\pi^2} \frac{(v_{\text{PQ}}/M_C) + (M_C/v_{\text{PQ}})}{(M_C^2 + v_{\text{PQ}}^2)^{1/2}} a F\tilde{F} \\ \cong (1/32\pi^2)(a/v_{\text{PQ}}) F\tilde{F} \quad (M_C \gg v_{\text{PQ}}). \quad (4)$$

Eq. (4) shows that a can be interpreted as an axion and hence its phenomenologies are the same as those discussed in the literature [5–8]. A remarkable feature is that even though $M_C \gg v_{\text{PQ}}$, the model is acceptable if $10^8 \text{ GeV} \leq v_{\text{PQ}} \leq 10^{12} \text{ GeV}$.

This argument can be generalized. If there exist many boson fields whose couplings are only to $F\tilde{F}$, one combination is the axion and the most dominant component of the axion is that with the smallest scale parameter.

It looks like this argument is in contradiction with the standard wisdom of the invisible axion that the invisible axion resides mostly within the component corresponding to the largest vacuum expectation value^{*1}. This is not so. In the usual invisible axion models there is only one $U(1)_A$ symmetry and there is really one boson field. From the $U(1)_A$ current $J_\mu^a \sim v_1 \partial_\mu a_1 + v_2 \partial_\mu a_2 + \dots$, we immediately see that the largest vacuum expectation value is the most important one.

What can we say about superstring models? All published superstring models are phenomenologically troublesome, because they have unacceptable axions. This is shown in the remainder of this paper.

Let us first show that M_a for the MI axion in superstring models is of the order of the Planck mass $M_{\text{Pl}} = 1.2 \times 10^{19} \text{ GeV}$. The indices $A, B, C, \dots$ will stand for the ten dimensions and $\mu, \nu, \rho, \dots$ will stand for the four dimensions. The ten-dimensional bosonic action relevant for our discussion is [1]

$$S_{10} = \int d^{10}x \, e_{10} [-(1/2k^2)R_{10} - (1/k^2)\phi^{-2}\partial_A\phi\partial^A\phi \\ - (1/4g^2)\phi^{-1}F_{AB}^a F^{aAB} \\ - (3k^2/2g^4)\phi^{-2}H_{ABC}H^{ABC}], \quad (5)$$

where $\dim g = -3$ and $\dim k = -4$. The MI action is defined by

$$H_{\mu\nu\rho} = M_a' \epsilon_{\mu\nu\rho\sigma} \partial^\sigma a, \quad (6)$$

^{*1} For a recent review see ref. [9].

where M_a' is related to M_a of eq. (1) by

$$M_a' = 8\pi^2 M_a. \quad (7)$$

After compactification the four-dimensional action for the kinetic energies of the graviton, the gauge boson and the axion is

$$S_4 = \int d^4x \, e_4 [-(1/16\pi)M_{\text{Pl}}^2 R_4 \\ - \frac{1}{4}F_{\mu\nu}^\alpha F^{\alpha\mu\nu} - \frac{1}{2}(\partial_\mu a)^2]. \quad (8)$$

The dimensional reduction does not change the relative ratios of the coefficients of the terms in eqs. (5) and (8):

$$\frac{1/2k^2}{1/4g^2\phi} = \frac{M_{\text{Pl}}^2/16\pi}{1/4}, \quad \frac{1/2k^2}{3k^2 6M_a'^2/2g^4\phi^2} = \frac{M_{\text{Pl}}^2/16\pi}{1/2},$$

from which we obtain the relation

$$M_a' = M_{\text{Pl}}/12\sqrt{\pi}. \quad (9)$$

The value M_a obtained from eqs. (7) and (9) is $7 \times 10^{15} \text{ GeV}$ and is outside the cosmologically allowed region.

Following the previous discussion, we therefore need an invisible axion in superstring models. There must be a global $U(1)_A$ Peccei–Quinn symmetry in the four-dimensional world. Obviously, this global symmetry does not belong to the gauge symmetry in four dimensions.

If one requires an $N = 1$ supersymmetry in four dimensions, one must have an $SU(3)$ holonomy [4]. This chooses the superstring model $E_8 \times E_8$ over $O(32)$, because the latter does not give chiral fermions. With this holonomy group, $E_8 \times E_8$ breaks down to $E_6 \times E_8$. If the standard model is embedded in E_8 , there do not exist interesting light fermions. The standard model is better to be embedded in E_6 . Because E_8 cannot contain light fermions, this model does not have the chance to contain dark matter invisible to us. In any case, we do not have a chance to introduce a global symmetry $U(1)_A$ from the $SU(3)$ holonomy since $E_6 \times SU(3)$ is a maximal subgroup of E_8 . Therefore, the $E_8 \times E_8$ superstring model with an $SU(3)$ holonomy is cosmologically unacceptable.

We cannot introduce any overall global symmetry which can give a desirable Peccei–Quinn symmetry, because this cannot be unbroken through the com-

pactification process. The reason is the following. Suppose the global symmetry is X , i.e. the superstring model may be $(X)_{\text{global}} \times (E_8 \times E_8)_{\text{local}}$. For X to become the Peccei–Quinn symmetry in four dimensions, the gauge fields (and gauginos) must carry the X charge. In the Calabi–Yau manifold, the $SU(3)$ gauge fields must have nonvanishing vacuum expectation values. These vacuum expectation values also break the X symmetry, because any possible linear combination of generators, $X \oplus (E_8/E_6)$ cannot commute with all the $SU(3)$ generators.

We conclude that the requirement [4] of the $N = 1$ supersymmetry in four dimensions gives severe problems.

Let us proceed to discuss the $O(32)$ superstring model. We do not require the $N = 1$ supersymmetry.

Witten [2] noted that the $SU(5)$ gauge symmetry from $O(32)$ in four dimensions brings along the global Peccei–Quinn P symmetry. The P charges of the $SU(5)$ adjoint or singlets are zero, while the P charges of 10 , $\bar{10}$, 5 , and $\bar{5}$ are nonzero. Therefore, the allowed scale for the vacuum expectation values of 5 and $\bar{5}$ is the electroweak scale, and hence the resulting axion is the Peccei–Quinn–Weinberg–Wilczek axion which is phenomenologically ruled out. In this case, existence of another invisible axion does not help as discussed in the introduction.

Therefore, the immediate questions are whether the P symmetry is avoided or the P symmetry is broken at a larger scale $10^8 \text{ GeV} \leq v \leq 10^{12} \text{ GeV}$ so that the axion becomes invisible. The first option does not help because of the cosmologically unacceptable MI axion. In fact, the P symmetry is not avoidable for the $SU(N)$ embeddings which we will discuss. The only hope in the superstring models is to have the P symmetry and break it at the allowed region.

In an effort to obtain the P charge carrying $SU(3) \times SU(2) \times U(1)$ singlets after compactification, we consider $SU(7)$ from $O(32)$ as a prototype example. Readers will notice that other $SU(N)$'s from $O(32)$ will have the same fate as the present example.

In analogy with the $SU(5)$ compactification scheme, the $SU(7)$ is embedded in $O(32)$ such that the fundamental representation of $O(32)$ transforms as $7 + \bar{7} + \text{singlets}$ under $SU(7)$. The P charge is defined by

$$P = \begin{bmatrix} i\sigma_2 & & & & & & 0 \\ & \ddots & & & & & \\ & & \ddots & & & & \\ & & & i\sigma_2 & & & \\ & & & & 0 & & \\ & & & & & i\sigma_2 & \\ & & & & & & 0 \end{bmatrix}, \quad (10)$$

where the upper left corner is the block diagonal matrix with seven entries of $i\sigma_2 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$, and the other elements are zeros. Then the adjoint representation of $O(32)$ is decomposed into

$$496 = 7 + \bar{7} + 21 + \bar{21} + 48 + \text{singlets}, \quad (11)$$

and the P charges of each $SU(7)$ multiplet is

$$P(21) = 2, \quad P(7) = 1, \quad P(\bar{21}) = -2, \quad P(\bar{7}) = -1,$$

$$P(48) = 0, \quad P(\text{singlets}) = 0. \quad (12)$$

The chiral fermions without the anomaly in four dimensions are n generations of $21 + \bar{7} + \bar{7} + \bar{7}$ where n can be an arbitrary number determined by the index theorem [2]. After the symmetry breaking $SU(7) \rightarrow SU(5)$, this gives n generations of the $SU(5)$ family [10] $10 + \bar{5}$. Now we have the needed P charge carrying $SU(3) \times SU(2) \times U(1)$ singlets in $7, \bar{7}, 21, \bar{21}$ of $SU(7)$. There exists the $P - SU(7) - SU(7)$ anomaly

$$\text{Tr } P T_{SU(7)}^2 = n(2 \text{Tr } T_{21}^2 - 3 \text{Tr } T_{\bar{7}}^2) = 7n \text{Tr } T_7^2, \quad (13)$$

which shows that P is a Peccei–Quinn symmetry.

The question is now whether the P charge carrying singlets break the global symmetry at $10^8 \text{ GeV} < v_{\text{PQ}} < 10^{12} \text{ GeV}$, which gives the invisible axion, solves the strong CP problem, and removes the cosmological energy density problem caused by the MI axion. This is not the case.

As is well known, a new global charge Γ can be defined. The Γ is a linear combination of P and an $SU(5)$ singlet gauge generator. For the fundamental representation of $SU(7)$, it is

$$\Gamma = P + \text{diag}\left(\frac{2}{5}, \frac{2}{5}, \frac{2}{5}, \frac{2}{5}, \frac{2}{5}, -1, -1\right). \quad (14)$$

Therefore, all the $SU(3) \times SU(2) \times U(1)$ singlets carry the vanishing Γ quantum number. The $SU(3) \times SU(2) \times U(1)$ singlets cannot break the Peccei–Quinn symmetry, and the axion scale comes down to the electroweak scale, implying the unacceptable Peccei–Quinn–Weinberg–Wilczek axion. This is due to the fact that the P charge of each $SU(N)$ representation from $O(32)$

superstring models is the N -ality. Therefore, this feature is not avoidable in any $SU(N)$ gauge model from $O(32)$.

The $SU(N)$ models with nonstandard fermions [12] cannot be obtained from $O(32)$ superstring models, because the spinor of $O(2N)$ is not obtained in this way.

In conclusion, there exist harmful axions in published superstring models.

Finally, we speculate on the physical implication of the possible generation of $(\phi_n/M_{Pl})F\tilde{F}$ term as an effective interaction below the Planck scale. The Peccei–Quinn symmetry with $10^8 \text{ GeV} \leq \nu_{PQ} \leq 10^{12} \text{ GeV}$ must be present in the low energy world, and the invisible axion is a necessary consequence. The invisible axion plays the dual role that it solves the strong CP problem and the cosmological energy density problem in a theory with the term $(\phi_n/M_{Pl})F\tilde{F}$.

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Note added. The MI axion in the $E_8 \times E'_8$ model can be heavy if the extra E'_8 becomes strong at relatively high energy scale Λ' . Then the MI axion can decay before the present age of the universe ($\approx 5 \times 10^{17} \text{ s}$). Numerically, for $\Lambda' \gtrsim 10^7 \text{ GeV}$ the lifetime of the MI axion is shorter than the age of the universe. To make the nucleosynthesis intact, i.e. by requiring the MI axion decay before 1 s, we obtain $\Lambda' \gtrsim 7 \times 10^9 \text{ GeV}$.

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