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Grand unification and heavy axion

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We argue that sufficiently complex grand unified theories involving extra strong intractions that confine at very short distances, may lead to a heavy axion solution of the CP problem of QCD. This axion may have a mass within accessible energy range, and its low energy intéractions emerge through mixing with axial Higgs boson(s). Another signature of this scenario is softly broken Peccei - Quinn symmetry in the electroweak Higgs sector. We present a toy GUT exhibiting these features.

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In QCD, the effective θ-parameter $\bar{\theta} = \theta + \arg\, \det M_{quark}$ breaks CP [1] and is experimentally constrained to be unnaturally small, $\bar{\theta} \lesssim 10^{-10}$ (for reviews see, e.g., ref. [2]). An elegant solution to this strong CP problem is based on the Peccei - Quinn (PQ) symmetry [3] and predicts a light particle, axion. In view of constraints from experimental searches for the Weinberg - Wilczek [4] axion, a widely accepted option is an extremely light invisible axion [5]. A potential problem with the latter comes from possible non-renormalizable terms in the low energy Lagrangian which may be due to very high (say, Planckian) scales and need not respect PQ symmetry [6]. Negligible for other purposes, these terms would introduce extra axion potential and ruin the PQ mechanism precisely because the QCD contribution into the axion potential is tiny. From this point of view it is more safe to have axion heavy enough.

In this paper we point out that heavy axions may appear in sufficiently complex grand unified theories containing extra gauge interactions (with unbroken gauge group) which become strong well above the accessible energies. The effective θ-parameters of QCD and these extra strong interactions may be equal to each other due to a symmtry built in a GUT. If there is *one* PQ symmetry relevant to *both* QCD and extra strong interactions, the PQ mechanism rotates away both of these θ-parameters, while axion obtains its mass predominantly from extra strong interactions and is therefore heavy (much heavier than Weinberg - Wilczek one).

Similar idea was put forward by Tye [7] in the context of technicolor plus Higgs models with PQ symmetry. However, many (if not all) such models predict numerous pseudo-Goldstone bosons; some of these are charged and have masses well below 40 GeV, which is ruled out experimentally. This problem is not inherent in GUTs[1)].

To be specific, let us consider a toy GUT. This model will not be realistic for several reasons, but we expect that it picks up generic features of possible heavy axions. The model is a non-supersymmetric GUT with the gauge group $SU(5) \times SU(5)$, where the first $SU(5)$ is meant to model real world and the second $SU(5)$ is a mirror group. Let the fermionic and Higgs content be mirror

[1)]Mechanisms that may make invisible axion heavy enough are discussed in ref. [8]

symmetric. Ordinary (mirror) fermions are singlets under mirror (ordinary) $SU(5)$ and form the usual $\bar{5}$- and 10-plets under ordinary (mirror) $SU(5)$. There is one Higgs 24-plet and two Higgs 5-plets in each $SU(5)$ sector which are singlets under partner $SU(5)$. Let us require that at this stage each $SU(5)$ sector has its own PQ symmetry that rotates the two Higgs 5-plets in the opposite ways,

$$\varphi_5^{(1)} \to e^{i\alpha}\varphi_5^{(1)}, \qquad \varphi_5^{(2)} \to e^{-i\alpha}\varphi_5^{(2)} \tag{1}$$

for ordinary Higgs 5-plets $\varphi_5^{(1,2)}$, and

$$\Phi_5^{(1)} \to e^{i\beta}\Phi_5^{(1)}, \qquad \Phi_5^{(2)} \to e^{-i\beta}\Phi_5^{(2)} \tag{2}$$

for mirror Higgs 5-plets $\Phi_5^{(1,2)}$. To have just one PQ symmetry, let us introduce an $SU(5) \times SU(5)$ singlet complex scalar field S of PQ charge 1 that interacts with both ordinary and mirror Higgs 5-plets,

$$L_{S,\varphi,\Phi} = h\varphi_5^{(1)\dagger}\varphi_5^{(2)}S^2 + h'\Phi_5^{(1)\dagger}\Phi_5^{(2)}S^2 + \text{h.c.} \tag{3}$$

The self-interaction of S is required to be symmetric under the phase rotations of S, so the remaining PQ symmetry is (1), (2) with $\beta = \alpha$ and $S \to e^{i\alpha}S$. Let us assume for definiteness that S does not obtain vacuum expectation value, though this assumption is not crucial for further discussion.

Let us now require that at the (high) energy scales where both $SU(5)$ groups are unbroken, hard (dimension 4) terms in the whole Lagrangian are mirror symmetric, while the soft terms are not. This implies, in particular, that $\theta_{ordinary} = \theta_{mirror}$ (the θ-terms are hard) and that the phases of Yukawa couplings are the same in ordinary and mirror sectors. This requirement also implies the equality of the couplings entering Eq.(3), $h' = h$. Hence, without loss of generality one sets h to be real (the phase of h can be rotated away by the phase rotation of S). In one loop, the interaction (3) introduces direct interaction between ordinary and mirror Higgs 5-plets,

$$L_{\varphi,\Phi} = \lambda\left(\varphi_5^{(1)\dagger}\varphi_5^{(2)}\right)\cdot\left(\Phi_5^{(2)\dagger}\Phi_5^{(1)}\right) + \text{h.c.} \tag{4}$$

where $\lambda \propto h^2 \ln(m_S/\mu)$ and μ is the normalization scale. Note that λ is real and the interaction (4) is still PQ symmetric.

Let us require that, just like ordinary $SU(5)$, mirror $SU(5)$ breaks down to $SU(3)_{mc} \times U(1)_{mEM}$, where mc and mEM refer to mirror color and mirror electromagnetism, respectively. Since the soft terms of the mirror sector are different from those of ordinary sector, this breaking occurs at different energy scales. Consider the case when mirror $SU(5)$ breaks down at much lower energy than the ordinary GUT scale. The coupling constant of $SU(5)$ runs faster than that of $SU(3)$, so the mirror coupling constant is larger than that of ordinary $SU(3)_c$ at the point where mirror $SU(5)$ breaks down. Hence, $SU(3)_{mc}$ becomes strong at the scale Λ_{mc} which is larger than ordinary Λ_{QCD}. Assuming

$$< \Phi_5^{(1)} > \sim < \Phi_5^{(2)} > \sim v_m > \Lambda_{mc} \tag{5}$$

we have the mirror world similar to the ordinary world, but scaled up in energy (and with v_m/Λ_{mc} not necessarily of the same order as the ratio of the ordinary Higgs expectation value to QCD confinement scale, $v/\Lambda_{QCD} \sim 10^3$).

By the mirror symmetry of the hard terms, the effective θ-parameters of ordinary and mirror sectors are equal to each other[2)], at least at the tree level. By performing PQ rotation, one makes both of them equal to zero. By the mirror PQ mechanism, the axion field then takes zero vacuum expectation value, and both mirror and ordinary strong interactions conserve CP. In other words, at non-zero mirror effective θ-parameter, $\bar{\theta}_{mirror}$, the phase of the vacuum expectation value of $\Phi_5^{(1)\dagger}\Phi_5^{(2)}$ is proportional to $\bar{\theta}_{mirror}$ by PQ mechanism; the interaction (4) aligns the phase of $\varphi_5^{(1)\dagger}\varphi_5^{(2)}$ to the same value, so the effective ordinary θ-parameter, after PQ rotation, becomes equal to $\bar{\theta}_{ordinary} - \bar{\theta}_{mirror} = 0$, at least at the tree level [3)].

The axion obtains its mass predominantly due to mirror strong interactions. It is, in fact, a mirror Weinberg – Wilczek axion. The expression for the mass is a scaled up version of the Weinberg formula. Recalling that the mass of the Weinberg – Wilczek axion scales as $m_{WW} \propto \Lambda_{QCD}^{3/2} v^{1/2}$ we estimate the axion mass in our model as

$$M_a \sim \left(\frac{\Lambda_{mc}}{\Lambda_{QCD}}\right)^{3/2} \left(\frac{v}{v_m}\right)^{1/2} m_{WW}.$$

This may certainly be much larger that m_{WW}.

To get an idea of numbers, let us point out that non-supersymmetric $SU(5)$ becomes strong at about 10^5 GeV. Hence, $\Lambda_{mc} \lesssim 10^5$ GeV. Under the assumption (5) and using $m_{WW} \sim 100$ KeV, we have

$$M_a \lesssim 1 \text{ TeV}.$$

Let us stress that by varying Λ_{mc} and v_m one can easily get the axion much lighter than 1 TeV. Say, at $\Lambda_{mc} \sim 3$ TeV and $v_m \sim 10$ TeV one has $M_a \sim 20$ GeV.

The axion interactions with ordinary matter come from the term (4). At energies below v_m we have

$$\Phi_5^{(2)\dagger}\Phi_5^{(1)} = c_1 v_m^2 + i c_2 v_m a(x) \tag{6}$$

where c_1 and c_2 are constants of order 1, and $a(x)$ is the axion field. The first term here produces the off-diagonal mass term for the ordinary Higgs fields that breaks the low energy PQ symmetry (1) explicitly and softly. The corresponding mass parameter, $m_{12} = \sqrt{\lambda c_1} v_m$ should be of order 100 GeV to avoid fine tuning in the ordinary electroweak Higgs sector. The second term in Eq.(6), being inserted into Eq.(4), induces mixing between axion and axial Higgs boson A^0 which is of order $m_{12}^2 v/v_m$. Hence, one expects the mixing angle

$$|\theta_{a,A^0}| \sim \frac{v}{v_m} \frac{m_{12}^2}{|M_{A^0}^2 - M_a^2|}.$$

With $v_m \sim 10^4 - 10^5$ GeV this angle is in the range $10^{-2} - 10^{-4}$, but this estimate is again strongly parameter-dependent, and the mixing may be somewhat higher.

[2)]Note that the soft terms consistent with PQ symmetry do not contain phases, which otherwise would be different in ordinary and mirror sectors.

[3)]The effective θ of ordinary strong interactions may acquire radiative corrections, but they are small [9].

Thus, in our toy model the axion is a relatively light remnant of extra strong interactions operating at very short distances. The axion mass may be well within accessible range of energies; its interactions with ordinary matter come from mixing with axial Higgs boson A^0, and the mixing angle may not be negligibly small. The scalar potential of the ordinary Higgs fields exhibits softly broken PQ symmetry. We expect that these features are generic to the class of grand unified theories where the strong CP problem is solved in a way discussed in this paper.

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