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$N = 1$ SUPERGRAVITY AND STRONG CP VIOLATION*

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A review of strong CP problem, with the emphasis on the axion solution, is presented. The possibility that $N = 1$ supergravity governs weak interactions is discussed. I then argue that supergravity can provide a simple solution to the strong CP problem, which is free from a domain wall problem.

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1. Introduction

It is well known that, due to nonperturbative effects, strong interactions do not conserve [1] P and CP. The parameter $\bar{\Theta}$ which characterizes the strength of the breaking of these symmetries is to be almost vanishingly small [2] $\bar{\Theta} < 10^{-9}$. Furthermore, in the presence of electroweak interactions, this coupling, through the renormalization of quark masses, is, like any other coupling of the theory, plagued by infinities in perturbation theory and so it cannot be set to zero naturally. This constitutes the so-called "strong CP problem", one of the "main" theoretical issues. Various ways out of this impasse have been offered in a course of years and the most popular solution invokes the existence of a new light pseudoscalar particle, the celebrated axion of Weinberg and Wilczek [3].

The fact that in the world with massless quarks U(1) chiral symmetry of the theory allows rotating $\bar{\Theta}$ away, led Peccei and Quinn [4] to argue in favor of describing weak interactions in such a way as to preserve this global symmetry, thus achieving vanishing $\bar{\Theta}$ to all orders in perturbation theory. The subsequent spontaneous breakdown of Peccei--Quinn symmetry $U(1)_{PQ}$, together with explicit instanton effects, predicts the existence of the axion. The $SU(2)_L \times U(1)$ axion, however, is ruled out and, furthermore, cosmological arguments [5] allow only extremely light axions in a very narrow window for their masses: 10^{-5} eV $< m_a < 10^{-2}$ eV. It is still possible, within the context of GUTS, to incorporate this fact and e.g. in SO(10) a realistic model can be constructed that relates axion to neutrino

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masses [6]. However, axion solution is furthermore plagued by a cosmological domain wall problem due to the fact that the Z_{2N} (N = number of flavors) discrete subgroup of $U(1)_{PQ}$ is preserved by instantons and only spontaneously broken through the Higgs mechanism [7]. A resolution of this problem tends to require the existence of superheavy, unobservable fermions and so is not very appealing.

Another "hierarchy" problem which has attracted the attention of theorists is the exceedingly small ratio of weak and GUT scales: $M_W/M_X < 10^{-12}$. Recently, it has been emphasized that supersymmetry [8] through its non-renormalization properties, will help keep this ratio small, if not explain its origin. The simplest realistic electroweak models seem to require local $N = 1$ symmetry, with gravitino mass being tied to the scale of weak interactions [9]. It was noticed subsequently [10] that the same property of finiteness will be responsible for the non-renormalization of $\bar{\Theta}$ in supersymmetric theories, giving hope that $\bar{\Theta}$ may remain small in perturbation theory.

This has led us [11] recently to study in depth the relation of strong CP violation and supersymmetry. A particular simple solution is offered in minimal $N = 1$ supergravity [11]:

(a) Peccei-Quinn symmetry is explicitly, but softly broken, making axion one of regular Higgs scalars of the theory, with $m \simeq m_W$.

(b) The same mechanism eliminates the domain wall problem, and

(c) The strong CP parameter is vanishingly small: $\bar{\Theta} < 10^{-16}$.

In this review I will go over some of the basic features of the strong CP problem and its axion solution; $N = 1$ supergravity and its possible role in solving the strong CP problem. The rest of this paper has then the following content:

Section 2. Strong CP problem
Section 3. Axion solution; domain wall problem
Section 4. $N = 1$ supergravity and weak interactions
Section 5. Supergravity and $\bar{\Theta}$
Section 6. Summary and comments

2. *Strong CP problem*

The most general, renormalizable QCD Lagrangian has the form

$$L_{QCD} = -\tfrac{1}{4}(F_{\mu\nu})^2 + \frac{\Theta g^2}{32\pi^2} F_{\mu\nu}\tilde{F}_{\mu\nu}, \tag{2.1}$$

where the color index is suppressed and

$$\tilde{F}_{\mu\nu} = \varepsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}. \tag{2.2}$$

Although the second term is a total divergence, it cannot be ignored, since it provides the breaking of an axial U(1) symmetry in the limit of massless quarks. Namely, the U(1) current

$$j_\mu^5 \equiv \sum_q \bar{q}\gamma_\mu\gamma_5 q \tag{2.3}$$

has a divergence

$$\partial^{\mu} j_{\mu}^{5} = \sum_{q} m_q \bar{q}\gamma_5 q + \frac{Ng^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}, \tag{2.4}$$

where N is the number of flavors. The dynamical breaking of this symmetry by the vacuum would lead to the existence of another light pion, if not for the $F\tilde{F}$ term. Its absence indicates the relevance of the $F\tilde{F}$ term and by now it is well known that instantons saturate the action, keeping $\int d^4x F\tilde{F} \neq 0$. This is good news since this provides a solution to the infamous $U(1)_A$ problem.

For the bad news: in the presence of a Θ term, the theory violates P and CP. Now, since in QCD Θ is not renormalized we could just choose $\Theta = 0$ and work in that sector. The problem arises in the presence of weak interactions. The general, arbitrary and complex quark mass matrices must be diagonalized by bi-unitary transformations

$$q_{L,R} \to U_{L,R} q_{L,R},$$

$$U_L^{+} M_q U_R = D_q \,(\text{diagonal}) \tag{2.5}$$

modifying Θ to an effective parameter

$$\bar{\Theta} \equiv \Theta - \arg\det M. \tag{2.6}$$

This is most easily seen from the form for the effective fermionic Hamiltonian [12] integrated over instantons

$$H_{\text{eff}}(\Theta) \simeq e^{i\Theta} \det |\bar{q}_L q_R| + \text{h.c.}, \tag{2.7}$$

where q covers all the flavors. In view of the above $\bar{\Theta}$ becomes logarithmically divergent like any other dimensionless coupling of the theory.

The best limit on $\bar{\Theta}$ comes from the measurements of the electric dipole moment of the neutron. The simple estimate, confirmed by more sophisticated computations [2] gives

$$d_n^e \simeq e \frac{\bar{\Theta}}{\Lambda_{\text{QCD}}} \frac{m_d}{\Lambda_{\text{QCD}}} \simeq \bar{\Theta} \times 10^{-16} e \text{ cm} \tag{2.8}$$

for $\Lambda_{\text{QCD}} \simeq 1$ GeV; where I have used the fact that in the $m_q \to 0$ limit, the physical effects of $\bar{\Theta}$ vanish. Namely, in this limit chiral symmetry operation

$$q \to e^{i\alpha\gamma_5} q \tag{2.9}$$

implies a change

$$\bar{\Theta} \to \bar{\Theta} - 2N\alpha \tag{2.10}$$

and so a proper choice of α can rotate $\bar{\Theta}$ away. The present experimental limit $(d_n^e)_{\text{exp}} < 10^{-25}$ $e$cm implies

$$\bar{\Theta} < 10^{-9}. \tag{2.11}$$

This is the strong CP problem: why is $\overline{\Theta}$ so small, or less ambitiously how to keep it small in perturbation theory!

Notice the similarity with the hierarchy problem in GUTS; however, the $\overline{\Theta}$ problem comes from the sole coexistence of electroweak and strong interactions. Let me go through some of the ways out o. this impasse, keeping the issue of the axion solution for the next Section.

(*i*) Assume the lightest quark, i.e. up quark to be massless: $m_u = 0$. Resulting chiral symmetry can be used then to rotate $\overline{\Theta}$ away. Most of the current algebra experts seem [13] to argue that $m_u \neq 0$, even if only 5–10 MeV. I will accept it in what follows.

(*ii*) We use some symmetry arguments to set $\overline{\Theta} = 0$ at the tree level. If this symmetry is subsequently spontaneously broken, the resulting $\overline{\Theta}$ is finite and calculable [14]. Example [15]:

Manifest left-right symmetry characterized by $M_q = M_q^+$, i.e. $U_L = U_R$. Therefore, Θ can be taken to vanish and further from (2.6): $\overline{\Theta}^{\text{tree}} = 0$. The up to now suggested models were unfortunately complicated; the idea is, however, sufficiently interesting to deserve further attention before being rejected.

(*iii*) Peccei-Quinn solution — see next Section.

3. *Axions; domain wall problem*

We have seen that $m_q = 0$ can be used to rotate $\overline{\Theta}$ away. Now, in electroweak theories quark masses originate from Yukawa couplings once the gauge symmetry is spontaneously broken. It is then natural, as Peccei and Quinn suggested [4], to construct gauge models so that they preserve chiral symmetry.

In the context of the standard SU(2) × U(1) model the minimal price that has be paid to achieve this is to add an additional Higgs doublet. The choice of Yukawa couplings that preserves the $U(1)_{PQ}$ chiral symmetry

$$q_L \to e^{i\alpha} q_L, \quad q_R \to e^{-i\alpha} q_R,$$
$$\varphi_a \to e^{2i\alpha}\varphi_a \quad (a = 1,2) \tag{3.1}$$

is [4]

$$L_Y = (\bar{u}\bar{d})^i_L (H_d)_{ij}\varphi_1 d^j_R + (\bar{u}\bar{d})^i_L (H_u)_{ij}\varphi_2 u^j_R + \text{h.c.}, \tag{3.2}$$

where $i, j = 1, \ldots, N$ counts quark flavors. Notice that the above form guarantees natural flavor conservation. By bi-unitary transformations we can put otherwise complex $H_{d,u}$ into the real, positive, and diagonal form, so that

$$\overline{\Theta} = \Theta + \arg\det H_d H_u. \tag{3.3}$$

Next, by a chiral transformation we can go into a $\overline{\Theta} = 0$ basis. The strong CP violation is eliminated if in this basis quark masses are real. To check this, let

$$\langle \varphi_a^0 \rangle = v_a e^{i\alpha_a},$$
$$\langle q_{L_i} q_{R_j} \rangle = \delta_{ij} \Lambda_q^3 \tag{3.4}$$

in which case the effective potential as a function of α_a takes the form

$$V_{\rm eff}(\alpha_a) = A\cos\alpha_{\rm d}+B\cos\alpha_{\rm u}, \tag{3.5}$$

where A, B depend on v_a, $\Lambda_{\rm q}$. Depending on the signs of A and B, α_a is either 0 or π, leading to real quark masses. This remarkably simple model, with a minimal extension of the standard model, solves therefore, strong CP problem.

The consequence of this mechanism is, however, profound. Spontaneous breaking of $U(1)_{\rm PQ}$ at the scale $M_{\rm PQ}$ generates the axion, whose mass and pseudoscalar couplings may be estimated by current algebra techniques [16]

$$m_a = m_\pi \frac{f_\pi}{M_{\rm PQ}}, \qquad h_a^5 = \frac{f_\pi}{M_{\rm PQ}}. \tag{3.6}$$

The original axion of Weinberg and Wilczek [3] with $M_{\rm PQ} = M_{\rm W}$ is now ruled out; furthermore the astrophysical and cosmological requirements constrain $M_{\rm PQ}$ in the interval [5]

$$10^9\ {\rm GeV} \leqslant M_{\rm PQ} \leqslant 10^{12}\ {\rm GeV}. \tag{3.7}$$

The lower bound arises simply from the existence of red giants and the upper bound keeps the axions from overclosing the universe. This is not much of a problem, since $M_{\rm PQ}$ could be an intermediate scale in a grand unified theory, e.g. the scale of the breakdown of parity in SO(10), as pointed out by Mohapatra and myself [6].

More serious problem stems from the fact that $\bar{\Theta}$ is cyclic variable [7] with a period 2π, as seen from (2.7), so that the discrete subgroup Z_{2N} of $U(1)_{\rm PQ}$ is only spontaneously broken through $\langle\varphi_a\rangle \neq 0$, resulting in the existence of different vacua, all carrying the same energy

$$\langle \bar{q}_{\rm L} q_{\rm R}\rangle = e^{\frac{2\pi}{N}k}\Lambda_{\rm q}^3,$$
$$\langle\varphi_a\rangle = e^{\frac{2\pi}{N}k} v_a; \qquad k = 0, \ldots, N-1. \tag{3.8}$$

This, of course, results in a domain picture of the universe [17], with the energy density in the domain walls many orders of magnitude larger than allowed by not overclosing the universe. The most elegant solution of this problem, as suggested by Lazarides and Shafi [18], is to find an appropriate model in which the discrete subgroup of $U(1)_{\rm PQ}$ would coincide with the center of a gauge group, which enables reaching different vacua by a continuous rotation, with no loss of energy. Unfortunately, this does not work in simple minimal SU(5) and SO(10) models [19].

4. N = 1 supergravity and weak interactions

I will not go through, by now familiar, motivations for low lying supersymmetry, the main being the possible solution to the hierarchy problem in GUTS. Various problems encountered by globally supersymmetric theories, lead towards supergravity, interesting in its own right as possible renormalizable extension of gravity. The requirement of chiral fermions selects uniquely $N = 1$ theory, which being non-renormalizable, should be viewed as only a part of a more complete theory ($N = 8$?), broken at very high energy $\gtrsim$ Planck mass. In what follows, I would like to discuss, if only briefly, some of the main features of the minimal $N = 1$ supergravity theory [20].

Minimal model

In addition to matter and gauge supermultiplets present in globally SS theories, we have an additional multiplet

$$(g_{\mu\nu}, \psi_{3/2}) \tag{4.1}$$

where $g_{\mu\nu}$ stands for the graviton (one really works with the spin 2 vierbein field) and $\psi_{3/2}$ is a Rarita-Schwinger spin 3/2 field-gravitino. Prior to SS breaking, gravitino is massless and in order to remedy this one uses the so-called super Higgs mechanism [21].

Recall first the notion of chiral (or scalar) supermultiplet; it contains a complex scalar field and a Majorana fermion. In my notation, the supermultiplets carry capital letters, the same letter that characterizes the basic member of the supermultiplet. For example, a supermultiplet containing right-handed down quark d_R and its superpartner (squark) $\tilde{d}_R$ (tilda will consistently stand for supersymmetric partners) will be denoted by D_R

$$D_R \equiv (d_R, \tilde{d}_R). \tag{4.2}$$

We use, by now established vocabulary, with superpartners called spartners, except for gauginos (partners of gauge bosons) and gravitino, the partner of the graviton.

The Lagrangian of the theory is obtained from the superpotential W, a general, gauge invariant function of superfields of the dimension $\leqslant 3$, to keep the theory renormalizable. In particular, the Higgs potential in $N = 1$ supergravity theory as a function of W is [21]

$$V = \exp\left(\frac{\sum |\varphi_i|^2}{M^2}\right) \times \left(\sum_i \left|\frac{\partial W}{\partial \varphi_i} + \frac{\varphi_i^* W}{M^2}\right|^2 - \frac{3|W|^2}{M^2}\right) + \tfrac{1}{2} D_\alpha D_\alpha \tag{4.3}$$

where φ_i covers all the scalar fields of the theory, $M \equiv M_{\rm Pl}/\sqrt{8\pi} \simeq 2\times 10^{18}$ GeV and

$$D_\alpha = g_\alpha(\sum_i \varphi_i^+, T_\alpha \varphi_i) \tag{4.4}$$

where g_α are the gauge couplings and T_α are the generators of the group.

Let us now specify the model and the particle content and study the consequences.

$$G = SU(2)_L \times U(1)$$

particle content

Fermions

$$\begin{aligned} Q_L &= \begin{pmatrix} U \\ D \end{pmatrix}_L \quad U^*_R, D^*_R, E^*_R \\ \psi_L &= \begin{pmatrix} \nu \\ E \end{pmatrix}_L \end{aligned} \tag{4.5}$$

Keep in mind that the superfields carry the chirality of the fermionic members; only the product of the superfields with the same chirality preserves the chirality and so we deal with the fields of the same chirality (complex conjugate of the right-handed superfield is left-handed and vice versa).

Higgs

We need two Higgs superfields with opposite $U(1)_Y$ charges

$$\begin{aligned} \Phi_{a_L} &= (\varphi_a, \tilde{\varphi}_a), \quad a = 1,2 \\ Y\Phi_1 &= \Phi_1, \quad Y\Phi_2 = -\Phi_2. \end{aligned} \tag{4.6}$$

Among other reasons, two doublets are needed so that the anomalies due to shiggses are canceled. The superpotential takes then the form

$$W\,(\text{light}) = he\psi_e\Phi_{1L}E^*_R + h_dQ_L\Phi_{1L}D^*_R + h_uQ_L\Phi_{2L}U^*_R + \mu\Phi_{1L}\Phi_{2L}, \tag{4.7}$$

where the $SU(2)_L$ indices have been suppressed. Notice again the need for two doublets; the chirality constraints decouple them in Yukawa sector. This is the essential fact: *both natural flavor conservation and Peccei-Quinn symmetry (in Yukawa couplings) result.*

The super Higgs mechanism requires an additional chiral multiplet [21]

$$Z = (z, \chi), \tag{4.8}$$

where z is a spin-0 complex field and χ spin 1/2 field (*a* would be Goldstino). The superpotential of theory in its simplest (Polony) form [22] is

$$W_{\text{total}} = mM(Z+a) + W\,(\text{light}). \tag{4.9}$$

It is easy to see that

$$\begin{aligned} \langle z \rangle &= (\sqrt{3}-1)M, \\ a &= (2-\sqrt{3})M \end{aligned} \tag{4.10}$$

minimizes the potential (4.3), so that $V(\langle z \rangle) = 0$, i.e. the cosmological constant vanishes. Expanding to the leading order in $1/M$ gives for the effective potential [9]

$$V_{\text{eff}}\,(\text{light}) = \sum_i \left|\frac{\partial \overline{W}\,(\text{light})}{\partial \varphi_i}\right|^2 + m^2_{3/2}\left(\sum_i |\varphi_i|^2\right)$$

$$+ m_{3/2}\left(\sum_i \varphi_i \frac{\partial \overline{W}(\text{light})}{\partial \varphi_i} - \sqrt{3}\,\overline{W}\,(\text{light}) + \text{h.c.}\right) + \tfrac{1}{2} D_\alpha D_\alpha, \tag{4.11}$$

where here φ_i stands for *all* the scalar fields; and

$$m_{3/2} = e^{\frac{1}{2}(\sqrt{3}-1)^2} m$$

$$\overline{W}\,(\text{light}) = e^{\frac{1}{2}(\sqrt{3}-1)^2} W\,(\text{light}). \tag{4.12}$$

The main features of the theory are easily read off from (4.7) and (4.11).

(a) Global supersymmetry in the light sector is explicitly, but softly broken by the operators of dimension $\leqslant 3$.

(b) Similarly, $U(1)_{PQ}$ is explicitly and softly broken.

(c) It can be seen that the structure of the fermionic part of the Lagrangian is the same as in global SS.

I will not discuss the analysis of symmetry breaking or the low energy predictions of this theory; suffice it to say that the model is completely realistic [25], with the interesting prediction for the mass of the usual standard neutral Higgs scalar η: $m_\eta = m_z$. Rather, in the next Section we shall see how supergravity induced terms in (4.11) can solve some of the axion's problems.

5. *N = 1 supergravity and* $\overline{\Theta}$

As I mentioned in the Introduction, it was noticed by Ellis et al. [10] that $\overline{\Theta}$ is finite in SS theories, since masses do not get renormalized. We shall see now further consequences [11] of $\overline{\Theta}$ on the issue of strong CP violation.

(*i*) $U(1)_{PQ}$ *is explicitly broken* [11], which results in *lifting the axion* [23]. It is easy to calculate its mass [24]

$$m_a^2 \simeq \mu m_{3/2}. \tag{5.1}$$

Since one of the charged shiggs masses is proportional to μ, there is an approximate lower limit [25] $\mu >$ (5–10) GeV; and since $m_{3/2} > 20$ GeV (it is the supergap of the theory), $m_a > 10$ GeV. The expected values $\mu \simeq m_{3/2} \simeq M_W$, suggest $m_a \simeq M_W$.

(*ii*) More importantly, the $\mu\varphi_1\varphi_2$ term in the potential (4.11) breaks Z_{2N} symmetry down to Z_2. But Z_2 is the center of $SU(2)_L$; *hence no domain wall problem.*

(*iii*) $\overline{\Theta} < 10^{-16}$. Here the situation is somewhat subtle, so we discuss the value of $\overline{\Theta}$ in some detail. First, it is easy to see, based on the analysis of Sec. 3, that the $\overline{\Theta}^{\text{tree}} = 0$ choice renders quark masses real [see below, Eq. (3.5)]. This choice is *necessary* in order to calculate $\overline{\Theta}$ in higher orders; although not natural, it is encouraged by the finiteness of $\overline{\Theta}$ and somewhat justified by the small value of $\overline{\Theta}^{\text{ind}}$. Of course, for the success of this program we must imagine some more complete theory to start with ($N = 1$ supergravity is not renormalizable theory, anyway) which would explain $\overline{\Theta}^{\text{tree}} = 0$.

Next, we compute higher order contributions to $\overline{\Theta}$. We will be working in the physical basis, using R gauge. Now, besides usual diagrams encountered originally by Ellis and Gaillard [26], there are additional contributions involving squark-gaugino and squark-

-shiggs intermediate states. However, we do not have to compute any of these graphs; we shall be able to use the super-GIM mechanism which characterizes the minimal supergravity theory. The super-GIM mechanism simply means that the only complex and nondiagonal coupling is Cabibbo-Kobayashi-Maskawa unitary matrix U; it is guaranteed by (4.7) and (4.11), i.e. by the fact that the split in quark and squark masses is given by the unit matrix in the flavor space, i.e. $\Delta m^2_{\tilde{q}} = \Delta m^2_{q}$. The same fact is responsible for the small $K_L - K_S$ mass difference.

In order to start our discussion, let us write [26]

$$M_q^{ind} = (1+C_q)M_q, \tag{5.2}$$

where M_q is the tree-level *diagonal* quark mass matrix (*physical mass matrix*), so that in perturbation theory [26]

$$\begin{aligned}\bar{\Theta} &= \arg\det M_u^{ind} M_d^{ind} \\ &= \mathrm{Im}\,[\mathrm{Tr}\ln(1+C_u) + \mathrm{Tr}\ln(1+C_d)] \\ &= \mathrm{Im}\,\mathrm{Tr}\,(\alpha/\pi)^n\,[C_u^{(n)} + C_d^{(n)}].\end{aligned} \tag{5.3}$$

One-loop

A typical diagram takes the form

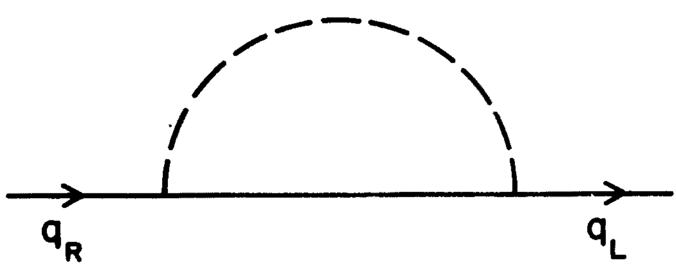

Fig. 1. One-loop contribution to quark masses. Solid internal line stands for quarks or gauginos (or shiggs), and dashed line stands for Higgs scalars or squarks

The resulting general form of C_q's is

$$\mathrm{Im\,Tr}\,C_q^{(1)} \propto \mathrm{Im\,Tr}\,UX_qU^+ = \mathrm{Im\,Tr}\,X_q = 0, \tag{5.4}$$

where we did not need to specify X_q, since it is necessarily real and diagonal in the basis we are working (it is just some number of mass insertions).

Similar analysis shows that the first nonvanishing contribution appears at the *three-loop* level [26], in order to have four U's and sufficient number of mass insertions (typical diagram is displayed in Fig. 2). The gluon line, chosen to give the largest contribution, is needed to add more mass insertions after the ends of the two dashed lines.

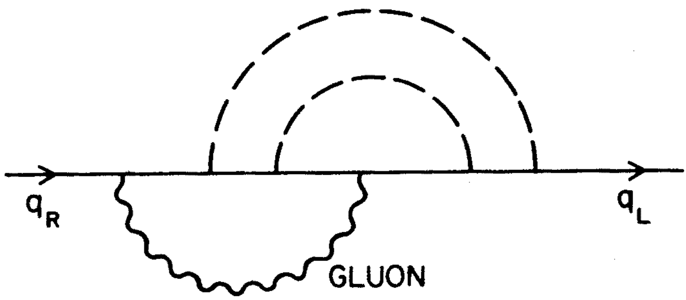

Fig. 2. Three-loop contribution to M_q

The leading contribution to $\bar{\Theta}$ is easily estimated to be [26]

$$\bar{\Theta} \simeq \frac{\alpha_s}{\pi}(\alpha/\pi)^2 \frac{m_t^2 m_b^2 m_c^2 m_s^2}{M_W^8} \,\mathrm{Im}\,(U_{22}U_{33}U_{23}^* U_{32}^*)$$

$$= \frac{\alpha_s}{\pi}(\alpha/\pi)^2 s_1^2 s_2 s_3 \sin\delta \,\frac{m_t^2 m_b^2 m_c^2 m_s^2}{M_W^8} \tag{5.5}$$

where I have used $m_{3/2} \simeq M_W$. For usual values of quark masses, conservative upper limit is

$$\bar{\Theta} < 10^{-16}. \tag{5.6}$$

I should remark that the crucial feature of this result is the super-GIM mechanism which appears at the tree-level of minimal supergravity. Now, the departures from this mechanism are expected at some level and in that case the experimental limit $\bar{\Theta} < 10^{-9}$ can be used as the constraint on the theory. This is now in process of investigation for general situations.

Let us summarize the situation with the following comments:

(a) The axion gets a large mass $m_a \simeq m_{3/2}$.
(b) Flavor conservation is natural.
(c) No domain wall problem — Z_{2N} is broken.
(d) In the minimal model $\bar{\Theta} \lesssim 10^{-16}$.
(e) The grand unified version of this model should be based on SO(10) [in view of (c)], since its center is Z_4, rather than on SU(5) whose center is Z_5 and so leads to a domain wall problem.

6. Summary and comments

In this short review I have tried to argue that for whatever its virtues or faults are, $N = 1$ supergravity electroweak theory may offer a simple solution to the strong CP problem, without invoking the existence of the axion. The mechanism is similar to the way the hierarchy problem is treated up to now, namely, one is forced to a choice $\bar{\Theta}^{\text{tree}} = 0$, which is then guaranteed to be small in perturbation theory. The essential feature of this approach is that the same explicit (soft) terms in the potential that break $U(1)_{PQ}$ and give axion the mass, also break its discrete subgroup Z_{2N} down to Z_2, and therefore, in the context of $SU(2)_L \times U(1)$, eliminate the domain wall problem.

In general, the induced value of $\overline{\Theta}$ is a model dependent quantity. Remarkably enough, the experiment favors the theory with minimal kinetic terms for scalars and real gaugino masses. If no departure from the super-GIM mechanism is encountered in this model, then $\overline{\Theta} < 10^{-16}$, leaving all the electroweak predictions for CP violation unobscured by the effects of strong interactions. The more general analysis is still needed, and even more, the mechanism that would explain the origin of the $\overline{\Theta}^{\text{tree}} = 0$ is missing at the moment.

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