Strong CP and Low-energy Supersymmetry

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Abstract

A spontaneously-broken CP provides an alternative to the KM mechanism for CP violation with the advantage that the strong CP problem is solved. We consider, for such a model with a new gauged $U(1)$, the incorporation of low-energy supersymmetry and find the constraints on alignment and squark degeneracy. The conclusion is that although the $\bar{\theta}$ constraints are much less severe than in other generic schemes with supersymmetry breaking and spontaneous CP violation, one restriction remains stronger than needed in the MSSM for suppression of FCNC.
Symmetries play a fundamental role in physics; in particular, study of discrete spacetime symmetries like P and T have revolutionized our theory of particle physics during the last forty years. Our present understanding of P violation is incorporated as a part of the standard model in the form of chiral fermions. Our view of T (or equivalently CP) violation is less mature and requires the acquisition of more empirical data.

A model of spontaneous CP violation (SCPV) with an extra gauged $U(1)$ symmetry was first proposed [1] in 1990 and developed in subsequent papers [2,3]. The principal advantage over the standard model is that the strong CP problem is solved. The gauged $U(1)$ also provides a new mechanism for generation CP-violating effects in neutral meson mixings. In the recent work with Glashow [3], it was emphasized how the (aspon) model is fully consistent with present experimental data and that a testable prediction is made in $B$-decay (see also [4]).

Here we consider whether the essence of the aspon mechanism can co-exist with low-energy supersymmetry (SUSY). In particular, we address the question of what the minimal supersymmetric aspon model (MSAM) is. An important requirement is that the MSAM permits SCPV in its Higgs potential. Also, we wish to specify the constraints on the soft SUSY breaking parameters (SSBP), e.g. proportionality of $A$-terms and squark mass degeneracy, which must be satisfied for consistency with experiment. Our aim here is not to make any specific proposal about how such constraints may be satisfied, though we will discuss the part of the issue related to specifying fully the MSAM and make some speculations beyond that. We hope to return to the question in future publications.

There already exists a considerable literature on the question of SCPV in supersymmetric extensions of the standard model, so we need to explain how the present paper differs from earlier work. It is well known that SCPV is not possible in the tree-level Higgs potential of a supersymmetric standard model with minimal Higgs content. The papers [5,6] study some alternative possibilities and arrive at interesting no-go theorems which rule out certain interesting classes of extended Higgs sectors. A model with an extra pure singlet Higgs, however, admits SCPV [7]. We shall use these results in defining our MSAM. The work of
gives constraints on the proportionality and degeneracy necessary for phenomenological consistency in generic models with SUSY and an SCPV solution to the strong CP problem (see also [9]). The authors then conclude that the constraints on the SSBP are much more severe than the corresponding ones from FCNC and cannot expected to be satisfied without unnatural fine tunings. However, in [8] the additional quark is assumed to have very heavy \( \geq 10^{11}\text{GeV} \) mass while in the aspon case discussed here, the new quark(s) are instead expected to be relatively light, below 600GeV [2] for example. A second difference from [8] is that the aspon model provides an additional mechanism for CP violation in the kaon system and so the constraint provided by the only measured CP violation parameter \( \epsilon \) is quite different.

The fields of the non-supersymmetric aspon model comprise the standard model with three families, together with a vector-like doublet of quarks \( Q_o \), two complex scalar singlets \( \chi_1, \chi_2 \) and the gauge field (aspon) of an additional \( U(1)_a \) with respect to which only the extra quarks and scalars are charged. The first question then is whether the simplest possible MSAM is to take just the same fields rewritten as superfields? To cancel anomalies of the fermionic partners \( \tilde{\chi}_1, \tilde{\chi}_2 \) we must introduce the conjugate superfields, designated \( \chi_3, \chi_4 \). The latter have no admissible Yukawa couplings to the quark superfields. But even then one must ensure that \( \langle \chi_{1,2} \rangle \) can be complex as necessary for the aspon scenario?

At tree level the resultant Higgs potential is sufficiently similar to that discussed in [3] that we deduce that SCPV can occur only at isolated points in parameter space and is therefore unacceptable. \(^1\) To allow SCPV, the minimal addition is of one singlet uncharged scalar \( \mathcal{N} \) which does not contribute to any anomaly and allows SCPV. This then completes the field content of our MSAM.

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\(^1\)It is possible that radiative corrections with appropriate soft SUSY breaking can induce additional terms [10] in the potential which can in principle allow SCPV but this requires strong restrictions on soft \( \chi \) mass terms.
In the spirit of the aspon model we shall assume that the soft breaking of SUSY respects CP invariance, \( i.e. \) the lagrangian is of the form \( \mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{\text{SUSY}} \) and \( \mathcal{L} \) is CP conserving. Recall that the quark mass matrices of the aspon model have the texture:

\[
m_q = \begin{pmatrix}
m & 0 \\
m_5 \alpha^\dagger & M
\end{pmatrix}
\]

where \( M \) denotes the mass of the vectorlike quark, \( m_5 \) the magnitude of the mixing induced by \( \langle \chi_{1,2} \rangle \), and \( \alpha \) the corresponding \( 3 \times 1 \) complex phase vector with \( \alpha^\dagger \alpha = 1 \). At tree-level \( \tilde{\theta} \) is zero. At one-loop order, both the gluino mass and quark mass matrices develop imaginary parts and our main purpose is to find the constraints necessary to keep \( \tilde{\theta} < 10^{-9} \) as dictated by the bound on the neutron electric dipole moment.

The situation with SUSY is in this regard quite different from the non-supersymmetric aspon model where the one-loop contribution \([4]\) comes from only one specific diagram (Figure 1) which vanishes at lowest order in the minimal supersymmetric case. The reason is that the crucial four-scalar coupling \( \lambda |\phi|^2 |\chi|^2 \) cannot arise from a superpotential which is gauge invariant. More important, there are now new quark mass and gluino mass one-loop diagrams (Figures 2 and 3 respectively) contributing significantly to \( \tilde{\theta} \), as a result of soft SUSY breaking. For the quark mass diagram, the case with a gluino running in the loop is by far the dominating one, due to the strong QCD coupling. Cases involving other neutral gauginos with the same structure are further suppressed. Unlike the case analyzed in \([8]\), here we cannot integrate out the vectorlike quark superfields before looking into the constraints on the SSBP and have to consider mixings among both the left- and right-handed quark states. This does give constraints that disappear in the large \( M \) limit. In this sense, our treatment is complimentary to that in \([8]\). We first apply the bi-unitary transformation diagonalizing the quark mass matrix to the superfields. We write

\[
U_R^\dagger m_q U_L = \begin{pmatrix}
m & 0 \\
0 & M
\end{pmatrix}
\]

where, without loss of generality, we assumed the \( 3 \times 3 \) matrix \( m \) to be diagonal. Then the SSBP can be written in the form:
The quantities "$\delta A$" and "$\delta \tilde{m}^2$" parameterize departure from proportionality and squark degeneracy. The only possible complex quantities, arising from CP violating VEVs, among the SSBP are here absorbed into the $3 \times 1$ phase vector $a$, with $a^\dagger a = 1$. The second term in each of these expressions is in general complex, as a result of the complex phases in $\alpha^\dagger$ from the quark mass matrix going into the off-diagonal entries of $U_R$ and $U_L$. All the other parameters are real. A $\delta A_M$ term can always be absorbed into $\tilde{m}_A$ but keeping it helps to illustrate some feature of the results below. The $\delta A_5$ term has a "hard" SUSY breaking piece involving VEV’s of the $F$-terms of the $\chi_{1,2}$ superfields, $F_{\chi_{1,2}}$. The exact definition for the term is given by

$$\delta A_5 m_5 a_5^\dagger + \tilde{m}_A m_5 \alpha_5^\dagger = A_{\chi_j}^i h_i^j \langle \chi_j \rangle - h_i^j \langle F_{\chi_j} \rangle$$

(5)

where summation over $j = 1$ and 2 should be taken, and $h_i^j$ denote Yukawa couplings with then $m_5 \alpha_5^\dagger = h_i^j \langle \chi_j \rangle$. Alignment between the phase vectors $\alpha^\dagger$ and $a^\dagger$ is by no means guaranteed. This is especially the case when the $\langle F_{\chi_j} \rangle$'s are nonzero. However, if $\langle \chi_j \rangle$'s break $U(1)_a$ in a F-flat direction, misalignment between $\alpha^\dagger$ and $a^\dagger$ is then a direct consequence of the lack of proportionality for the $A_{\chi_j}^i$'s. The above expressions (2-4) clearly illustrate that in the limit of strict proportionality and degeneracy, the SSBP give no contribution to $\bar{\theta}$.

2In principle, an alignment of the phases in $\langle F_{\chi_j} \rangle$'s with those in $\langle \chi_j \rangle$'s would make the $F$-term contributions themselves satisfy proportionality and be totally absorbed into the $\tilde{m}_A$ term. This alternative, however, does not seem to be realistic.
Now we go on to derive the constraints on the lack of proportionality and degeneracy from $\bar{\theta} < 10^{-9}$. First note that both the quark and gluino mass diagrams require a $\tilde{M}_{RL}^2$ mass insertion on the squark line. The first order contribution to $\delta m_q$ (Fig. 2) is then proportional to $\tilde{M}_{RL}^2$. However, as the latter has the same type of texture as $m_q$, it always gives a real trace to $m_q^{-1}\delta m_q$ and hence does not contribute to $\bar{\theta}$. Similarly, if we take only the proportional part of the insertion and add an extra squark degeneracy violating mass insertion in either the left- or the right-handed squark line, the trace is again real. Complex phases in $m_q^{-1}\delta m_q$ contributing to $\bar{\theta}$ arise from: 1) one proportionality violating insertion together with one degeneracy violating insertion; 2) two degeneracy violating insertions; 3) two proportionality violating insertions. For each specific diagram of $\delta m_q$, there is a corresponding gluino mass ($\delta m_\lambda$) diagram (Fig.3) that is related by interchanging internal and external fermion lines. The $\delta m_\lambda$ diagram so obtained leads to a $\bar{\theta}$ contribution suppressed relative to the $\delta m_q$ diagram by $m_i^2/m_\lambda^2$ ($m_i$ being the mass of a light quark) or $M^2/m_\lambda^2$ and is hence uninteresting. The only exception is the case of a single proportionality violating insertion; because unlike the $m_q^{-1}\delta m_q$ case where individual contributions to the imaginary part cancel in the trace as noted above, here they give genuine contribution to $\bar{\theta}$.

To arrive at the explicit constraints, we use expressions of the $U_R$ and $U_L$ transformation matrices up to second order in $x$ \cite{2,11,12} where $x = m_5/M$ is a small parameter characterizing mixing between the light and heavy quarks. Actually, $x^2 \sim 3 \times 10^{-5}$ can still give rise to sufficient CP violation in the $K - \bar{K}$ system through the aspon exchange mechanism \cite{2}. The strength of each proportionality or degeneracy violating insertion can be obtained by going to the quark mass eigenstate basis and working out the second term in each of the Eq.(2-4). To simplify the expressions, we use $m_S$ to denote the assumed common scale of SSBP (including $m_\lambda$), assuming also $M \lesssim m_S$. The constraints resulted are listed in Table 1.

A few comments are in order. Firstly, the numerical constraints listed in the Table are obtained by taking a "central" value for $x^2$ at $10^{-4}$ and assuming a common scale for the SSBP (including gaugino masses) with $M$ at about the same order. This choice of $x^2$ could
possibly be further reduced by up to an extra order of magnitude. The smallness of the $x$
value is an important feature of the aspon model that weakens the constraints on the SSBP,
as compare to other generic SCPV schemes, and gives some hope that they can be satisfied.
In specific SUSY breaking scenario with small $A$-terms \cite{13, 14}, constraint expressions with
a $\delta A/A$ factor are explicitly weakened by an extra factor of $A/\tilde{m}_S$. Actually, small $A$-term,
e.g. $\sim 10^{-3}\tilde{m}_S$ goes a long way towards satisfying all constraints involving proportionality
violations, except for constraint (6). The only constraint not involving proportionality vi-
olation, no.(8), is also much weakened due to a necessary $A$-insertion. Reducing the gluino
mass relative to squark masses strengthens the constraints (1)-(3) but weakens (4)-(10) by
the same factor. Second, we have taken $M \sim \tilde{m}_S$ which is what is to be expected in the
aspon model. The case of large $M$, however, cannot be read off directly from the table.
While constraint (7) is reduced by at least a factor of $\tilde{m}_S^2/M^2$, others have to be tracked
down more carefully by identifying the heavy squark propagators with masses $\sim (M^2 + \tilde{m}_S^2)$
which are then dominated by the supersymmetric contribution. When this is done carefully,
the constraints fall in agreement with the results in \cite{8}. Note that to match our analysis
with that of \cite{8}, one has to take only the down-sector results and flip the $L$ and $R$ indices.
This leads to our last comment about MSAM constraints. We have been sticking to the
original version of the aspon model with a vectorlike quark doublet, which has constraints
of the form given in both the up- and down-sector. As illustrated in the Table, some of
the up-sector constraints are stronger than the corresponding down-sector ones, essentially
due to the heavy top mass.\footnote{Further suppression to the down-sector constraints could be obtained in the large tan $\beta$ setting, from $\langle H_d \rangle / \tilde{m}_S$.} In an alternative aspon model with the vectorlike quark being
a down-type singlet\footnote{Again, a flipping of $L$ and $R$ indices is needed.}, there is no contribution to $\bar{\theta}$ from the up-sector and all constraints
for the sector go away. This gives it an advantage. One should note that the vectorlike
down-type singlet could not be replaced by an up-type one — CP violation then can only affect the $K - \bar{K}$ system through the KM-mechanism which requires $x \gtrsim 0.1$. The essence of the aspon model is then gone.\footnote{\textit{}}

Now we take a brief look at what kind of features in a more complete model, including details of the sector charged under $U(1)_a$ and a specific supersymmetry breaking mechanism, that have a better chance at satisfying the constraints. The first thing we notice is that the doublet aspon model is most probably unrealistic in a supersymmetric setting. The constraints on up-type squark degeneracy are most certainly going to be violated as a result of the large top Yukawa which enforces a much larger renormalization group (RG-)running on the top squark, breaking any degeneracy imposed at the SUSY breaking scale. For the rest of the discussion, we will concentrate on the aspon model with a vectorlike down-type singlet. The degeneracy constraints are still stringent. In particular there is one very strong constraint (no.\(6\)) requiring

$$\frac{\delta A \delta \tilde{m}_L^2 - \delta \tilde{m}_L^2}{A \tilde{m}_S^2} \lesssim 10^{-8}$$

There is not much chance of satisfying the constraint together with all the others without having $\frac{\delta \tilde{m}_L^2 - \delta \tilde{M}_L^2}{\tilde{m}_S^2} \lesssim 10^{-4}$ (remember that here $R$ reads $L$ from the table), at least. This sounds difficult. However, once this condition is assumed, the other constraints on the SSBP involving the scalar partner of the light quarks are in general not much stronger than those demanded by FCNC experiments \cite{13}. This requires good degeneracy among the light ($\tilde{d}$) singlets and the new quark, $\tilde{D}$. The latter though having the same standard model quantum number as the light singlets, bears an $U(1)_a$ charge. RG-running again distinguishes it from the light singlets with an effect dependent on the the $U(1)_a$ gauge coupling. The best hope,\footnote{In relation to the issue, an interesting feature of the singlet version of the aspon model is that CP violation in the up-sector is much suppressed relative to the down-sector, as the former has to come from the KM phase. This is a unique characteristic of the model that could have interesting phenomenological consequences.}
we believe, is offered by some sort of low-energy SUSY breaking scenario such as gauge mediated models [13]. This tames the RG-runnings. To name a possible scenario, if we have a gauge mediated model the messenger sector of which has no $U(1)_a$ charge, the effective soft SUSY breaking terms would be blind to the $U(1)_a$ as well as to flavor, thus allowing the degeneracy at first order.

The more interesting part concerning our MSAM are the $\delta A_5$ related constraints, as they are related to the $U(1)_a$ symmetry breaking. Constraints (1) and (2) concern the lack of proportionality between the $A_5$ term (c.f. Eq.5), coming from mixing between the light and heavy squarks, and the corresponding term in the superpotential. Both terms are complex, as a result of SCPV coming with $U(1)_a$ symmetry breaking. What is needed is then a matching of the complex phases, $a^i \alpha \lesssim 10^{-3}$ from constraints (1). Constraint (2) has a term with a slightly different phase structure but, for the down-sector only where the constraints now apply, it goes away. We have mentioned above that the symmetry breaking has to go along a F-flat direction for $\chi_{1,2}$. Assuming this, and considering that the constraint (1) comes from the gluino mass diagram with a single proportionality violating insertion where each of the three families contribute independently, we can rewrite the constraint as

$$\frac{\delta A_5^i}{A_\chi^i} \lesssim 10^{-3}$$

for each $i$ ($A_\chi^i \sim A_{\chi_j} \sim \tilde{m}_S$ is assumed). This makes the physics content of the constraint more transparent. Constraints involving the $\frac{\delta A_5 - \delta A_M}{\tilde{m}_S}$ factor imply a more complicated restriction on the sector charged under $U(1)_a$. The factor has phase vector components not shown explicitly in the Table. For example, the particularly stringent constraint (10) is actually given by

$$\frac{\delta A |\delta A_5 a_i^* - \delta A_M a^*_i|}{\tilde{m}_S} \lesssim 10^{-8}.$$  

In constraints (4) and (5) the same factor, $\frac{|\delta A_5 a_i^* - \delta A_M a^*_i|}{\tilde{m}_S}$ involved. To suppress the factor requires alignment between the $A_\chi$-terms and the $A_M$ term, as well as the phase vectors $a$ and $\alpha$.  

9
Of course we still have to write down a superpotential for the $\chi$ and $\mathbb{N}$ superfields that breaks $U(1)_a$ in the way required. For instance, we can have

$$W_{\chi,\mathbb{N}} = \sum_{j=1,2}^{k=3,4} y_{jk} \mathbb{R}_j \chi_j \chi_k + P(\mathbb{N})$$

(9)

where $P(\mathbb{N})$ is a general cubic polynomial in pure singlet $\mathbb{N}$. This is similar to a well known example [16] from which one can easily see that it admits a SUSY preserving vacuum with $\langle \mathbb{N} \rangle = 0$. This holds even in the presence of a Fayet-Iliopoulos $D$-term for $U(1)_a$.

In summary, the inclusion of low-energy supersymmetry makes it more difficult to solve the strong CP problem with spontaneous CP violation. We have constructed a minimal supersymmetric aspon model (MSAM) with just one additional singlet superfield $\mathbb{N}$, and explicitly evaluated the $\bar{\theta}$ constraints. The constraints on $A$-term proportionality and squark degeneracy require that the stringent inequality given by Eq.(6) be satisfied, but beyond that the usual FCNC constraints for the MSSM are about sufficient. The major extra constraints are given by Eq.(7) and (8). It remains for future work to study whether the constraints can be satisfied in a more complete theory incorporating specific mechanism of SUSY breaking.

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Table 1. Interesting terms in $\bar{\theta}$ and estimates of resultant constraints on the soft supersymmetry breaking parameters (SSBP). The magnitude of $\bar{\theta}$ contributions from each term has been split into factors from different proportionality and squark degeneracy violations. Explicit dependence on the phase vectors $a$ and $\alpha$ is shown only for the first two constraints, where they may be of interest. Numerical constraints listed in the last column, apply to the (products of) the proportionality and/or degeneracy violating factor(s). No suppression from $\langle H \rangle / m_S$ is assumed. $m_i$ could be the mass of a light quark of any family. A numerical constraint with a $(u)$ or a $(d)$, refers to the up- or down-sector respectively; otherwise, the constraint is common to both sectors. The constraints marked by * are the more important ones; all the others are very likely to be satisfied if they are.

| No. | magnitude of $\bar{\theta}$ contribution | constraints |
|-----|-----------------------------------------|-------------|
| (1)* | $\frac{3\alpha s}{4\pi} x^2 M^2 \langle a \hat{\alpha} \rangle / m^2_S$ | $\approx 10^{-3}$ |
| (2) | $\frac{3\alpha s}{4\pi} x^2 \langle H \rangle m_i / m^2_S$ | $\approx 10^{-3}$ |
| (3) | $\frac{3\alpha s}{4\pi} x^2 \langle H \rangle m_i / m^2_S$ | $\sqrt{\text{by (9)}}$ |
| (4) | $\frac{\alpha s}{4\pi} x^2 m_i / m^2_S$ | $\approx 10^{-3}$ |
| (5) | $\frac{\alpha s}{4\pi} x^2 m_i / m^2_S$ | $\approx 10^{-3}$ |
| (6)* | $\frac{\alpha s}{4\pi} x^2 \langle H \rangle m_i / m^2_S$ | $\approx 10^{-8}$ |
| (7) | $\frac{\alpha s}{4\pi} x^2 \langle H \rangle m_i / m^2_S$ | $\sqrt{\text{by (9)}}$ |
| (8)* | $\frac{\alpha s}{4\pi} x^2 A(m_i) (i \neq j) / m^2_S$ | $\approx 10^{-6}$ $(d)$ ; $10^{-7}$ $(u)$ |
| (9)* | $\frac{\alpha s}{4\pi} x^2 A^2(m_i) / m^2_S$ | $\approx 10^{-6}$ $(d)$ ; $10^{-7}$ $(u)$ |
| (10)* | $\frac{\alpha s}{4\pi} x^2 A^2(m_i) / m^2_S$ | $\approx 10^{-8}$ |
Figure Captions:-

1. 1-loop quark mass diagram contributing to $\tilde{\theta}$ in the nonsupersymmetric aspon model (with vectorlike doublet $Q_o$).

2. 1-loop quark mass diagram contributing to $\tilde{\theta}$ in the supersymmetric aspon model.

3. 1-loop gluino mass diagram contributing to $\tilde{\theta}$ in the supersymmetric aspon model.
FIG. 1. 1-loop quark mass diagram contributing to $\bar{\theta}$ in the nonsupersymmetric aspon model (with vectorlike doublet $Q_o$).
FIG. 2. 1-loop quark mass diagram contributing to $\bar{\theta}$ in the supersymmetric aspon model.
FIG. 3. 1-loop gluino mass diagram contributing to $\tilde{\theta}$ in the supersymmetric aspon model.