Gauge Mediated Supersymmetry Breaking and Spontaneous CP Violation as a Solution to the Strong CP Problem

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Abstract

The origin of CP violation is a major mystery, especially in relation to the strong CP problem. CP being a spontaneously broken symmetry could provide an elegant solution. However, such models have difficulty making themselves compatible with low-energy supersymmetry, which is popularly accepted as the solution to the hierarchy problem. We demonstrate that a certain class of low scale supersymmetric “Nelson-Barr” type models can solve the strong and supersymmetric CP problems while at the same time generating sufficient weak CP violation in the $K^0 - \bar{K}^0$ system. Gauge-mediated supersymmetry breaking is used to provide the needed squark mass degeneracies and A-term proportionalities; though that proves to be still insufficient for a generic Nelson-Barr model. The workable model we consider here, essentially a supersymmetric version of the aspon model, has the Nelson-Barr mass texture enforced by a U(1) gauge symmetry, broken at the TeV scale. The resulting model is predictive with rich phenomenology soon to be available. Feasibility of the model considered is established by a detailed renormalization group studies.

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The origin of CP violation is a major mystery, especially in relation to the strong CP problem. CP being a spontaneously broken symmetry could provide an elegant solution. However, such models have difficulty making themselves compatible with low-energy supersymmetry, which is popularly accepted as the solution to the hierarchy problem. We demonstrate that a certain class of low scale supersymmetric “Nelson-Barr” type models can solve the strong and supersymmetric CP problems while at the same time generating sufficient weak CP violation in the $K^0 - \bar{K}^0$ system. Gauge-mediated supersymmetry breaking is used to provide the needed squark mass degeneracies and $A$-term proportionalities; though that proves to be still insufficient for a generic Nelson-Barr model. The workable model we consider here, essentially a supersymmetric version of the aspom model, has the Nelson-Barr mass texture enforced by a U(1) gauge symmetry, broken at the TeV scale. The resulting model is predictive with rich phenomenology soon to be available. Feasibility of the model considered is established by a detailed renormalization group studies.

The sources of CP violation is still a major puzzle. While the only experimentally observed CP violating effect, in the $K^0 - \bar{K}^0$ system, is compatible with the Kabayashi-Maskawa (KM) prescription within the standard model, there are evidents for a more elaborate theory of CP violation. Among them, the strong CP problem is the most pressing. A potential strong interaction contribution to the neutron electric dipole moment and leads to the very stringent experimental constraint

$$\tilde{\theta} < 10^{-9} \, .$$

Here, $\tilde{\theta}$ is the physical combination of the strong CP parameter $\theta$ and the CP phase(s) of the color fermion mass matrices. In the case of the supersymmetric standard model, this is to be given by

$$\tilde{\theta} = \theta - \arg \det M_q - 3 \arg M_g \, ,$$

where $M_q$ is the quark mass matrix and $M_g$ the gluino mass. The incredible smallness of this a priori arbitrary parameter demands an explanation. With supersymmetry (SUSY), there are also a large number of admissible CP violating phases among the soft SUSY breaking parameters (SSBP), which are also constrained to be quite small ($\sim 10^{-3}$).
Using spontaneous CP violation to solve the strong CP problem was pioneered by Nelson and Barr. Extending the approach to a SUSY model could take care of the SUSY CP phases easily. Attempts to realize the Nelson-Barr mechanism in SUSY models have, however, run up against a formidable difficulty: There generically exist potentially large 1-loop contributions to $\theta$ in these models. As discussed at length in Ref. one requires an exceptionally high degree of proportionality of the soft SUSY breaking trilinear scalar couplings to their associated Yukawa couplings as well as degeneracy among the soft squark mass terms for each charge and color sector, if these contributions are to be sufficiently suppressed. The degree of proportionality and degeneracy required among the SSBP is very difficult to maintain due to the effects of renormalization.

A particularly interesting modified version of the Nelson-Barr type model is given by the aspon model. Here the extra symmetry needed to enforce the Nelson-Barr mass texture is promoted to a new $U(1)$ gauge symmetry. This $U(1)$ gauge boson (aspon) then mediates a tree level CP violating $K^0 - \bar{K}^0$ mixing. This allows the effective KM phase to be small. A preliminary study suggested a SUSY version of the model has a much better chance to provide a feasible solution. The detail model is constructed in the framework of gauge mediated SUSY breaking (GMSB), and demonstrated to work, through a careful renormalization group (RG) study.

The model have CP spontaneously broken at low energies (of order a TeV). It has an extra right-handed down quark superfield $\bar{D}$ together with its mirror $D$ coupling to the ordinary down quarks via the superpotential

$$W_d = Y_d^{ij} Q_j \bar{d}_i H_d + \mu_D D \bar{D} + \gamma^{ia} D \chi_a \bar{d}_i, \quad (3)$$

where the VEVs of the scalar components of the two $\chi_a$’s contain a relative phase, thus breaking CP. $D$ and $\chi_a$ have opposite $U(1)_A$ charges. The down-sector quark mass matrix can be written as

$$m_q = \begin{pmatrix} m_d x_{\mu_D a} \\ 0 \\ \mu_D \end{pmatrix}, \quad (4)$$

and squark mass matrices as

$$\tilde{M}_{RL}^2 = \begin{pmatrix} \tilde{A}_d m_q (1 + \mu \tan \beta) A_{\gamma \mu_D} & (H_d) \delta A_d x_{\mu_D a} c - \gamma^{ia} (F_{\chi_a}) \\ 0 & 0 \end{pmatrix}$$

$$\tilde{M}_{RR}^2 = \tilde{m}_R^2 I + \begin{pmatrix} \delta m_R^2 \delta \tilde{M}_{RR}^2 \\ 0 \delta \tilde{M}_{RR}^2 \end{pmatrix} + m_q m_q^\dagger, \quad (5)$$

$$\tilde{M}_{LL}^2 = \tilde{m}_L^2 I + \begin{pmatrix} \delta m_L^2 \delta \tilde{M}_{LL}^2 \\ 0 \delta \tilde{M}_{LL}^2 \end{pmatrix} + m_q m_q^\dagger, \quad (6)$$

$$\tilde{M}_{LR}^2 = \tilde{m}_R^2 I + \begin{pmatrix} \delta m_R^2 \delta \tilde{M}_{LR}^2 \\ 0 \delta \tilde{M}_{LR}^2 \end{pmatrix} + m_q m_{\tilde{q}}^\dagger, \quad (7)$$
where \( a^i = \frac{1}{x_{\mu D}} \gamma^{ia} \langle \chi_a \rangle \), such that \( a^i a = 1 \), and

\[
\delta A_c c^i = \frac{1}{x_{\mu D}} h^{ia}_{\gamma} \langle \chi_a \rangle - \bar{A}_{\gamma} a^i ,
\]

with \( c^i c = 1 \). Hence, the complex phases are all contained in three-vectors \( a \) and \( c \), and the most dangerous \( \langle F_{\chi_a} \rangle \)’s.

The spontaneous CP violation (SCPV) is obtained from a superpotential of \( \chi_a \)’s together with two oppositely charged \( \bar{\chi}_a \)’s and a neutral \( \tilde{\alpha} \) superfield,

\[
W_X = \bar{\chi}_a \mu^{ab} \chi_b + \mathbb{R} \bar{\chi}_a \lambda^{ab} \chi_b + \lambda_3 \mathbb{N}^3 + \mu_2 \mathbb{N}^2 ,
\]

which generally gives a SUSY preserving vacuum with complex VEV’s breaking CP. The sector is minimal for anomaly cancellation and SCPV. Without nonzero SSBP for superfields of the sector, the \( \langle F_{\chi_a} \rangle \)’s are then vanishing. A minimal GMSB scenario is used to suppress proportionality violations \( \delta A_d, \delta A_{\gamma} \), and \( (B_D-\bar{A}_{\gamma}) \), degeneracy violations, as well as the SSBP for that lifts the zero \( \langle F_{\chi_a} \rangle \)’s. The latter is then estimates both analytically and diagrammatically, based on RG analysis of all SSBP. The 1-loop \( \bar{\theta} \) contributions from each terms is calculated through the mass insertion method. The model predicts a measureable neutron EDM, which could be close to the present experimental bound for \( x > 0.01 \), with some region of the admissible \( x \)-values (of the non-SUSY version) plausibly rule out by having the \( \langle F_{\chi_a} \rangle \)’s too large, and also a very rich spectrum of new particles around the TeV scale.

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