CP in $R$-parity violating models

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Abstract

It is shown that in $R$-parity violating models of supersymmetry, the CP violation observed in the kaon system could arise purely from the $R$-parity violating scalar interactions ($A$-terms), with no CP violation in the CKM matrix. The direct CP violating parameter, $\epsilon'$, could be as large or larger than that expected in the Standard Model. CP violation in the $B$ system however is expected to be negligible.
1 Introduction

In the Standard Model (SM) the only possible source for the CP violation observed in the kaon system is in the Yukawa couplings. By a suitable redefinition of the fields, the CP violation can be described by a single phase appearing in the charged-current couplings (i.e. in the Kobayashi-Maskawa matrix). The fact that this phase can exist only if there are three (or more) generations is often seen as providing some support for the KM mechanism [1].

In supersymmetry however, there are many other possible sources of CP violation, particularly in the scalar couplings [2]. Despite this, the usual (sometimes referred to as 'minimal') choice of degenerate and real soft-supersymmetry breaking terms neglects these, and simply incorporates the KM mechanism. I shall refer to this model as the ‘Constrained’ Minimal Supersymmetric Standard Model (CMSSM).

There are two reasons why the CMSSM receives the lion’s share of attention in work on supersymmetry (apart from the fact that it has the fewest parameters). Firstly it arises in the simplest supergravity models in which the supersymmetry breaking occurs in a hidden sector and is transmitted gravitationally to the visible sector. Secondly, the realness and degeneracy of the supersymmetry breaking couplings protects against large FCNCs and electric dipole moments (EDMs).

The first of these reasons is probably unjustified, since in the light of string theory, it has become apparent that there are many other patterns of supersymmetry breaking which can occur [3, 4]. The second reason has of course the drawback that the CMSSM restricts (by construction) significant supersymmetric contributions to CP violation in the kaon system (typically to a fraction of those observed, and those expected in the SM) [5].

In the CMSSM therefore, one is effectively forced to use the KM mechanism to explain the CP violation observed for kaons. In fact this is true even when one keeps the degeneracy but allows a CP violating phase in the supersymmetry breaking terms [6].

In a recent paper, an alternative pattern of supersymmetry breaking was proposed for the MSSM, in which the observed CP violation can arise only from the scalar couplings [6]. This relied on the fact that EDMs provide rather restrictive constraints on the generation diagonal scalar couplings, but that the CP violation observed in the kaon system is a flavour-changing process. Here FCNCs provide relatively weak constraints on the generation off-diagonal scalar couplings. So with a judicious choice of supersymmetry breaking terms, it is possible to generate $\varepsilon$ through supersymmetric box diagrams, without generating large EDMs. It was also argued that this type of off-diagonal texture for the scalar couplings should be justifiable in string effective supergravity simply by a choice of quantum numbers [3, 4].

This paper considers another mechanism for generating $\varepsilon$ from scalars, in the context of $R$-parity violating models. Because they introduce new interactions, these models lead to flavour changing scalar-exchange diagrams, which can produce the observed $\varepsilon$. As a picture of CP violation, this is more akin to the original ‘superweak’ models in which a $\Delta S = 2$ boson was exchanged [7, 8]. Here the boson in question is the sneutrino. The experimental signature can be different to that in the model of Ref. [6]; certain choices of $R$-parity violating couplings can give measurable contributions to $\varepsilon'$, but the CP violation in the $B$-system is again expected to be insignificant.

There are good reasons why explaining CP violation by scalar interactions is attractive.
CP is a symmetry of pure gauge theory + fermions. In gauge theory, CP violation is possible only on the breaking of gauge symmetry by some scalars (composite or otherwise), when Yukawa couplings give masses to fermions. CP is also thought to be a discrete gauge symmetry of string theory. Hence CP violation does not occur in the Yukawa couplings of string theory at lowest order, and if it is to appear anywhere it seems that it must do so via spontaneous CP violation [9]. If CP is spontaneously broken by moduli, this can naturally show up in the (supersymmetry breaking) scalar interactions [4]. Finally CP violation through the KM mechanism does not lead to a natural explanation of the only other observed CP violating phenomenon, the existence of a baryonic rather than anti-baryonic Universe.

The next section introduces the $R$-parity violating model, and describes the restrictions on the new Yukawa couplings. Following this the new CP-violating diagrams contributing to the observed value of $\varepsilon$ will be considered. Finally the possible contributions to $\varepsilon' \varepsilon$ will be determined, and it will be shown that $\varepsilon' \varepsilon$ can be measurable in certain cases.

2 $R$-parity violation

$R$-parity was introduced into supersymmetry to prevent fast proton decay, and may be described as the invariance of the lagrangian derived from the MSSM superpotential

$$W_{yuk} = \epsilon (\lambda_E H_1 L E^c + \lambda_D H_1 Q D^c + \lambda_U H_2 U^c + \mu H_1 H_2)$$

where colour and generation indices have been suppressed, under the transformation on the fields, $f_i$,

$$f_i \rightarrow (-1)^{(2S_i+3B_i+L_i)} f_i$$

where $f_i$ is an arbitrary field of spin $S_i$, baryon number $B_i$ and lepton number $L_i$. (Here $\epsilon$ is a Levi-Cevita symbol, and the superfields are defined as $Q(3,2,\frac{1}{6})$, $U^c(3,1,-\frac{2}{3})$, $D^c(1,2,\frac{1}{2})$, $L(1,2,-\frac{1}{2})$, $E^c(1,1,1)$, $H_1(1,2,-\frac{1}{2})$ and $H_2(1,2,\frac{1}{2})$, so that the conventional fermion mass matrices are given by $m_U = \lambda_U^* \langle h_2^0 \rangle$, $m_D = \lambda_D^* \langle h_1^0 \rangle$, $m_E = \lambda_E^* \langle h_1^0 \rangle$.)

This symmetry is often imposed on the lagrangian in order to forbid other baryon number violating operators which would lead to proton decay. The net effect of $R$-parity, is to allow a single superpartner to decay to only an odd number of lighter superpartners plus any number of SM particles. Thus the lightest supersymmetric particle (LSP) will be absolutely stable, and provides a good candidate for the cold component of dark matter. The other operators which are allowed in the superpotential by gauge symmetry, but are forbidden by $R$-parity are

$$U^c D^c D^c ; \epsilon L L E^c ; \epsilon L Q D^c ; \mu_i \epsilon L_i H_2,$$

where in the first term there is an implicit Levi-Cevita symbol summing over colour. However not all of them need to be forbidden in order to prevent proton decay, and in fact one can safely add either

$$W_L = \epsilon \left( \frac{1}{2} \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k \right)$$

or

$$W_B = \frac{1}{2} \lambda''_{ijk} U_i^c U_j^c D^c_k,$$

3
where $ijk$ are generation indices, to the MSSM superpotential. From now on we take $\mu_i = 0$ to avoid large masses for the heaviest neutrino (generically $1\text{MeV} \lesssim \nu_\tau \lesssim 1\text{GeV}$). Generally this implies that $(\mu, \mu_i)$ and $(\langle h_0^i, \tilde{\nu}_{Li}\rangle)$ should be sufficiently aligned and, as discussed in Ref. [11], this may be ensured using horizontal symmetries. The following analysis is not further constrained by, and is independent of the considerations in Ref. [11].

The (equally valid) terms in $W_L$ and $W_B$ allow baryon violation or lepton violation but not both. They are said to be $R$–parity breaking [10, 11, 12, 13, 14, 15, 16]. The first is particularly interesting and corresponds to the lagrangian being invariant under the following transformation known as baryon–parity [13, 14],

$$f_i \rightarrow (-1)^{(2S_i+3B_i)} f_i.$$  \hfill (6)

We shall concentrate on this case in which the superpotential looks like

$$W = \epsilon (\lambda_E H_1 L E^c + \lambda_D H_1 Q D^c + \lambda_U Q H_2 U^c$$
$$+ \frac{1}{2} \lambda L L E^c + \lambda' L Q D^c + \mu H_1 H_2).$$  \hfill (7)

The reason for this preference is that the generation of $\epsilon$ will rely on the exchange of sneutrinos. Because they do not couple strongly, sneutrinos tend to be much lighter than squarks at the weak scale (given the assumption of nearly degenerate scalar masses at the GUT scale).

The soft supersymmetry breaking terms appearing in the lagrangian are as follows

$$-\delta L = m_{ij}^2 \phi_i \phi_j^* + \frac{1}{2} M_A \lambda_A \lambda_A$$
$$+ \epsilon \left( A_E h_1 \tilde{e}^c + A_D h_1 \tilde{q} \tilde{d}^c + A_U \tilde{q} h_2 \tilde{u}^c + B \mu h_1 h_2$$
$$+ \frac{1}{2} C \tilde{l} \tilde{e}^c + C' \tilde{l} \tilde{q} \tilde{d}^c + \text{h.c.} \right)$$ \hfill (8)

The $A$ and $C$ terms are trilinear scalar couplings, and the $m_{ij}^2$ and $M_A$ are masses for the scalars (generically denoted by $\phi_i$) and gauginos respectively.

The coupling of interest here is $\lambda'$ since this is the one which mediates sneutrino exchange between down quarks. So with this choice of superpotential, the new terms in the lagrangian which are important from the point of view of CP violation in the $K$ system, are the following;

$$-\delta L = \lambda'_{ijk} \left( \overline{\nu}_{Li} d_{Lj} \tilde{d}_{Rk} - \overline{\nu}_{Ri} u_{Lj} \tilde{d}_{Rk} + \nu_{Li} \tilde{d}_{Lj} \tilde{d}_{Rk} - \epsilon_{Li} \tilde{u}_{Lj} \tilde{d}_{Rk} + \tilde{\nu}_{Li} d_{Lj} \tilde{d}_{Rk} - \tilde{\epsilon}_{Li} u_{Lj} \tilde{d}_{Rk}$$
$$+ A'_{ijk} \overline{\nu}_{Li} \tilde{d}_{Lj} \tilde{d}_{Rk} - A'_{ijk} \overline{\tilde{\nu}}_{Li} \tilde{u}_{Lj} \tilde{d}_{Rk} \right) + \text{h.c.} + \ldots$$ \hfill (9)

For the sake of argument, the trilinear $C$-terms have been defined to include the Yukawa coupling. There are various constraints on the new Yukawa couplings coming from both direct and indirect (i.e. renormalisation group effects, and contributions to the mass matrices) sources. Important bounds on $\lambda'$ have been derived from the contribution of the new couplings to the sneutrino mass-squared terms, via the renormalisation group running of the couplings. These contributions may push the sneutrino mass below its current...
experimental bound. This was discussed in Ref. [12] assuming degenerate supersymmetry breaking, of the form

\[
A_{U_{ij}} = A\lambda_{U_{ij}}
\]
\[
A_{D_{ij}} = A\lambda_{D_{ij}}
\]
\[
A_{E_{ij}} = A\lambda_{E_{ij}}
\]
\[
C'_{i+1} = A'\lambda'_{i+1}
\]
\[
m^2_{ij} = \delta_{ij}m^2_0
\]
\[
M_A = \frac{m_{1/2}}{2},
\]

(10)

where \( A, A', B, m_{1/2} \) and \( m_0 \) have dimensions of mass and are all less than \( \sim 1 \) TeV in order to protect the weak scale. To prevent large EDMs for the neutron, \( A, B \) and \( m_{1/2} \) are taken to be real. Later more general \( A' \) couplings will be required, but the other supersymmetry breaking terms will remain as they are here. The corresponding low energy values of the sneutrino masses may be approximated by running the RGEs numerically [12],

\[
m^2_{L_i} = \frac{1}{2} M^2_Z \cos 2\beta + m^2_0 + 0.51m^2_{1/2} - \chi^2_{ijk}(M_{GUT}) \left(13m^2_0 + 49m^2_{1/2} - 1.5m_{1/2}A' - 12A'^2\right).
\]

(11)

In Ref. [12] it was found that

\[
\chi'_{ijk}(M_{GUT}) \approx 0.15
\]

(12)
is enough to prevent the sneutrino masses becoming too light. The Yukawa couplings are enhanced by a factor of 3.5 by the time they reach the weak scale, so that we shall adopt the bound

\[
\chi'_{ijk}(M_Z) \approx 0.5,
\]

(13)

for all indices \( i j k \). In addition there is the danger that renormalisation effects will induce an \( m^2_{L_i}H_i \) term and cause the sneutrinos to get a VEV. Such a VEV can cause all manner of problems.

\[
\begin{aligned}
\tilde{g} &\quad \bar{\nu} \quad \tilde{d}_L \\
\bar{\nu} &\quad \tilde{d}_L \\
\bar{\nu} &\quad \tilde{d}_R \\
\bar{\nu} &\quad \tilde{d}_R
\end{aligned}
\]

\[
\text{figure (1): Possible contribution to neutron EDM from sneutrino VEV.}
\]
For example, the diagram shown in figure (1) can lead to large imaginary contributions to the neutron EDM. Imposing
\[ \lambda'_{i33} \approx 0, \] (14)
is sufficient to prevent this [12]. These bounds of course depend on the values of \( m_0 \) and in most cases may be relaxed somewhat. Quite restrictive bounds also come from the (non-observation) of the rare decay \( \mu \to e\gamma \); for example [12]
\[ \lambda'_{1jk}(M_Z)\lambda'_{2jk}(M_Z) \lesssim 5 \times 10^{-4} \left( \frac{\tilde{m}}{100 \text{GeV}} \right)^2, \]
\[ j, k = 1, 2 \] (15)
where \( \tilde{m} \) is a measure of the squark masses. If all the \( \lambda'_{ijk} \) couplings other than \( \lambda'_{i33} \) are the same, then for squark/ gluino masses less than \( \sim 1.4 \text{TeV} \) this bound is the most restrictive. Other bounds may also been derived from \( b \to s\gamma \), the most important of which is [12],
\[ \lambda'_{ij2}(M_Z)\lambda'_{ij3}(M_Z) \lesssim 0.003 \left( \frac{\tilde{m}}{100 \text{GeV}} \right)^2. \] (16)
For this analysis the relevant products will be \( \lambda'_{i12}\lambda'_{i21} \) and \( \lambda'_{i11}\lambda'_{i21} \). The only experimental limits on these come from the contribution to \( \Delta m_K \) itself.

Hopefully it will be possible in the near future to probe many of these couplings (for example \( \lambda'_{1j1} \)) individually at HERA, if the squark masses are less than 300GeV [13]. There are also bounds from cosmological considerations (see Ref.[14] and references therein). However, these are strongly dependent on the assumed scenario of baryogenesis, and so will not be employed. (In fact for one baryogenesis scheme which has recently been suggested, the couplings are not constrained by this at all [17].)

### 3 CP violating parameters in the kaon system

Let us go on to consider the new contributions to \( \Delta m_K \) and \( \varepsilon \). These \( \Delta S = 2 \) processes receive contribution from the sneutrino exchange diagrams shown in figure (2). By assumption all the Yukawa couplings have no imaginary part and so the tree level diagram contributes only to \( \Delta m_K \).
If CP violation arises only in the trilinear couplings (specifically in $A'_{ijk}$), then it is clear that the one loop diagrams must be responsible for $\varepsilon$. The one loop gluino contribution to the $\lambda'_{ijk}\tilde{\nu}_L d_L d_R$ coupling is found to be

$$\delta\lambda'_{ijk} = \lambda'_{ijk} F_1(x_{Lj}, x_{Rk}) \frac{2\alpha_s A'_{ijk}}{3\pi m_{\tilde{g}}} \tag{17}$$

where $x_i = \tilde{m}_i^2/m_{\tilde{g}}^2$, and where $F_1$ is given by the integral,

$$F_1(x_j, x_k) = \int_0^1 \int_0^1 \frac{ydydz}{(1-y) + y((1-z)x_i + zx_j)}. \tag{18}$$

In calculating this, the small mixing between the left and right down squarks has been neglected for simplicity. If for example $x_{Lj} = x_{Rk} = x = \tilde{m}^2/m_{\tilde{g}}^2$ then

$$F_1(x, x) = \frac{x - 1 - \log x}{(x - 1)^2}, \tag{19}$$

and for $x \leq 0.5$ we have $F_1 \gtrsim 1$. The diagrams in figure (2) lead to the operator

$$\delta H_{eff} = \sum_i (\lambda'_{i21} + \delta\lambda'_{i21})(\lambda'_{i12} + \delta\lambda'_{i12}) m_{\tilde{\nu}_i}^2 Q_4 \tag{20}$$

where

$$Q_4 = \overline{d}_R s^\alpha L d_L s^\beta R. \tag{21}$$

The summation above is over the three generations of exchanged sneutrinos, and $\alpha$ and $\beta$ are colour indices. In order to simplify things, it will be assumed that one of the sneutrinos, $\tilde{\nu}_i$, couples more strongly through the $\lambda'_{ijk}$, and the summation will be dropped.

Since there are many unknowns in the model, including the relative importance of the various sneutrino exchanges, it is only worth obtaining order of magnitude estimates here,
and for the rest of the present discussion, the vacuum saturation approximation will be sufficient. Despite these uncertainties, an order of magnitude estimate makes it possible to see roughly how close to experimental bounds, or otherwise, the new couplings must be if they are to explain the observed CP violation in the Kaon system. We shall find that the direct CP violating parameter can be observable within the current experimental bounds which is, in itself, a useful result. QCD effects are expected to contribute a factor of order a few to the final estimate as in other discussions of FCNCs in supersymmetry. Since we do not anticipate any cancellations, the precise value of the $B$-factors should not be as crucial as in the SM, and also the effects of operator mixing should not change our estimate significantly.

Using the matrix element \[18\],
\[
\langle K | Q^4 | K \rangle = \frac{m_K f_K^2}{m_{\tilde{\nu}_i}^2} \left( \frac{1}{24} + \frac{1}{4} \left( \frac{m_K}{m_s + m_d} \right)^2 \right),
\]
where the vacuum insertion approximation has been made, the $\Delta S = 2$ parameters are found to be,
\[
\Delta m_K^{SUSY} = 2 \text{Re}(\langle M_{12} \rangle) = (1_{21}) \lambda_{i12} \lambda_{i21} \frac{m_K f_K^2}{m_{\tilde{\nu}_i}^2} \left( \frac{1}{12} + \frac{1}{2} \left( \frac{m_K}{m_s + m_d} \right)^2 \right),
\]
and
\[
\varepsilon = -\frac{e^{i\pi/4}}{2\sqrt{2}} \text{Re}(\langle M_{12} \rangle) = \frac{e^{i\pi/4}}{3\pi \sqrt{2}} \frac{\text{Im}(A_{121} - A'_{112})}{m_{\tilde{\nu}}} \frac{\left( \Delta m_K^{SUSY} / \Delta m_K \right)}{m_{\tilde{\nu}}}.
\]
Assuming degeneracy in $x_{L_i}$ and $x_{R_i}$ leads to errors of at most $O(m_{\tilde{\nu}}^2 / m_{\tilde{\nu}}^2)$. As in the model of CP proposed in Ref.\[3\], the generation of $\varepsilon$ relies on having a sufficient off-diagonality in the trilinear terms. Since the prefactor in $\varepsilon$ is $\sim 10^{-2}$, this implies that some non-degeneracy and asymmetry is required in the $A_{ijk}$ matrices at the GUT scale (the RGEs being unlikely to generate enough). It is also clear that the supersymmetric contribution to $\Delta m_K$ must be substantial. This last point ($\Delta m_K^{SUSY} \approx \Delta m_K$) leads to an estimate of a product of $R$-parity violating couplings,
\[
\lambda_{i12}^\prime \lambda_{i21}^\prime \approx 10^{-9} \left( \frac{m_{\tilde{\nu}}}{100 \text{GeV}} \right)^2,
\]
which is in accord with the bounds coming from the same quantity in Refs.\[10, 11, 12\]. This is easily compatible with all known bounds on $R$-parity violating couplings.
Now consider the $\Delta S = 1$ contributions to the effective Hamiltonian. These occur through the sneutrino exchange diagrams shown in figure (3) and corresponding diagrams with up quarks and selectron exchange, which lead to operators of the form

$$Q = \bar{d}_R s_L \bar{d}_L d_R.$$  \hfill (26)

in the effective potential. A Fierz rearrangement shows this to be similar to the operator $Q_8$ of Ref.\cite{19}, and the isospin two part of the matrix element $\langle \pi \pi | H_{eff} | K \rangle$ is therefore of order:

$$f_\pi m_K^2 \left( \sqrt{3} \left( \frac{m_K^2}{m_s + m_d} \right)^2 - \frac{1}{2\sqrt{3}} \left( 1 - \frac{m_\pi^2}{M_K^2} \right) \right).$$  \hfill (27)

Again, since we are ignorant of the relative contributions of the sneutrino and selectron exchanges, the vacuum saturation approximation is sufficient to obtain an order of magnitude estimate. The parameter $\varepsilon' / \varepsilon$ is given by

$$\left| \frac{\varepsilon'}{\varepsilon} \right| = \frac{\omega}{\sqrt{2}|\varepsilon|} \left| \frac{\text{Im}(A_0)}{\text{Re}(A_0)} - \frac{\text{Im}(A_2)}{\text{Re}(A_2)} \right|$$

$$\sim \frac{\sqrt{6} \Delta m_K}{\text{Re}(A_0)} \frac{f_\pi m_K^2}{\text{Re}(A_0)} \frac{\text{Im}(A'_{121} + A'_{111})}{\text{Im}(A'_{122} + A'_{112})} \frac{\lambda_{121}^{*}}{\lambda_{112}^{*}} \lambda_{21}. \quad (28)$$

Since the contributions to the isospin-2 and isospin-0 parts are comparable, there is no factor of $\omega = 1/22$ in this expression since the isospin-2 contribution is dominant here (provided that long distance contributions do not contribute too much to the relative sizes of $\text{Re}(A_0)$ and $\text{Re}(A_2)$). There is no credible mechanism whereby the different $A'_{ijk}$ can differ by the four orders of magnitude which will be required if $\varepsilon'$ is to be significant. Instead there must be a hierarchy in the Yukawa couplings for this to be the case. For example, setting $A'_{111} = A'_{112}$, and again taking exchanges in the $i$'th generation to be
dominant, one finds an order of magnitude estimate for \( \varepsilon' \):

\[
\left| \varepsilon' \right| \sim 10^{-7} \frac{\lambda_{i11}'}{\lambda_{i12}}
\]

where the value \( \text{Re}(A_0) = 2.7 \times 10^{-7} \text{GeV} \) has been used. Together with the estimate in Eq.(25), this means that for the product \( \lambda_{i11}' \lambda_{i21}' \):

\[
\lambda_{i11}' \lambda_{i21}' \sim 0.01 \left| \varepsilon' \right| \left( \frac{m_{\tilde{\nu}_i}}{100 \text{GeV}} \right)^{-2}.
\]

Clearly this is compatible with both ‘superweak’ scenarios (\( \varepsilon' / \varepsilon = 0 \)) and with ‘miliweak’ theories such as the Standard Model which predicts \( |\varepsilon'| = \text{few} \times 10^{-4} \). It is even consistent with values of \( |\varepsilon'| \) larger than that predicted in the Standard Model. This is of interest in the light of the high values for \( \varepsilon' \) currently claimed by the NA31 collaboration.

4 Discussion

What do these estimates mean for the new \( R \)-parity violating couplings? Clearly little can be said about the \( \lambda_{ijk} \) couplings. For the \( \lambda_{ijk}' \) couplings, the values for \( \varepsilon \) and \( \varepsilon' \) together with the bound coming from the sneutrino masses in Eq.(13) and VEVs in Eq.(14) imply that there must be some hierarchy in the couplings if \( \varepsilon' \) is to be measurable (although this is as nothing compared to the hierarchy in \( \lambda_U, \lambda_D \) and \( \lambda_E \)). Interestingly however, there already exist in the literature examples where such a hierarchy is partially generated. In Ref.[16], it was found that in models of spontaneously broken gauged \( R \)-symmetry, the low energy models break \( R \)-parity. Furthermore, the discipline of anomaly cancellation forbids \( \lambda_{ijk}' \) couplings involving the third generation. The generation of a larger \( \varepsilon' \) in these models would therefore be a natural possibility.

The picture of CP violation described in this paper should be easily differentiable from the CMSSM and the SM. It is expected that there will be enough experimental data to considerably overdetermine the Kobayashi-Maskawa matrix. In addition, the contribution to CP violation in the \( B \)-system should again be small; in the Standard Model and the MSSM, this occurs at tree-level, whereas in this case CP violation may only be generated through one-loop diagrams.

This paper, as Ref.[1], highlights the fact that the current ‘paradigm’ for the MSSM is perhaps a little too constrained from the point of view of FCNCs and CP violating phenomena. In fact there is room to generate all observed CP violating phenomena from the scalar sector alone. Relaxing the assumption of \( R \)-parity allows the possibility of direct CP violation which can even be larger than that predicted in the Standard Model. It should be stressed therefore that the adoption of the Kobayashi-Maskawa model of CP violation is not the ‘minimal’ choice for supersymmetry. It is no longer preferred from a theoretical point of view, and there is no definition of ‘naturalness’ under which it is somehow more qualified. Furthermore siting the CP violating in the scalar sector of supersymmetry, may lead to a better understanding of other questions concerning CP violation such as baryogenesis, and the strong CP problem.

Finally, given that the CP here is spontaneously broken, there is the hope of a solution to the strong CP problem. At the Planck scale the value of \( \tilde{\theta} \) is naturally zero, and here
it is clear that all radiative corrections are suppressed. This question arises because of the obvious similarity of this model to the strong CP solutions discussed in ref. [8]. There the strong CP problem was solved if the $\Delta S = 2$ boson maintained a very small VEV. The boson in this case is the sneutrino and it may be that its VEV remains small enough even in models with broken $R$-parity. This will be the subject of future work.

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