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LOW ENERGY CP VIOLATION IN BROKEN SUPERSYMMETRY *)

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A B S T R A C T

We investigate the CP violation effects in supersymmetry broken models, due to the exchange of new fermions (gauginos and Higgsinos). When the real part of the $K^0-\bar{K}^0$ amplitude is compatible with the experimental value, the possible imaginary part is too small to account for the ϵ parameter. In contrast, the experimental bounds on the ϵ' parameter and the electric dipole moments, and especially the θ parameter, impose in general severe constraints on the possible CP violating phases. However, in some specific models there are extra suppression factors, leaving those phases essentially unconstrained except perhaps for the θ parameter.

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Supersymmetric models are in vogue^[1,2,3]. They could solve the hierarchy problem and give the link with gravity. For solving the hierarchy problem supersymmetry (SUSY) must be broken effectively at low energy in the standard sector. This implies that the superpartners of the standard particles cannot have very large masses, and their effects at low energy could be detectable. They could be produced in the future, or modify higher order effects^[4]. Here we shall examine possible CP violating effects^[5], mainly in the kaonic system.

In the standard model weak CP violation can arise from the Yukawa couplings (KM)^[6] or from a more complicated Higgs sector^[7]. The KM angles can be chosen to produce the correct amount of CP violation in the $K^0-\bar{K}^0$ system^[8] but the fact that ϵ is so small ($\sim 10^{-3}$) might point to a different source of CP violation. If the CP violation were coming from the Higgs sector, the ϵ parameter in the kaonic system could be explained rather naturally, but then problems would appear with the ϵ' parameter and EDM (electric dipole moments)^[9]. A new source of CP violation can be considered in supersymmetric models, arising from possible phases in the mass matrices of gauginos and Higgsinos^[5,10]. We shall show that the CP violating parameter ϵ in the $K^0-\bar{K}^0$ system cannot be explained by those phases; whereas for current softly broken models they are constrained by the ϵ' parameter and EDM, and especially by the θ parameter.

Let us consider the charged $\tilde{W}$, $\tilde{H}$ system, described by the (complex) mass matrix

$$\begin{array}{|c|c|} \hline \tilde{W}_L^- & \tilde{H}_L'^- \\ \hline \end{array} \quad \begin{array}{|cc|} \hline m_{11} & m_{12} \\ m_{21} & m_{22} \\ \hline \end{array} \quad \begin{array}{|c|} \hline \tilde{W}_R^- \\ \tilde{H}_R^- \\ \hline \end{array} \quad (1)$$

$\tilde{W}_{R,L}^-$ are the fermionic partners of the weak gauge bosons $W^\pm$, whereas $\tilde{H}_L' (\tilde{H}_R)$ is the fermionic partner of the Higgs doublet giving mass to the down (up) fermions. We shall assume that the sfermions diagonalize simultaneously with the usual fermions*.

* This makes the neutral fermion-sfermion couplings diagonal. We shall comment later on the general case, where the neutral $\tilde{W}$, $\tilde{H}$ can also be exchanged through non-diagonal couplings.

This does not change our conclusions which are concerned with the possible CP violation in the gaugino and Higgsino sector. It must be emphasized that in general the phases in (1) are observable because both left and right handed parts of these two Dirac spinors are coupled to matter. We take the usual KM phase equal to zero. The real part of the $K^0-\bar{K}^0$ amplitude arising from the diagram of Fig.1 is [4] *

$$\text{Re}(K^0-\bar{K}^0) \sim \frac{1}{m_W^2} \frac{g_2^4}{192\pi^2} \sin^2 \theta_C \left(\frac{\Delta m_{sf}^2}{m_{sf}^2} \right)^2, \quad (2)$$

where θ_C is the Cabibbo angle. The experimental value gives the upper bound [4]

$$\frac{\Delta m_{sf}^2}{m_{sf}^2} \lesssim 0 \left(\frac{1}{30} \right), \quad (3)$$

where we assume $m_W \sim m_{sf} \sim 0$ (100 GeV) to be specific. The phases in (1) can give an imaginary part through diagrams like that of Fig.1 but with complex mixing in the internal fermion line. Since $\tilde{W}_{L,R}$ only couple to left handed fermions and $\tilde{H}_L' (\tilde{H}_R^-)$ couples only to right (left) handed down quarks, the most important diagrams contributing to the imaginary part are those of Fig.2. The diagram of Fig.2(a) gives a contribution

$$\text{Im}(K^0-\bar{K}^0) \sim \left(\frac{m_s}{m_W} \right)^2 \left[\frac{1}{m_W^2} \frac{g_2^4}{192\pi^2} \sin^2 \theta_C \left(\frac{\Delta m_{sf}^2}{m_{sf}^2} \right)^2 \right] < 4 \times 10^{-6} \text{Re}(K^0-\bar{K}^0) \quad (4)$$

according to (2). It is then too small to account for the experimental value $\text{Im}(K^0-\bar{K}^0) \sim 10^{-3} \text{Re}(K^0-\bar{K}^0)$. To evaluate (4) we have taken

$$O_{L_{KH}}^* \frac{m_k}{p^2 - m_k^2} O_{R_{kW}} \sim \frac{1}{m_W} \times \text{phase} \quad (5)$$

in the fermion line, consistent with (2) and the current models (O_L and O_R^+ are the diagonalizing matrices in (1), $O_L M O_R^+ = D$). The

* Other diagrams give in principle smaller contributions (see below).

suppressing factor $\left(\frac{m_S}{M_W}\right)^2$ results from the Higgs couplings. The diagram of Fig.2(b) gives,

$$\begin{aligned} \text{Im}(K^0-\bar{K}^0) &\sim \eta^2 \left[\frac{1}{m_W^2} \frac{g_2^4}{192\pi^2} \sin^2\theta_C \frac{m_C^2}{M_W^2} \right] \\ &\sim \eta^2 \text{Re}(K^0-\bar{K}^0), \end{aligned} \quad (6)$$

where η stands for the left-right mixing factor in the squark line. This diagram is not suppressed by an extra factor $\frac{\Delta m_{sf}^2}{m_{sf}^2}$ because $\tilde{H}$ couples proportionally to the up quark masses spoiling the GIM mechanism in the squark lines. Then it is not constrained by (3), but the $\frac{m_C^2}{M_W^2}$ factor makes the expression in brackets comparable to the standard $\text{Re}(K^0-\bar{K}^0)$ contribution. In broken supergravity models, η is of order $m_f/m_{sf}^{[1]}$, which would be too small to explain $\text{Im}(K^0-\bar{K}^0)$. Moreover the diagram of Fig.2(b) is effectively cancelled by another diagram where $\tilde{H}$ and $\tilde{W}$ are interchanged carrying then an opposite phase. This does not happen in the diagram of Fig.2(a) because the Higgs coupling is proportional to the external fermion mass, whereas in the diagram of Fig.2(b) it is proportional to the fermion mass corresponding to the sfermion line. The most optimistic estimate is to assume that the cancellation occurs up to terms of order $\eta^2 \sin^2\theta_C \text{Re}(K^0-\bar{K}^0)$. This contribution to the ϵ parameter is negligible. Thus, $\text{Im}(K^0-\bar{K}^0)$ is insensitive to possible phases in (1).

If the assumption of simultaneous diagonalization of the mass matrices of the usual fermion and their scalar partners is relaxed, diagrams similar to those previously considered exist for neutral $SU(2) \times U(1)$ gauge and Higgs fermions. An analogous analysis then follows for the phases appearing in their mass matrices, leading to the same conclusion. The gluino, however, cannot contribute to $\text{Im}(K^0-\bar{K}^0)$.

In contrast with the case just discussed, the EDM, especially through the θ parameter, and the ϵ' parameter impose important constraints to the considered phases (as in other alternatives to the KM model). In the EDM or ϵ' case the relevant diagrams are of the type of that of Fig.3 with a photon or a gluon attached. In particular, the EDM of the neutron can be estimated^[5,10] to be

$$d_n/e \sim \frac{m_{u,d}(\text{MeV})}{M_W^2(\text{TeV}^2)} \times [10^{-25} \text{ cm}] \times \sin\delta \quad (7)$$

where δ is a typical phase*. The experimental bound on d_n would imply (with $M_{\tilde{W}} \sim 100 \text{ GeV}$)

$$\sin\delta < 10^{-2} \quad (8)$$

i.e. a rather small value. We expect ϵ' to give an analogous limit within one order of magnitude^[12].

A more stringent limit on these phases comes in general from the θ parameter. Once supersymmetry is broken the θ parameter^[5] would receive a typical contribution (see Fig.3) $\sim \frac{\alpha}{\pi} \sin\delta$. Then, the experimental limit on $\theta < 10^{-9}$ ^[13] would imply

$$\sin\delta < 10^{-6} \quad (9)$$

Obviously this bound is quite severe, constraining in general possible models without an axion mechanism^[14]. However in specific models Eqs.(8) and (9) do not need to apply. For instance, if there are only phases in m_{11} and m_{22} , and $|m_{11}|, |m_{22}| \ll m_{12}, m_{21} \sim m_W$, $\sin\delta$ should be replaced by $\left| \frac{m_{11} m_{22}}{m_{12} m_{21}} \right| \sin\delta$. For $m_{11}, m_{22} \sim 1 \text{ GeV}$ and $m_{12}, m_{21} \sim 100 \text{ GeV}$, Eq.(8) does not constrain $\sin\delta$, whereas the θ parameter renormalization imposes $\sin\delta < 10^{-2}$.

To summarize, phases appearing in the mass matrices of the fermionic partners of gauge and Higgs bosons contribute negligibly to $\text{Im}(K^0 - \bar{K}^0)$. On the other hand if they were in general $O(1)$, they would give too large contributions to EDM and ϵ' . In particular the θ parameter would be extremely large. For specific models, however, extra suppression factors can exist, possibly allowing large PC violating phases in the gaugino and Higgsino mass matrices,

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* Gluinos would give a still larger contribution, proportional to η ^[5,10]. If η were very small for some unknown reason, the gluino contribution to the EDM could be acceptable. Here we choose to concentrate on diagrams which are not suppressed by a small η .

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FIGURE CAPTIONS

FIG. 1.- Leading supersymmetric contribution to $\text{Re}(K^0-\bar{K}^0)$.

FIG. 2.- Leading supersymmetric contributions to $\text{Im}(K^0-\bar{K}^0)$ in the models considered.

FIG. 3.- Typical diagram contributing to the EDM and ϵ' parameter, and to the θ parameter.

- Figure 1 -

- Figure 2 -

- Figure 3 -