Can the CKM phase be the only source of CP violation

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Abstract

We address the question of whether the CP violating phase in the CKM mixing matrix (\(\delta_{\text{CKM}}\)) can be the only source of all CP violation. We show that in supersymmetric models with new flavour structure beyond the Yukawa matrices, \(\delta_{\text{CKM}}\) can generate the required baryon asymmetry and also accounts for all observed results in \(K\) and \(B\) systems, in particular \(\varepsilon'/\varepsilon\) and the CP asymmetry of \(B \rightarrow \phi K_S\).

1 Introduction

In the Standard Model (SM), the only source of CP violation arises from the Cabibbo-Kobayashi-Maskawa (CKM) phase which, so far, can saturate the observed CP violation in the kaon system. However, it has been pointed out that the strength of the CP violation in the SM is not enough to generalize the cosmological baryon asymmetry of our universe and a new source of CP violation is required \cite{1}. Also, the recent experimental results on the CP asymmetries of \(B \rightarrow \phi K_S\) \((S_{\phi K_S})\) \cite{2} and \(B \rightarrow \eta' K_S\) \((S_{\eta' K_S})\) \cite{3} reveal deviations from the SM prediction which have been considered as a hint of a new CP violating source beyond the SM. In this paper we demonstrate that this conclusion is not necessarily true. We argue that in the presence of new flavor structures beyond the Yukawa matrices, the CP violating phase in the CKM mixing matrix can accommodate all the observed results, in particular \(\varepsilon'/\varepsilon\), \(S_{\phi K_S}\) and the cosmological baryon asymmetry, which might be different from the SM predictions. In fact, supersymmetric models with additional sources of CP violation usually face severe constraints from the experimental bounds on the electric dipole moments (EDM) of the neutron, the electron and the mercury atom \cite{4}, leading to what is known as SUSY CP problem.

It is customary assumed that the supersymmetric extensions of the SM have additional sources of CP violation which may arise from the complexity of the soft SUSY breaking
and also from the SUSY conserving $\mu$-parameter. However, the SUSY breaking and the CP violation are in general not related and they could have different origins and different scales of breaking. Indeed, in a broad class of string and brane models, it is feasible to spontaneously violate CP and generate the CKM phase while the SUSY parameters remain real [5]. Therefore, we assume that the SUSY breaking sector conserves CP and the only source of CP violation is $\delta_{\text{CKM}}$. The details of the realization of this scenario in supergravity inspired models derived from heterotic and type I string theories will be presented elsewhere.

It is important to note that even in case of real SUSY soft breaking terms, the EDM experimental bounds impose strong constraints on the flavour structure of the trilinear parameters [6]. These constraints are very sensitive to the structure of the Yukawa couplings. It has been shown that the constraints on the $A$-terms are stronger in the case of non-hierarchical Yukawas than in the hierarchical case. However, there are a number of possible flavour patterns that can overcome these constraints and suppress SUSY contributions to the EDMs by many orders of magnitude.

This paper is organized as follows. In section 2 we present the non-minimal flavour SUSY models that we will use. In section 3 we show that within this class of models one can generate enough baryon asymmetry in the Universe with only the $\delta_{\text{CKM}}$ phase. Section 4 is devoted to the SUSY prediction of the direct CP violation parameter $\varepsilon'/\varepsilon$. In section 5 we analyze the CP violation in the $B$-sector and show that with the new source of flavour, it is natural to reduce $S_{\phi K_S}$ to negative values inside the experimental range. Our conclusions are presented in section 5.

2 SUSY models with non-minimal flavour violation

As mentioned in the introduction, non-universal soft breaking terms are the crucial ingredients in order to have a new flavour structure beyond the usual Yukawa matrices and then enhance the effect of the $\delta_{\text{CKM}}$ phase. Moreover, most of string inspired models naturally lead to SUSY realizations with non-universality, in particular non-universal $A$-terms and non-universal scalar masses for the quark singlets $M_{\tilde{u}}^2$ and $M_{\tilde{d}}^2$. Concerning the non-universality of the $A$-terms, it has been emphasized [7] that in this case the gluino contributions to the CP violating processes are enhanced through large imaginary parts of the $LR$ mass insertions. However, the observed EDM bounds restrict the non-universality of even real $A$-terms. In particular, the EDM of the mercury atom implies that $\text{Im}(\delta_{11}^{d(u)})_{LR} \lesssim 10^{-7} - 10^{-8}$ and $\text{Im}(\delta_{22}^{d})_{LR} \lesssim 10^{-5} - 10^{-6}$ [4], which are strong constraints for most of the SUSY models. Thus, only certain type of patterns for $A$-terms can be allowed.
We assume that the trilinear couplings have the following structure:

\[ A^{(d,u)} = m_0 \begin{pmatrix} a^{(d,u)} & b^{(d,u)} & c^{(d,u)} \\ a^{(d,u)} & b^{(d,u)} & c^{(d,u)} \\ a^{(d,u)} & b^{(d,u)} & c^{(d,u)} \end{pmatrix} \]  

(1)

This pattern is known as factorizable \( A \)-terms. Since \( A_{ij}Y_{ij} = Y_{ij} \) diag \( (a,b,c) \), the relevant mass insertions for the EDM contributions \( (\delta^{(d,u)}_{11})_{LR} \) are suppressed by the factors \( m^{(d,u)}/\tilde{m} \). This special structure of \( A \)-terms could arise naturally in D-brane models as explained in Ref.[8]. We have explicitly checked that in this case the EDMs are many orders of magnitude below the experimental limits for all possible values of the parameters \( a, b \) and \( c \).

Another possibility for new flavour structure in supersymmetric models is to have non-universal squark masses. While the masses of the squark doublets are bounded by \( \Delta M_K \) and \( \varepsilon_K \) to be almost universal, the masses of the squark singlets are essentially unconstrained. The non-universality of the squark singlets can be also obtained in string and D-brane models. However, as we will show, we do not need to consider this type of non-universality and it will suffice to use \( A \)-terms as in Eq.(1) in order to satisfy all the CP violating measurements. Hence thorough the paper we will assume that at GUT scale the soft scalar masses and the gaugino masses are universal and are given by \( m_0 \) and \( m_{1/2} \) respectively.

It is worth mentioning that with non-universal soft SUSY breaking terms, the Yukawa textures play a crucial role in the CP and flavour supersymmetric results and one has to specify the type of the employed Yukawa in order to completely define the model. In our analysis, we assume that the Yukawa has the non-hierarchical structure used in Ref.[6].

3 Baryon asymmetry and non-universal soft terms

The most precise measurement of the ratio of the baryon-to-entropy in the Universe is given by [9]

\[ 0.78 \times 10^{-10} < \eta = \frac{n_B}{s} < 1.0 \times 10^{-10} , \]

where we require that \( \eta \) lies on the 3\( \sigma \) range.

As mentioned in the introduction, in the context of the SM there is no mechanism able to produce enough amount of BAU at the electroweak phase transition [1] and several models with additional sources of CP violation beyond the SM phase \( \delta_{CKM} \) have been proposed, in particular supersymmetric models are well motivated extensions of the SM mechanism [10–12]. However the experimental bounds on the EDM of the electron, neutron and mercury impose severe constraints on these additional sources of CP violation. In this section we show that in supersymmetric theories with non-universal soft terms the electroweak baryogenesis can take place with no CP phases besides the \( \delta_{CKM} \).
The first step in electroweak baryogenesis is to identify which local charges are approximately conserved in the symmetric phase [11]. Once a charge asymmetry is produced on the wall separating both phases, they will efficiently diffuse to the unbroken phase, where sphaleron processes are active, and a net baryon number will be produced [12]. In the supersymmetric theories, these charges are the axial stop charge and the Higgsino charge. The latter had received much of the attention mainly because the left handed squarks were assumed to be very heavy and in this case stop current is suppressed compared with the Higgsino current. However, the Higgsino contributions depend on the relative phase \( \phi^\mu \) between the \( \mu \) parameter and the gaugino mass \( M_2 \) which is strongly constrained by the EDM limits. It has been emphasized in Ref.[13] that in SUSY models with new flavour structure beyond the usual Yukawa matrices, the stop contributions are enhanced and can accommodate the measurement of the BAU. In our model with no new SUSY CP violating phases, the stop contribution is found to be significant and can easily provide enough baryon asymmetry.

Following the notation of Refs.[12, 13], the right-handed squark contributions to the baryon asymmetry is given by

\[
\frac{n_B}{s} \approx 10^{-9} \times \text{Im} \left( \mu \text{Tr} \left\{ [ (Z_R Y_u^A)^T W_L^\dagger ] I_{RR} \right\} \cdot [ W_L h_u^* Z_R^\dagger ] \right). \tag{3}
\]

The prefactor is obtained from:

\[
-\frac{v(T)^2 \Delta \beta}{T^3} \frac{5 \Gamma_{w_6}}{96 \pi^2 g_s} \frac{v_w}{DR + v_w^2} \frac{f_{\lambda_+}}{\lambda_+} \frac{(9 k_T - k_B)(9 k_Q k_B - 8 k_B k_T - 5 k_B k_Q)}{k_T - k_B} \tag{4}
\]

where all the definitions can be found in Ref.[13]. The matrix \( I_{RR} \) is the integration corresponding to the propagators of the right and left-handed squarks and \( W_L \ (Z_R) \) is the diagonalizing matrix of the \( LL \ (RR) \) squark squared mass matrix. The matrix \( Y_u^A \) is given by \( (Y_u^A)_{ij} = (Y_u)_{ij} A^u_{ij} \). In order to estimate a model independent bound on the relevant \( LR \) mass insertions, it was assumed in Ref. [13] that the squark mass matrices \( M_{LL}^2 \) and \( M_{RR}^2 \) were diagonal, \( i.e., W_L = Z_R = 1 \). Hence, the typical form of the baryon-to-entropy ratio was given by

\[
\frac{n_B}{s} \approx 10^{-9} I_{RR} \mu Y_t^2 \frac{m_\tilde{t}^2}{m_t} \text{Im} (\delta_{LR})_{3i}^y \tag{5}
\]

which imposes strong bounds on the \( \text{Im}(\delta_{LR})_{3i}^y \), typically to be of the order of \( \mathcal{O}(10^{-1}) \). Such values might not be easy to obtain in SUSY models and also it may contradict the constraints derived from the experimental measurements of \( B - \bar{B} \) mixing and the CP asymmetry in the decay of \( B \to J/\psi K_S \) [14]. In our analysis, we find that due to the non-universality of the soft terms, the diagonalizing matrices \( W_L \) and \( Z_R \) turn out to have sizable phases (\( \mathcal{O}(1 - 10^{-1}) \)), playing an important role in relaxing the constraints on \( \text{Im}(\delta_{LR})_{3i}^y \).
Figure 1: (Left) The BAU as functions of the Im$(\delta_{LR}^{u})_{31}$ and Im$(\delta_{LR}^{u})_{32}$ for $m_0 = m_{1/2} = 200$ GeV. (Right) The allowed range of the trilinear couplings by BAU limits.

In Fig. 1, we plot the amount of baryon asymmetry in terms of the imaginary part of the relevant mass insertions: $(\delta_{LR}^{u})_{31}$ and $(\delta_{LR}^{u})_{32}$ for $m_0 = m_{1/2} = 200$ GeV, $a^u = 4$, $c^u = 3$ and $b^u$ varying in the range $b^u = (1.5 - 2.7)$. As can been seen from this figure, the typical values of the mass insertions lie on a scale 2 or 3 orders of magnitude smaller than the estimates given in [13]. Also we present in this figure the regions for the trilinear couplings $a^u$, $b^u$ and $c^u$ that lead to $n_B/s$ within the observed range.

4 Supersymmetric contributions to meson decays

The enhancement of CP violation by the new flavor structure has also interesting consequences in kaon and B-systems. In particular, we will study the effect on the direct CP violation in the kaon decays $\varepsilon'/\varepsilon$ and the mixing CP asymmetry of the $B \to \phi K_S$ process. The measured values of the indirect CP violation $\varepsilon_K$ and the CP asymmetry in $B \to J/\psi K_S$ are saturated by the SM contributions with $\delta_{CKM}$ of order one. It is also worth mentioning that due to the fact that BAU constrains only the up-squark sector and has no impact on the down-squark sector, the dominant gluino contributions to the $\varepsilon'/\varepsilon$ and $S_{\phi K_S}$ are free from the constraints mentioned in the previous section, however for the chargino contribution it should be taken into account. We find that the chargino loops are irrelevant to the computed CP violating observables.

Direct CP violation has been observed in kaon decays and its measured value lies in the range

$$Re \left( \frac{\varepsilon'}{\varepsilon} \right) = (1.8 \pm 0.4) \times 10^{-3}$$

the SM contribution [15] is dominated by the QCD penguin $Q_6$ and the electroweak
Figure 2: $\varepsilon'/\varepsilon$ versus $\delta A$ for $\tan \beta = 5$ and $m_0 = 200$ GeV. The red (solid) line corresponds to $m_{1/2} = 200$ GeV, while the blue (dashed) line corresponds to $m_{1/2} = 300$ GeV. The yellow band corresponds to the experimental 1 $\sigma$ uncertainty.

Penguin $Q_8$ density operators. It can be written as

$$Re \left( \frac{\varepsilon'}{\varepsilon} \right)^{SM} = \frac{Im(\lambda_t \lambda^*_u)}{\lambda_u} F_{\varepsilon'}$$

where $F_{\varepsilon'}$ depends on the non-perturbative parameters $B_6^{(1/2)}$ and $B_8^{(3/2)}$ associated with the QCD and electroweak operators, respectively

$$F_{\varepsilon'} = \left( \alpha_1 B_6^{(1/2)} - \alpha_2 B_8^{(3/2)} \right) .$$

The values of $\alpha_1$, $\alpha_2$ are given in [16]. The computation of $F_{\varepsilon'}$ requires an accurate determination of the involved penguin operators and of the prefactors $\alpha_i$, which depend on $\Lambda_{MS}^{(4)}/m_s(2\text{GeV})^2$, the parameter associated with isospin breaking effects $\Omega_{IB}$ and the top mass. Uncertainties on all these quantities make the theoretical prediction of the SM contribution to the parameter $\varepsilon'/\varepsilon$ to lie in a rather wide range from $5 \times 10^{-4}$ to $4 \times 10^{-3}$. Therefore, the SM agrees with the observed value but opens the possibility of sizable non-standard contribution to $\varepsilon'/\varepsilon$. In the following we explore the option that non-universal $A$ terms can account for the observed direct CP asymmetry in kaon decays.

The dominant gluino contributions to the direct CP violation in kaon decays can be safely approximated by the chromomagnetic operator,

$$Re \left( \frac{\varepsilon'}{\varepsilon} \right) \tilde{g} \approx 3 \times 10^6 Im \{ C_g - \tilde{C}_g \}$$

where $C_g$ is the Wilson coefficient corresponding to the chromomagnetic operator $O_g$, and $\tilde{C}_g$ is obtained from $C_g$ by changing $L \leftrightarrow R$. The leading part comes from the $LR$ mass
insertion, which is enhanced by a factor $m_{\tilde{g}}/m_{s}$. In this limit, neglecting the $LL$ and $RR$ mass insertion effects, we have

$$C_{g} \sim \frac{\alpha_{s} \pi}{m_{\tilde{q}}^{2}} \frac{m_{\tilde{g}}}{m_{s}} (\delta_{12}^{d})_{LR} .$$

Due to the fact that the relevant mass insertion is $Im\{ (\delta_{12}^{d})_{RL} \}$ is proportional to $a^{d} - b^{d}$, we find that the parameter $\varepsilon'/\varepsilon$ is insensitive to the value of the parameter $c^{d}$ and depends only on the combination $a^{d} - b^{d}$. In Fig. (2) we plot the SUSY contributions (including the complete gluino and chargino loops) to the parameter $\varepsilon'/\varepsilon$ versus the relevant combination $\delta A = a^{d} - b^{d}$, for $\tan \beta = 5$, $m_{0} = 200$ GeV and $m_{1/2} = 200, 300$ GeV. In this class of models where $A_{d} \propto m_{0}$, the value of $\varepsilon'/\varepsilon$ slightly depends on $m_{0}$.

Figure 3: The CP asymmetry $S_{\phi}$ as function of the parameter $c^{d}$ for $a^{d} = b^{d} - 1.5$ and $b^{d} = 4, 2, -1$ and $\tan \beta = 5$, $m_{0} = m_{1/2} = 200$ GeV and $\delta_{12} = 0$. The discontinuities correspond to the regions constrained by the bound on BR($b \to s\gamma$). The yellow band corresponds to the experimental 1$\sigma$ uncertainty.

Now we turn to the CP violation in the $B$-meson decays. As mentioned before, the recent measurements by BaBar and Belle for $S_{\phi K_{S}}$ evidence a deviation from the SM prediction of 2.7$\sigma$. Here we argue that this discrepancy can be entirely explained in SUSY models with new sources of flavour violation and with no need of any further CP violating source besides $\delta_{\text{CKM}}$. Following the parametrization of the SM and SUSY amplitudes given in .[17], $S_{\phi K_{S}}$ can be written as

$$S_{\phi K_{S}} = \frac{\sin 2\beta + 2R_{\phi} \cos \delta_{12} \sin(\theta_{\phi} + 2\beta) + R_{\phi}^{2} \sin(2\theta_{\phi} + 2\beta)}{1 + 2R_{\phi} \cos \delta_{12} \cos \theta_{\phi} + R_{\phi}^{2} \cos 2\theta_{\phi}}$$

(11)

where $R_{\phi} = |A_{\text{SUSY}}/A_{\text{SM}}|$, $\theta_{\phi} = \arg(A_{\text{SUSY}}/A_{\text{SM}})$, and in the following we set the strong phase, $\delta_{12}$, to be zero. As it is emphasized in Ref.[17], the gluino contributions can accommodate the experimental results of $S_{\phi K_{S}}$ if the magnitude of the mass insertion $(\delta_{LR(RL)}^{d})_{32}$ is of order $10^{-3}$ and its phase is of order one. In our model with non-universal $A$-terms,
these values can be reached and the gluino contribution is found to be the dominant one. Furthermore, since we have a well defined model, our numerical analysis is not based on the mass insertion approximation but we will use the full one loop computation of the Wilson coefficients [18]. We also impose the constraints from the $b \to s\gamma$ branching ratio and $B - \bar{B}$ mixing.

Our result for $S_{\phi K_S}$ is given in Fig. 3, where we plot the CP asymmetry as a function of the trilinear parameter $c^d$. As discussed in the previous section, the value of $\varepsilon'/\varepsilon$ depends only on the difference $b^d - a^d$ and it is insensitive to the value of $c^d$, which is quite relevant for $S_{\phi K_S}$. Hence, we could easily find suitable values of the trilinear couplings that satisfy simultaneously all the meson decay observables. In this plot, we have fixed $b^d - a^d \simeq 1.5$ which leads to $\varepsilon'/\varepsilon$ of order $1.8 \times 10^{-3}$ and considered three representative values for $b^d$ and $a^d$. As can be seen from the figure, positive values of $b^d$ are favored by predicting $S_{\phi K_S}$ within the experimental range. The sign of $b^d$ depends on the relative sign of the strong phase, $\delta_{12}$. In the case that we have considered $\delta_{12}$ is zero, hence positive values of $b^d$ can be regarded as natural.

5 Conclusions

We have shown that, in supersymmetric models with non minimal flavour structures, the SM phase $\delta_{\text{CKM}}$ could be the only source of CP violation and could naturally account for all the CP violating measurements. We have computed the baryon asymmetry generated during the electroweak phase transition and the parameters corresponding to the CP violation in meson decays, proving that our proposal for real and non-universal soft SUSY breaking terms provides a natural explanation for all of them.

As it is well known, any new source of CP phases in the supersymmetric theories induces large contributions to the EDMs which exceed their experimental limits. We argued that SUSY models with new sources of flavour structures, rather than additional sources of CP violation, can readily overcome this problem and, at the same time, explain the possible discrepancy between the SM results and the experimental measurements of the BAU, $\varepsilon'/\varepsilon$ and $S_{\phi K_S}$. We have focused on the case of non-universal $A$-terms (which is quite natural in many SUSY models), however for non-universal squark masses the same conclusion can be reached.

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