Fully Supersymmetric *CP* Violation in *K* and *B* Systems

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We analyze *CP* violation in supersymmetric extensions of the standard model with heavy scalar fermions of the first two generations. Neglecting intergenerational mixing in the sfermion mass matrices and thus considering only chargino, charged Higgs-boson, and *W*-boson diagrams we show that it is possible to fully account for *CP* violation in the kaon system even in the absence of the standard CKM phase. This opens new possibilities for large supersymmetric contributions to *CP* violation in the *B* system. [S0031-9007(99)08753-0]

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Beginning with its experimental discovery in *K*-meson decays, about three decades ago, the origin of *CP* violation has been one of the most intriguing questions in particle phenomenology. Notably, the subsequent experiments in the search for electric dipole moments (EDM) of the neutron and electron have observed no sign of new *CP*-violating effects despite their considerably high precision. However, this situation is expected to change in the near future with the advent of the new *B* factories. Indeed, experimental studies of the neutral *B*-meson systems can provide a window to new physics beyond the standard model (SM) much earlier than the direct collider searches at the Cern Large Hadron Collider.

In the standard electroweak theory the *CP*-violating phenomena find their explanation uniquely in the phase $\delta_{\rm CKM}$ of the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix. However, in the minimal supersymmetric extension of the SM (MSSM) there are additional phases which can cause deviations from the predictions of the SM. Indeed, after all possible rephasings of the parameters and fields there remain two new physical phases in the MSSM Lagrangian that can be chosen to be the phases of the Higgsino Dirac mass parameter ($\varphi_\mu = \arg[\mu]$) and the trilinear sfermion coupling ($\tilde{f}$) to the Higgs, ($\varphi_{A_f} = \arg[A_f]$) [1]. In the absence of the strict universality, as is generally the case at low energies, each sfermion species has a distinct phase φ_{A_f}. In the presence of such *CP*-violating phases a natural question to be raised would be "Is it possible to account for the observed *CP* violation only by supersymmetric effects?"

The traditional answer to this question has always been negative because of the fact that the electric dipole moments of the electron and neutron constrain $\varphi_{A_f,\mu}$ to be at most $\mathcal{O}(10^{-2})$. However, recent studies have revealed new pathways to small enough EDM's while allowing supersymmetry (SUSY) phases $\mathcal{O}(1)$. Methods of suppressing the EDM's consist of cancellation of various SUSY contributions among themselves [2], nonuniversality of the soft breaking parameters at the unification scale [3], and approximately degenerate heavy sfermions for the first two generations [4]. In this Letter we shall follow the last alternative and assume a general low energy SUSY model with heavy and almost degenerate sfermions for the first two generations. Now the question at the end of the last paragraph takes a more specific form: "In such a scheme, can φ_{A_f} and φ_μ account for the experimental observation of *CP* violation with vanishing $\delta_{\rm CKM}$?"

To investigate the answer to this question we follow a simplifying assumption; that is, we neglect all intergenerational mixings in the sfermion mass matrices. Then, neutralino and gluino vertices are approximately flavor diagonal and these particles do not contribute to the flavor changing neutral current processes. Under this assumption, all flavor mixing effects originate from the elements of the CKM matrix, as in the SM. In this scenario, $\Delta F = 2$ transitions proceed only through box diagrams exchanging ($W^\pm$) quarks, charged Higgs boson ($H^\pm$) quarks, and chargino ($\chi^\pm$) squarks. The first contribution is the usual SM while the other two are of SUSY origin. These three types of contributions are always present independently of the existence/absence of intergenerational mixings, and thus the results we present in this Letter can be regarded as conservative limits on SUSY effects.

Under the conditions mentioned above it turns out that (1) relevant new SUSY contributions to *CP* violation observables are possible only when the masses of the light chargino and stop are close to the Z mass (M_{χ_1}, $M_{\tilde{t}_1} \lesssim 150$ GeV), and $\tan\beta \gtrsim 30$. (2) In such case, the answer to our question is definitely positive, ε_K and the corresponding observable in the B system, ε_B, get large contributions from SUSY that can even saturate the measured value for ε_K.

The K^0-$\bar{K}^0$ and B^0-$\bar{B}^0$ mixings are conveniently described by the corresponding $\Delta F = 2$ effective Hamiltonian

$$\mathcal{H}_{\rm eff}^{\Delta F=2} = -\frac{G_F^2 M_W^2}{(2\pi)^2}(V_{td}^* V_{tq})^2 \times [C_1(\mu)Q_1(\mu) + C_2(\mu)Q_2(\mu) + C_3(\mu)Q_3(\mu)], \quad (1)$$

where $Q_1 = \bar{d}_L^\alpha \gamma^\mu q_L^\alpha \cdot \bar{d}_L^\beta \gamma_\mu q_L^\beta$, $Q_2 = \bar{d}_L^\alpha q_R^\alpha \cdot \bar{d}_L^\beta q_R^\beta$, $Q_3 = \bar{d}_L^\alpha q_R^\beta \cdot \bar{d}_L^\beta q_R^\alpha$ are the effective four-fermion operators with $q = s, b$ for the K and B systems, respectively, α, β are color indices, and $C_{1,2,3}$ are the corresponding Wilson coefficients. These are evaluated at the corresponding meson mass, μ, with the initial conditions specified at $\mu_0 \sim M_{\tilde{t}}$. Without the inclusion of QCD corrections, $C_2(\mu_0)$ receives no contribution from $W^\pm$, charged Higgs, and chargino boxes, and the other two coefficients can be decomposed according to the particles in the loop as $C_1(\mu_0) = C_1^W(\mu_0) + C_1^H(\mu_0) + C_1^\chi(\mu_0)$, $C_3(\mu_0) = C_3^H(\mu_0) + C_3^\chi(\mu_0)$. The contributions of W boson, $C_1^W(\mu_0)$, and charged Higgs, $C_{1,3}^H(\mu_0)$, are real.

The chargino boxes are the only genuine SUSY contribution to the mixing. The explicit expressions for their contribution to the Wilson coefficients are

$$\begin{aligned} C_1^\chi(\mu_0) &= \frac{1}{4}\sum_{i,j=1}^{2}\sum_{k,l=1}^{2} G^{(3,k)i}G^{(3,k)j*}G^{(3,l)i*}G^{(3,l)j}Y_1(z_k, z_l, s_i, s_j), \\ C_3^\chi(\mu_0) &= \sum_{i,j=1}^{2}\sum_{k,l=1}^{2} H^{(3,k)i}G^{(3,k)j*}G^{(3,l)i*}H^{(3,l)j}Y_2(z_k, z_l, s_i, s_j), \end{aligned} \quad (2)$$

where $z_k = M_{\tilde{t}_k}^2/M_W^2$, $s_i = M_{\tilde{\chi}_i}^2/M_W^2$, and the stop-chargino-quark coupling matrices $G^{(3,k)i}$ and $H^{(3,k)i}$ are combinations of the stop (S_t) and chargino ($C_{R,L}$) mixing matrices

$$\begin{aligned} G^{(3,k)i} &= \sqrt{2}\, C_{R1i}^* S_{tk1} - \frac{C_{R2i}^* S_{tk2}}{\sin\beta}\frac{m_t}{M_W}, \\ H^{(3,k)i} &= \frac{C_{L2i}^* S_{tk1}}{\cos\beta}\frac{m_q}{M_W}. \end{aligned} \quad (3)$$

The complete expressions for the loop functions $Y_{1,2}(a, b, c, d)$ as well as $W^\pm$ and charged Higgs contributions can be found in [5]. The matrices $G^{(3,k)i}$ and $H^{(3,k)i}$ represent the coupling of chargino and stop to left- and right-handed down quarks, respectively. As can be seen from Eq. (2), unlike $C_1^\chi(\mu_0)$, $C_3^\chi(\mu_0)$ depends on both $G^{(3,k)i}$ and $H^{(3,k)i}$, and, thus, in general, it is complex. On the other hand, unless one admits large enough $\tan\beta$ values, $|H^{(3,k)i}|$ becomes much smaller than $|G^{(3,k)i}|$ since the former is suppressed by the ratio of $m_{q=b,s}$ to M_W.

Solution of renormalization group equations (RGE) at the corresponding meson mass scale yield [6]

$$C_1(\mu) = 0.790C_1(\mu_0), \qquad C_2(\mu) = -0.056C_3(\mu_0), \qquad C_3(\mu) = 2.930C_3(\mu_0), \quad (4)$$

where the enhancement of the $C_3(\mu)$ Wilson coefficient is specially interesting.

With the complete expression of the $\Delta F = 2$ effective Hamiltonian, it is now a straightforward issue to analyze CP-violation observables. For both K- and B-meson systems we follow the usual definition of the ε parameter factoring out global phases,

$$\varepsilon_{\mathcal{M}} = \frac{1}{\sqrt{2}}\frac{\mathrm{Im}\langle \mathcal{M}^0|\mathcal{H}_{\rm eff}^{\Delta F=2}|\bar{\mathcal{M}}^0\rangle}{\Delta M_{\mathcal{M}}}, \quad (5)$$

where $\mathcal{M}^0 = K^0, B^0$, and correspondingly, $q = s, b$ in the effective Hamiltonian. The off-diagonal matrix element of the effective Hamiltonian in the neutral meson mass matrix is

$$\langle \mathcal{M}^0|\mathcal{H}_{\rm eff}^{\Delta F=2}|\bar{\mathcal{M}}^0\rangle = -\frac{G_F^2 M_W^2}{(2\pi)^2}(V_{td}^* V_{tq})^2 F_{\mathcal{M}}^2 M_{\mathcal{M}}\left\{\frac{1}{3}C_1(\mu)B_1(\mu) + \left(\frac{M_{\mathcal{M}}}{m_q(\mu) + m_d(\mu)}\right)^2 \times \left(-\frac{5}{24}C_2(\mu)B_2(\mu) + \frac{1}{24}C_3(\mu)B_3(\mu)\right)\right\}. \quad (6)$$

In this expression $M_{\mathcal{M}}$ and $F_{\mathcal{M}}$ denote the mass and decay constant of the neutral meson $\mathcal{M}^0$, $m_{q=s,b}(\mu)$, and $m_d(\mu)$ are the quark masses in the corresponding renormalization scheme at the scale μ. The B parameters at $\mu = 2$ GeV are $B_1(\mu) = 0.60$, $B_2(\mu) = 0.66$, and $B_3(\mu) = 1.05$ [6].

Using Eq. (5) we can easily calculate the amount of indirect CP violation in the K and B systems. As Eqs. (5) and (6) suggest $\varepsilon_{\mathcal{M}}$ gets contributions from two different sources: the usual CKM phase $\delta_{\rm CKM}$ coming through $(V_{td}^* V_{tq})^2$ and the complex Wilson coefficients $C_{2,3}(\mu)$. While the former is the usual source of CP violating phenomena in the SM the latter is completely a SUSY effect. In the following, we will *always assume that there is no physical phase in the CKM mixing matrix, and CP violation is purely of supersymmetric origin.*

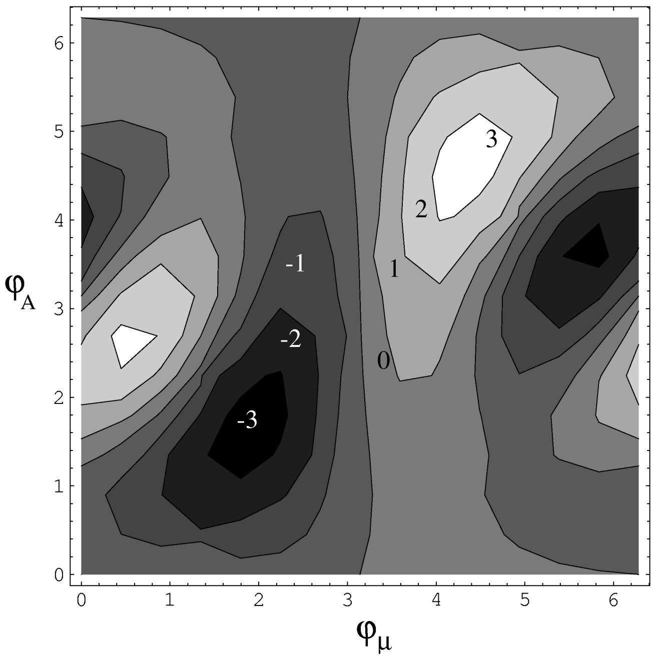

FIG. 1. Values of $10^3\varepsilon_K$ in the φ_μ, φ_{A_f} plane for the region of SUSY parameter space specified in the text.

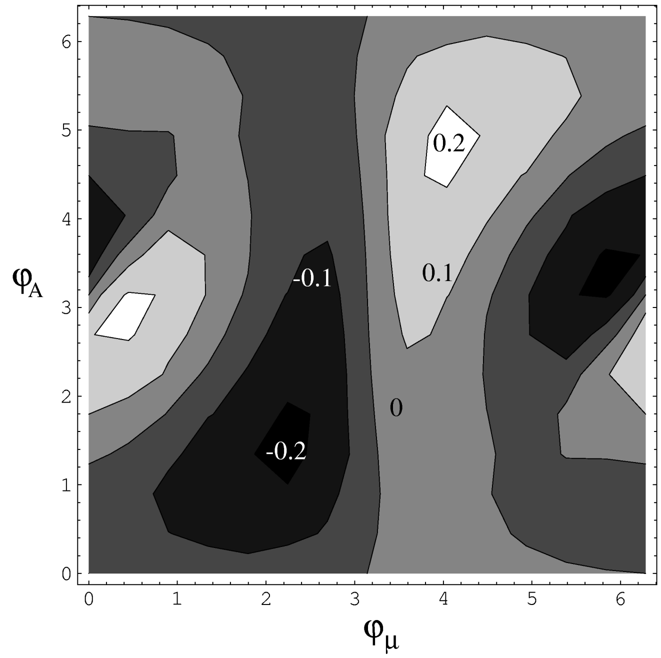

FIG. 2. Values of ε_B in the φ_μ, φ_{A_f} plane for the same region of SUSY parameter space as in Fig. 1.

In the first place we analyze the K system where we have experimental confirmation of CP violation. At first sight, one would completely neglect any SUSY contribution to ε_K because of the huge suppression factor associated with the s-quark Yukawa coupling in $H^{(3,k)i}$. However, this is not necessarily true for large $\tan\beta$ [with $\tan\beta = 60$ we get $(m_s/(M_W\cos\beta))^2 = \mathcal{O}(10^{-2})$]. Besides this, we have additional enhancements from the hadronic matrix elements, $\langle\bar{K}^0|Q_3|K^0\rangle \approx 3\langle\bar{K}^0|Q_1|K^0\rangle$ and the RGE evolution, Eq. (4). At this point, it is clear that it is not correct to neglect the C_3 contribution to the imaginary part of M_{12} for large $\tan\beta$. Nevertheless sizable effects can be expected only for light enough stop and chargino. In Fig. 1 we show ε_K as a function of φ_μ and φ_{A_t} for $\tilde{M}_2 = \mu = 125$ GeV, $M_{\tilde{t}_L} = M_{\tilde{t}_R} = 150$ GeV, $A_t = 250$ GeV, and $\tan\beta = 60$ which give on average $M_{\tilde{t}_1} = 83$ GeV and $M_{\tilde{\chi}_1} = 80$ GeV. As we can see in this figure, it is still possible to fully saturate the measured value of ε_K relying only on SUSY phases.

Indirect CP violation in the B system can be analyzed in the same way from the $\Delta B = 2$ effective Hamiltonian, Eq. (1). The effects in the corresponding observable ε_B will increase roughly as $(m_b/m_s)^2$ with respect to ε_K. In Fig. 2 we show ε_B as a function of φ_μ and φ_{A_t} for the same region of SUSY parameter space that we used in the ε_K analysis. Notice that for the set of values for which ε_K is fully saturated we obtain large effects for CP violation in the B system. In this system, the mixing-induced CP phase, θ_M, measurable in B^0 CP asymmetries, is related to ε_B by $\theta_M = \arcsin\{2\sqrt{2}\,\varepsilon_B\}$. For $\varepsilon_B = 0.2$, it reaches the value $\theta_M \approx 0.6$ which can be cleanly observed in the future B factories. Even for smaller values of $\tan\beta$, for which ε_K is not entirely reproduced by SUSY effects, we still have quite sizable SUSY contributions to CP violation in B mixing with appreciable deviations from the SM results [7].

In conclusion we have shown in this Letter that in a general SUSY extension of the SM with heavy scalar fermions of the first two generations it is possible to fully account for the observed CP violation in the kaon system while respecting the bounds on the electric dipole moment of the neutron. However, the assumption of negligible flavor mixing in the sfermion mass matrices may be too restrictive when including rare B decays in our analysis. This point, as well as the CP violating effects in the B system deserve further investigation.

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