FULLY SUPERSYMMETRIC CP VIOLATIONS
IN THE KAON SYSTEM

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We show that, on the contrary to the usual claims, fully supersymmetric CP violations in the kaon system are possible through the gluino mediated flavor changing interactions. Both $\epsilon_K$ and $\text{Re}(\epsilon'/\epsilon_K)$ can be accommodated for relatively large $\tan \beta$ without any fine tunings or contradictions to the FCNC and EDM constraints.

Recent observation of $\text{Re}(\epsilon'/\epsilon_K)$ by KTeV collaboration, $\text{Re}(\epsilon'/\epsilon_K) = (28 \pm 4 \times 10^{-2})$, nicely confirms the earlier NA31 experiment $\text{Re}(\epsilon'/\epsilon_K) = (23 \pm 7) \times 10^{-4}$. This nonvanishing number indicates unambiguously the existence of CP violation in the decay amplitude ($\Delta S = 1$). Along with another CP violating parameter known for long time, $\epsilon_K = e^{i\pi/4} \times (2.280 \pm 0.013) \times 10^{-3}$ these two parameters quantifying CP violations in the kaon system can be accommodated by the KM phase in the standard model (SM). The SM prediction for $\text{Re}(\epsilon'/\epsilon_K)$ is about $5 \times 10^{-4}$ and lies in the lower side of the data, although theoretical uncertainties are rather large.

However, it would be interesting to consider a possibility that both $\epsilon_K$ and $\text{Re}(\epsilon'/\epsilon_K)$ have their origins entirely different from the KM phase in the SM, in particular in supersymmetric models. In this talk, we argue that all the observed CP violating phenomena in the kaon system in fact can be accommodated in terms of a single complex number $(\delta_{12})_{LL}$ that parameterizes the squark mass mixings in the chirality and flavor spaces for relatively large $\tan \beta$ without any fine tuning or any contradictions with experimental data on FCNC, even if we assume $\delta_{KM} = 0$ as in this talk. This talk is based on Ref. 1.

In order to study the gluino mediated flavor changing phenomena in the quark sector, it is convenient to use the so-called mass insertion approximation (MIA) 2. The parameters $(\delta_{ij}^d)_{AB}$ characterize the size of the gluino-mediated flavor ($i,j$) and chirality ($A,B$) changing amplitudes. They may be also CP violating complex numbers.

Now, if one saturates $\Delta m_K$ and $\epsilon_K$ with $(\delta_{12})_{LL}$ alone, the resulting $\text{Re}(\epsilon'/\epsilon_K)$ is too small by more than an order of magnitude, unless one invokes some finetuning. 2. On the other hand, if one saturates $\text{Re}(\epsilon'/\epsilon_K)$ by $|\text{Im}(\delta_{12})_{LR}| \sim 10^{-5}$, the resulting $\epsilon_K$ is too small by more than an order of magnitude, unless one invokes some finetuning. Therefore the folklore was that the supesymmetric contributions to $\text{Re}(\epsilon'/\epsilon_K)$ is small. Recently, Masiero and Murayama showed that this conclusion can be evaded in generalized SUSY models 3 with a few reasonable assumptions on the size of the $(\delta_{12})_{LR}$. But in their model, one has to introduce a new CP violating parameter $(\delta_{12})_{LL}$ in order to generate $\epsilon_K$ and also predict too large neutron EDM which is very close to the current upper limit.

In the following, we show that there is another generic way to evade this folklore in supersymmetric models if $|\mu \tan \beta|$ is relatively large, say $\sim 10 - 20 \text{ TeV}$. Moreover, both $\epsilon_K$ and $\text{Re}(\epsilon'/\epsilon_K)$ can be generated by a single CP violating complex parameter in the MSSM. In other words, fully supersymmetric CP violations are possible in the kaon system. The argument goes as follows : if $|\langle \delta_{12}^d \rangle_{LL} | \sim O(10^{-3} - 10^{-2})$ with the phase $\sim O(1)$ saturates $\epsilon_K$, this same parameter...
can lead to a sizable $\text{Re}(\epsilon'/\epsilon_K)$ through the $(\delta_{12}^d)_{LL}$ insertion followed by the FP (LR) mass insertion, which is proportional to

$$(\delta_{22}^d)_{LR} = m_s(A_s^* - \mu \tan \beta)/\hat{m}^2 \sim O(10^{-2}),$$

where $\hat{m}$ denotes the common squark mass in the MIA. It should be emphasized that the induced $(\delta_{12}^d)_{LR}$ is different from the conventional $(\delta_{12}^d)_{LR}$ in the literature. The LR mixing $(\delta_{12}^d)_{LR}$ induced by $(\delta_{12}^d)_{LL}$ is typically very small in size $\sim O(10^{-3})$, but this is enough to generate the full size of $\text{Re}(\epsilon'/\epsilon_K)$ as shown below. Thus the usual folklore can be simply evaded. Our spirit to generate supersymmetric $\text{Re}(\epsilon'/\epsilon_K)$ is different from Ref. 3, where the LR mass matrix form is assumed to be similar to the Yukawa matrix so that they predict the neutron EDM to be close to the current upper limit. On the other hand, we do not assume any specific flavor structure in trilinear $A$ couplings. Also our model does not suffer from the EDM constraint at all.

Let us first consider the gluino-squark contributions to the $K^0 - \bar{K}^0$ mixing due to two insertions of $(\delta_{12}^d)_{LL}$. The corresponding $\Delta S = 2$ effective Hamiltonian is given by

$$\mathcal{H}_{\text{eff}}(\Delta S = 2) = C_1 \delta_{12}^d \gamma_\mu s^0_L \delta_{12}^d \gamma_\mu s^0_L$$

with the Wilson coefficient $C_1$ being

$$C_1 = -\frac{\alpha_s^2}{216 \hat{m}^2} (\delta_{12}^d)_{LL}^2 f_1(x)$$

Here, $x = m_s^2/\hat{m}^2$ and the loop function $f_1(x)$ is given in Ref. 1.

Now we turn to the $\Delta S = 1$ effective Hamiltonian $\mathcal{H}_{\text{eff}}(\Delta S = 1) = \sum_{i=3}^6 C_i \mathcal{O}_i$. The $sdg$ operator $O_8$ which is relevant to $\text{Re}(\epsilon'/\epsilon_K)$ is defined as

$$O_8 = \frac{g_s}{4\pi} m_s d_L^a \gamma^\mu T^a s_R^b G^a_{\mu\nu},$$

and other four quark operators $O_{i=3,...,6}$ and the corresponding Wilson coefficients from $C_3$ to $C_8$ with a single mass insertion are available in the literature. If we consider the penguin diagram Fig. 1 with the double mass insertion, the Wilson coefficient $C_8$ is given by

$$C_8^{(2)} = \frac{\alpha_s}{m^2} \frac{m_{\tilde{g}}}{m_s} (\delta_{12}^d)_{LR} \text{M}_8(x)$$

where the explicit form of the $\sim O(1)$ function $M_8(x)$ can be found in Ref. 3. Since $C_8^{(2)}$ is proportional to $m_{\tilde{g}}/m_s$, it is very important for generating $\text{Re}(\epsilon'/\epsilon_K)$ even if $(\delta_{12}^d)_{LR}$ is fairly small.

![Figure 1. Feynman diagram for $\Delta S = 1$ process. The cross denotes the flavor changing (LL) and the flavor preserving (LR) mixings, respectively.](image)

It is straightforward to calculate $\epsilon_K$ and $\epsilon'/\epsilon_K$ using the same parameters as in Ref. 2 with $m_s(2 \text{ GeV}) = 130$ MeV. The corresponding SM prediction for $\text{Re}(\epsilon'/\epsilon_K) = 5.7 \times 10^{-4}$. For those points which satisfy $\Delta m_K(SUSY) \leq \Delta m_K(\text{exp})$ and $|\epsilon_K(SUSY) - \epsilon_K(\text{exp})| < 1 \sigma$, we plot $\epsilon'/\epsilon_K$ in Fig. 2 as functions of the modulus $r$ and the phase $\varphi$ of the parameter $(\delta_{12}^d)_{LL} \equiv r e^{i\varphi}$ for the common squark mass $\hat{m} = 500$ GeV. The upper (lower) rows correspond to $A_s \equiv (A_s - \mu^\dagger \tan \beta) = -10(20)$ TeV. It is clear that both $\epsilon_K$ and $\text{Re}(\epsilon'/\epsilon_K)$ can be nicely accommodated with a single complex number $(\delta_{12}^d)_{LL}$ with $\sim O(1)$ phase in our model without any difficulty, if $|\mu|$ and $\tan \beta$ is relatively large so that $|A_s|$ becomes a few tens of TeV. It is important to realize that in our model there is no conflict between neutron EDM from $(\delta_{12}^d)_{LL}$, since the EDM is generated by another parameter $(\delta_{12}^d)_{LR}$, which can be taken as real independent of $(\delta_{12}^d)_{LL}$. This is in sharp contrast with the case of Ref. 2, where the neutron edm is inevitably close to the current upper limit. Note that we are not assuming any specific flavor structures in
Figure 2. $\Re(\epsilon'/\epsilon_K)$ as a function of the modulus $r$ [(a) and (c)] and the phase $\phi$ [(b) and (d)] of the parameter $(\delta^d_{12})_{LL}$ with $A_S$ to be $-10 \, TeV$ [(a),(b)] and $-20 \, TeV$ [(c),(d)]. The common squark mass is chosen to be $\tilde{m} = 500 \, GeV$, and the solid, the dashed and the dotted curves correspond to $x = 0.3, 1.0, 2.0$, respectively.

In conclusion, we showed that both $\epsilon_K$ and $\Re(\epsilon'/\epsilon_K)$ can be accommodated with a single CP violating and flavor changing down-squark mass matrix elements $[|\delta^d_{12}]_{LL} \sim 10^{-3}]$ without any fine tuning or any conflict with the data on FCNC processes, if $|\mu \tan \beta| \sim O(10) \, TeV$. Our mechanism utilizes this FC $LL$ mass insertion along with the FP $LR$ mass insertion proportional to $(\delta^d_{22})_{LR} \sim 10^{-2}$. The latter is generically present in any SUSY models including the MSSM, and thus there is no fine tuning in our model for accommodating both $\epsilon_K$ and $\Re(\epsilon'/\epsilon_K)$ in terms of a single $(\delta^d_{12})_{LL}$. Phrasing differently, the SUSY $\epsilon_K$ problem implies SUSY $\epsilon'$ problem if $|\mu \tan \beta|(\sim O(10 - 20) \, TeV)$ is relatively large. One can also consider our mechanism in the more minimal SUSY model, where $(\delta^d_{22})_{LR}^d$ is proportional to $m_b(A_b - \mu \tan \beta)$ so that $A_b - \mu \tan \beta$ may be lowered significantly. The best discriminant between our model and the SM model would be probably the branching ratios for $K \to \pi \nu \nu$ and CP violations in $B$ decays. For example, the time dependent asymmetry in $B^0 \to J/\psi K_S$, $\sin 2\beta$, can be completely different from the SM prediction. Also if the KM phase is nonzero, there will be additional contributions to $\epsilon_K$ and $\Re(\epsilon'/\epsilon_K)$ from the SM and other SUSY loop diagrams. All these finer details will be discussed elsewhere in the forthcoming publication.

Acknowledgments

This work is supported by BK21 program of Ministry of Education.

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