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R-parity-violating SUSY and *CP* violation in $B\to\phi K_S$

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Recent measurements of CP asymmetry in $B\to\phi K_S$ appear to be inconsistent with standard model expectations. We explore the effect of *R*-parity-violating SUSY to understand the data.

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I. INTRODUCTION

In the standard model (SM), CP violation is due to the presence of phases in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. The SM predicts large CP violation in B decays [1] and the B factories BaBar and Belle will test the SM explanation of CP violation. One of the CP phases of the CKM unitarity triangle has already been measured: $\sin 2\beta=0.78\pm 0.08$ [2], which is consistent with the SM.[1]

The goal of the B factories is not only to test the standard model (SM) picture of CP violation but also to discover evidence of new physics. Decays that get significant contributions from penguin diagrams are most likely to be affected by new physics [4]. In particular the decay $B\to\phi K_S$ is very interesting because it is a pure penguin diagram and is dominated by a single amplitude in the SM. Hence this decay can be used to measure $\sin(2\beta)$ and if this measurement is found to disagree with $\sin(2\beta)$ from other measurements, like $B\to J/\psi K_S$, then it will be a clear sign of new physics [5].

There have been recent reported measurements of CP asymmetries in $B\to\phi K_S$ decays by BaBar [6]

$$\sin(2\beta(\phi K_S))_{BaBar}=-0.19^{+0.52}_{-0.50}\pm 0.09 \tag{1}$$

and Belle [7]

$$\sin(2\beta(\phi K_S))_{Belle}=-0.73\pm 0.64\pm 0.18. \tag{2}$$

Combining the two measurements and adding the errors in quadrature one obtains

$$\sin(2\beta(\phi K_S))_{ave}=-0.39\pm 0.41. \tag{3}$$

This result appears to be inconsistent with SM prediction as $\sin(2\beta)$ from $B\to J/\psi K_s$ should agree with $\sin(2\beta)$ from $B\to\phi K_s$ up to $0(\lambda^2)$ with $\lambda\sim 0.2$. However, the measurements presented above seem to indicate a 2.8 σ deviation from SM expectation. Implications of these measurements were discussed in Ref. [8] and a possible explanation of the data with substantial flavor changing nutral current (FCNC) couplings of the Z was suggested. In this paper we study the effect of *R*-parity-violating SUSY for the decay $B\to\phi K_S$ in the light of the new data and show that the present measurements of $\sin(2\beta)$ can be easily accommodated in the presence of *R*-parity-violating SUSY.

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[1] A new world average for $\sin 2\beta=0.734\pm 0.051$ has been reported in Ref. [3] but this new value has little impact on the numbers as well as the conclusions presented in the paper.

II. *R*-PARITY BREAKING SUSY AND $B\to\phi K_S$

In supersymmetric models, *R*-parity invariance is often imposed on the Lagrangian in order to maintain the separate conservation of baryon number and lepton number. The *R* parity of a field with spin *S*, baryon number *B* and lepton number *L* is defined to be

$$R=(-1)^{2S+3B+L}. \tag{4}$$

R is $+1$ for all the SM particles and -1 for all the supersymmetric particles.

The presence of *R*-parity conservation implies that super particles must be produced in pairs in collider experiments and the lightest super particle (LSP) must be absolutely stable. The LSP therefore provides a good candidate for cold dark matter. There is, however, no compelling theoretical motivation, such as gauge invariance, to impose R-parity conservation.

The most general superpotential of the minimal supersymmetric standard model (MSSM) consistent with $SU(3)\times SU(2)\times U(1)$ gauge symmetry and supersymmetry, can be written as

$$\mathcal{W}=\mathcal{W}_R+\mathcal{W}_{\not R}, \tag{5}$$

where $\mathcal{W}_R$ is the *R*-parity conserving piece, and $\mathcal{W}_{\not R}$ breaks *R* parity. They are given by

$$\mathcal{W}_R=h_{ij}L_iH_2E_j^c+h'_{ij}Q_iH_2D_j^c+h''_{ij}Q_iH_1U_j^c, \tag{6}$$

$$\mathcal{W}_{\not R}=\frac{1}{2}\lambda_{[ij]k}L_iL_jE_k^c+\lambda'_{ijk}L_iQ_jD_k^c+\frac{1}{2}\lambda''_{i[jk]}U_i^cD_j^cD_k^c+\mu_iL_iH_2. \tag{7}$$

Here $L_i(Q_i)$ and $E_i(U_i,D_i)$ are the left-handed lepton (quark) doublet and lepton (quark) singlet chiral superfields, where i,j,k are generation indices and c denotes a charge conjugate field. $H_{1,2}$ are the chiral superfields representing the two Higgs doublets.

The λ and λ' couplings in [Eq. (7)], violate lepton number conservation, while the λ'' couplings violate baryon number conservation. There are 27 λ'-type couplings and 9 each of the λ and λ'' couplings as $\lambda_{[ij]k}$ is antisymmetric in the first two indices and $\lambda''_{i[jk]}$ is antisymmetric in the last two indices. The nonobservation of proton decay imposes

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very stringent conditions on the simultaneous presence of both the baryon-number and lepton-number violating terms in the Lagrangian [9]. It is therefore customary to assume the existence of either L-violating couplings or B-violating couplings, but not both. The terms proportional to λ are not relevant to our present discussion and will not be considered further.

The antisymmetry of the B-violating couplings, $\lambda''_{i[jk]}$ in the last two indices, implies that there are no operators that can generate the $b\to s\bar{s}s$ transition, and hence cannot contribute to $B\to\phi K_S$ at least at the tree level.

We now turn to the L-violating couplings. In terms of four-component Dirac spinors, these are given by [10]

$$\mathcal{L}_{\lambda'}=-\lambda'_{ijk}[\tilde{\nu}^i_L\overline{d^k_R}d^j_L+\tilde{d}^j_L\overline{d^k_R}\nu^i_L+(\tilde{d}^k_R)^*(\overline{\nu^i_L})^c d^j_L-\tilde{e}^i_L\overline{d^k_R}u^j_L$$
$$-\tilde{u}^j_L\overline{d^k_R}e^i_L-(\tilde{d}^k_R)^*(\overline{e^i_L})^c u^j_L]+\text{H.c.} \tag{8}$$

For the $b\to s\bar{s}s$ transition, the relevant Lagrangian is

$$L_{eff}=\frac{\lambda'_{i32}\lambda'^{*}_{i22}}{m^2_{\tilde{\nu}_i}}\bar{s}\gamma_R s\,\bar{s}\gamma_L b+\frac{\lambda'_{i22}\lambda'^{*}_{i23}}{m^2_{\tilde{\nu}_i}}\bar{s}\gamma_L s\,\bar{s}\gamma_R b, \tag{9}$$

where $\gamma_{RL}=(1\pm\gamma_5)/2$. There are a variety of sources which bound the above couplings [11] but the present bounds are fairly weak and the contribution from the L-violating couplings can significantly affect $B\to\phi K_S$ measurements.

In the SM, the amplitude for $B\to\phi K_S$, can be written within factorization as[2]

$$A^{SM,}_{\phi K_S}=-\frac{G_F}{\sqrt{2}}V_{tb}V^*_{ts}\left[a^t_3+a^t_4+a^t_5-\frac{1}{2}a^t_7-\frac{1}{2}a^t_9-\frac{1}{2}a^t_{10}-a^c_3\right.$$
$$\left.-a^c_4-a^c_5+\frac{1}{2}a^c_7+\frac{1}{2}a^c_9+\frac{1}{2}a^c_{10}\right]Z, \tag{10}$$
$$Z=2f_\phi m_\phi F_{BK}(m^2_\phi)\varepsilon^*\cdot p_B,$$

where f_ϕ is the ϕ decay constant and F_{BK} is the $B\to K$ semileptonic form factor. The $a^{t,c}_i$ are the usual combination of Wilson's coefficient in the effective Hamiltonian. For a_i as well as the quark masses we use the values used in Ref. [14]. The R-parity contribution can be written as[3]

$$A^{\not{R}}_{\phi K_S}=(X_1+X_2)Z,$$
$$X_1=-\frac{\lambda'_{i32}\lambda'^{*}_{i22}}{24m^2_{\tilde{\nu}_i}},$$
$$X_2=-\frac{\lambda'_{i22}\lambda'^{*}_{i23}}{24m^2_{\tilde{\nu}_i}}. \tag{11}$$

[2]This decay has been recently studied in QCD factorization in Ref. [12].

[3]The effect of R-parity-violating SUSY on $B\to\phi K_S$ was considered in Ref. [13].

We write

$$X_1+X_2=\frac{X}{12M^2}e^{i\phi}, \tag{12}$$

where ϕ is the weak phase in the R-parity-violating couplings and M is some mass scale with $M\sim m_{\tilde{\nu}_i}$. We require $|X|$ to be such that $|A^{SM,}_{\phi K_S}|$ and $|A^{\not{R}}_{\phi K_S}|$ are of the same size, which then fixes $|X|\sim1.5\times10^{-3}$ for $M=100$ GeV which is smaller than or within the existing constraints on $|X|$ from Ref. [11].

We can now calculate $\sin(2\beta)_{eff}$ from

$$\sin(2\beta)_{eff}=-\frac{2\,\text{Im}[\lambda_f]}{(1+|\lambda_f|^2)},$$
$$\lambda_f=e^{-2i\beta}\frac{\bar{A}}{A}, \tag{13}$$

where $A=A^{SM,}_{\phi K_S}+A^{\not{R}}_{\phi K_S}$ and $\bar{A}$ is the amplitude for the CP-conjugate process. Note that from Eq. (10) and Eq. (11) $\sin(2\beta)_{eff}$ is independent of Z and hence free from uncertainties in the form factor and decay constants. It is also possible that nonfactorizable effects may be less important in $\sin(2\beta)_{eff}$ as we are taking ratios of amplitudes. In Fig. 1 we plot $\sin(2\beta)_{eff}$ versus the phase ϕ and it is clear from the figure that the present measurements in Eq. (1) and Eq. (2) can be easily explained.

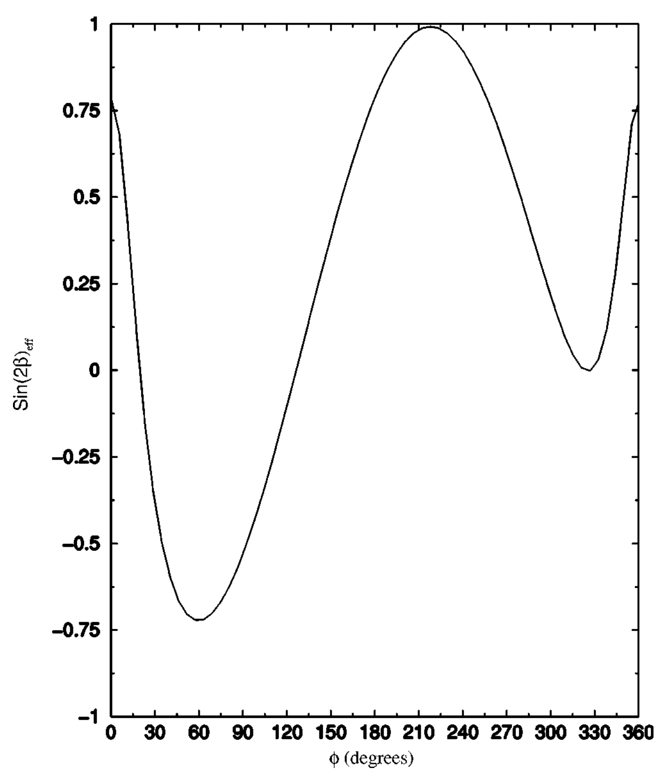

FIG. 1. $\text{Sin}(2\beta)_{eff}$ vs ϕ.

We now turn to the calculation of branching ratios and the direct CP asymmetry. The measured branching ratio for ($B\to\Phi K^0$) is $(8.1^{+3.1}_{-2.5}\pm0.8)\times10^{-6}$ [15] while Belle measures a value for the direct CP asymmetry, i.e. the cosine term $C=-0.56\pm0.41\pm0.12$ [7] which is consistent with zero. The calculation of the branching ratio as well as the direct CP asymmetry is difficult and suffers from hadronic uncertainties even within factorization. The branching ratio, within naive factorization, depends on the form factors and the ϕ decay constants. The uncertainties in these quantities can easily change the predicted branching ratio by a factor of 2 or so. The direct CP asymmetry could potentially be large as there are two interfering amplitudes of the same size. However the direct CP asymmetry crucially depends on the strong phase which can be perturbatively generated through tree level rescattering in factorization. The size of this strong phase, in this case, depends on the charm quark mass as well and the gluon momentum in the penguin diagram. Using the values of the form factor $F_{BK}=0.38$ and the ϕ decay constant $f_\phi=0.237$ [12] and taking a typical value for the phase $\phi=1.5$ radians (86°) we obtain the branching ratio for ($B\to\Phi K^0)=9.5\times10^{-6}$, $\sin2\beta=-0.57$ and the direct CP asymmetry $\sim35\%$. We have used $m_c=1.4$ GeV, $m_b=5$ GeV and the gluon momentum $q^2=m_b^2/2$ to obtain these numbers. We would like to stress here that even in the absence of the strong phase one can still easily accommodate the data for $\sin2\beta$ in $B\to\phi K_S$. If in fact the strong phases are small one could look for T-violating correlation in $B\to\phi K^*$ or in the corresponding Λ_b decays [16].

If R-parity-breaking SUSY with L violation is the correct explanation for the data in Eq. (1) and Eq. (2), then proton decay constraints [9] would lead one to expect that the B-violating couplings are very small and effects associated with these couplings will not be measurable. We also point out that the R-parity-violating operator for $b\to s\bar{s}s$ is not the related to the $b\to s\bar{u}(\bar{d})u(d)$, unlike some models of new physics. Hence R-parity-violating effects in $B\to\phi K_S$ can be very different than in $B\to K\pi$, for example, which is a $b\to s\bar{u}u$ transition. However the new R-parity-violating SUSY generated $b\to s\bar{s}s$ operators will affect decays like $B\to K(K^*)\eta(\eta')$, $\Lambda_b\to\Lambda\eta(\eta')$, $\Lambda_b\to\Lambda\phi$, etc. [17].

In conclusion, recent measurements of CP asymmetry in $B\to\phi K_S$ appear to be inconsistent with standard model expectations. We show that the effect of R-parity-violating SUSY can easily accommodate the data.

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