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CP asymmetry in $\bar{B}^0 \to K^- \pi^+$ from supersymmetric flavor changing interactions

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Recently *BABAR* and Belle Collaborations have measured direct CP asymmetry $A_{CP} = -0.114 \pm 0.020$ in $\bar{B}^0 \to K^- \pi^+$. The experimental value is substantially different from the QCD factorization prediction. We show that supersymmetry flavor changing neutral current interaction via gluonic dipole can explain the difference. CP asymmetries in other $B \to K\pi$ decays are predicted to be sizable. Taking this asymmetry as a constraint, we find that the allowed supersymmetry parameter space is considerably reduced compared with constraint from $B \to X_s \gamma$ alone. We also find the allowed time-dependent CP asymmetries S_f in $\bar{B}^0 \to \bar{K}^{*0}\gamma \to \pi^0 K_S \gamma$ and $\bar{B}^0 \to \phi K_S$ to be large. These predictions are quite different than those predicted in the standard model and can be tested in the near future.

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Recently *BABAR* and Belle Collaborations have measured direct CP asymmetry A_{CP} in $\bar{B}^0 \to K^- \pi^+$ with a value of -0.114 ± 0.020 [1]. Also with precision determinations of the branching ratios of $B \to X_s\gamma$, $B \to K\pi$, and other rare B decays [2–4], the study of rare B decays has entered a precision era. These decays, being rare in the standard model (SM), are very sensitive probes for new physics beyond the SM.

The recently measured CP asymmetry $A_{CP}(\bar{B}^0 \to K^-\pi^+)$ has important implications for B decays and there have been some discussions in the literature [5]. The experimental value for $A_{CP}(\bar{B}^0 \to K^-\pi^+)$ is substantially different from the predictions based on factorization calculations which predict $A_{CP}(\bar{B}^0 \to K^-\pi^+)$ to be positive [6,7] for a set of favored hadronic parameters. For example, the default values given in Ref. [6] for the hadronic parameter with γ fixed to be 60° gives the CP asymmetry to be 0.15. However, there are uncertainties in the hadronic parameters. Allowing the relevant hadronic parameters to vary in some reasonable ranges, the range for the CP asymmetry can spread from -0.1 to 0.35. There are also methods which can give a value close to the experimental data, such as pQCD calculations [8]. We would like to emphasize that at present there is not a method which can explain all data, branching ratios (too small $\bar{B}^0 \to \bar{K}^0\pi^0$, for example) ,and CP asymmetries in B decays simultaneously. This is an unsatisfactory situation. Further theoretical improvements are needed.

There is also the possibility that new physics beyond the SM is responsible for the deviations. Because of the hadronic uncertainties pointed out above, it is not possible to draw a definitive conclusion. It is, nevertheless, important to see what new physics may be needed to explain the data and what predictions can be made by consistently using one method. When combined with other processes, which are more hadronic model independent, crucial information about new physics beyond the SM can be extracted. In this work we take such an approach to study implications of the CP asymmetry in $\bar{B}^0 \to K^-\pi^+$ on a supersymmetric (SUSY) flavor changing neutral current (FCNC) interaction via a gluonic dipole term using QCD improved factorization. We then combine more hadronic model-independent processes $B \to X_s\gamma$ to constrain the relevant parameters. Predictions for direct CP asymmetries in other $B \to K\pi$ decays, and time-dependent CP asymmetries in $B \to K^*\gamma \to \pi K_S\gamma$ and $B \to \phi K_S$ are also studied.

In the SM, the Hamiltonian for the B decays to be considered is well known which is of the form [9]

$$H = \frac{G_F}{\sqrt{2}}\left[V_{ub}V_{us}^*(c_1O_1 + c_2O_2) - \sum_{i=3}^{12} V_{jb}V_{js}^* c_i^j O_i \right], \quad (1)$$

where V_{ij} are the CKM matrix elements. c_i are the Wilson coefficients for the operators O_i which have been evaluated in different schemes, of which values from the naive dimensional regularization scheme will be used [9]. We will not display the full sets of O_i and c_i here, but only give the definitions of the gluonic and photonic dipole operators O_{11} and O_{12} for the convenience of later discussions. They are given by

$$\begin{aligned} O_{11} &= \frac{g_s}{8\pi^2}\bar{s}\sigma_{\mu\nu}G_a^{\mu\nu}T^a[m_b(1+\gamma_5) + m_s(1-\gamma_5)]b, \\ O_{12} &= \frac{e}{8\pi^2}\bar{s}\sigma_{\mu\nu}F^{\mu\nu}[m_b(1+\gamma_5) + m_s(1-\gamma_5)]b, \end{aligned} \quad (2)$$

where T^a is the color SU(3) generator normalized to $\mathrm{Tr}(T^aT^b) = \delta^{ab}/2$. $G_{\mu\nu}$ and $F_{\mu\nu}$ are the gluon and photon

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field strengths. In the SM $c_{11} = -0.151$ and $c_{12} = -0.318$ [9–11].

When going beyond the SM, there are some modifications of the above coefficients. In SUSY models, exchanges of gluino and squark with left-right squark mixing can generate a large contribution to $c_{11,12}$ at one-loop level [12,13] since their interactions are strong couplings in strength and also enhanced by a factor of the ratio of gluino mass to the b quark mass [14]. We will concentrate on the effects of this interaction, although there are also possible large contributions from other sources [15]. In general, exchange of squarks and gluinos can generate nonzero $c_{11,12}$ for dipole operators with $1 + \gamma_5$, as well as nonzero $c'_{11,12}$ for dipole operators with $1 - \gamma_5$.

The Wilson coefficients $c^{\mathrm{SUSY}}_{11,12}$ from SUSY contributions obtained in the mass insertion approximation are given by, for the case with $1 + \gamma_5$ [13],

$$
\begin{aligned}
c^{\mathrm{SUSY}}_{11}(m_{\tilde g}) &= \frac{\sqrt{2}\pi\alpha_s(m_{\tilde g})}{G_F m^2_{\tilde g}} \frac{\delta^{bs}_{\mathrm{LR}}}{V_{tb}V^*_{ts}} \frac{m_{\tilde g}}{m_b} G_0(x_{gq}),\\
c^{\mathrm{SUSY}}_{12}(m_{\tilde g}) &= \frac{\sqrt{2}\pi\alpha_s(m_{\tilde g})}{G_F m^2_{\tilde g}} \frac{\delta^{bs}_{\mathrm{LR}}}{V_{tb}V^*_{ts}} \frac{m_{\tilde g}}{m_b} F_0(x_{gq}),\\
G_0(x) &= \frac{x[22 - 20x - 2x^2 + (16x - x^2 + 9)\ln(x)]}{3(1-x)^4},\\
F_0(x) &= -\frac{4x[1 + 4x - 5x^2 + (4x + 2x^2)\ln(x)]}{9(1-x)^4},
\end{aligned}
\tag{3}
$$

where $\delta^{bs}_{\mathrm{LR}}$ parametrizes the mixing of left and right squarks, and $x_{gq} = m^2_{\tilde g}/m^2_{\tilde q}$ is the ratio of gluino mass $m_{\tilde g}$ and squark mass $m_{\tilde q}$. The Wilson coefficients $c'^{\mathrm{SUSY}}_{11,12}$ for the case with $1 - \gamma_5$ can be easily obtained by replacing the left-right mixing parameter $\delta^{bs}_{\mathrm{LR}}$ by the right-left mixing parameter $\delta^{bs}_{\mathrm{RL}}$.

At the energy scale relevant for B decays, $\mu \approx m_b$, the coefficients $c^{(')\mathrm{SUSY}}_{11,12}$ are modified to be [9] $c^{(')\mathrm{SUSY}}_{11}(\mu) = \eta^7 c^{(')\mathrm{SUSY}}_{11}(m_{\tilde g})$ and $c^{(')\mathrm{SUSY}}_{12}(\mu) = \eta^8 c^{(')\mathrm{SUSY}}_{12}(m_{\tilde g}) + \frac{8}{3} \times (\eta^7 - \eta^8) c^{(')\mathrm{SUSY}}_{11}(m_{\tilde g})$, with $\eta = [\alpha_s(m_{\tilde g})/\alpha_s(m_t)]^{2/21} \times [\alpha_s(m_t)/\alpha_s(m_b)]^{2/23}$.

From the expressions in Eq. (3), one can see that the SUSY contributions are proportional to $m_{\tilde g}$. If $m_{\tilde g}$ is of order a few hundred GeV, there is an enhancement factor of $(m_{\tilde g}/m_b)(m^2_W/m^2_{\tilde g})$ for the SUSY dipole interactions. In this case even a small $\delta^{bs}_{\mathrm{LR,RL}}$, which can easily satisfy constraints from $B^0 - \bar B^0$ mixing and other data, can have large effects on rare B decays.

We first consider a constraint on the SUSY parameters $\delta^{bs}_{\mathrm{LR,RL}}$ from $B \to X_S\gamma$. The branching ratio of this process has been measured to a good precision with $(3.54^{+0.30}_{-0.28}) \times 10^{-4}$ [2]. Theoretically the branching ratio has been evaluated to the next-to-leading order (NLO) QCD corrections. The branching ratio with the photon energy cut to have $E_\gamma > (1-\delta)E^{\max}_\gamma$ is given by [11]

$$
2.57 \times 10^{-3} \times K_{\mathrm{NLO}}(\delta) \times \frac{\mathrm{Br}(B \to X_c e\bar\nu)}{10.5\%}, \tag{4}
$$

where the factor $K_{\mathrm{NLO}}(\delta)$ related to the Wilson coefficients c_i is given by

$$
\begin{aligned}
K_{\mathrm{NLO}}(\delta) = &\sum_{\substack{i,j=2,11,12\\ i\le j}} k_{ij}(\delta)[c_i c^*_j + c'_i c'^*_j]\\
&+ k^{(1)}_{12,12}(\delta)[c^{(1)}_{12} c^*_{12} + c'^{(1)}_{12} c'^*_{12}].
\end{aligned}
$$

The values of c'_2 and $k_{ij}(\delta)$ can be obtained by using the expressions given in Ref. [11]. We use $\delta = 90\%$ which gives $\mathrm{Br}(B \to X_S\gamma) \approx 3.5 \times 10^{-4}$, which is consistent with the data and the complete NLO QCD results in Ref. [16].

Although experimentally CP asymmetry in $B \to X_S\gamma$ has not been well established, there are constraints from experiments with 0.005 ± 0.036 [3]. We will also take this information into account. In the SM, the leading contribution to $A_{CP}(B \to X_S\gamma)$ is given by

$$
\begin{aligned}
A_{X_S\gamma} = \frac{1}{|c^{\mathrm{SM}}_{12}|^2}\{&a_{27}\mathrm{Im}[c^{\mathrm{SM}}_2 c^{\mathrm{SM}*}_{12}] + a_{28}\mathrm{Im}[c^{\mathrm{SM}}_2 c^{\mathrm{SM}*}_{11}]\\
&+ a_{87}\mathrm{Im}[c^{\mathrm{SM}}_{11} c^{\mathrm{SM}*}_{12}]\}.
\end{aligned}
\tag{5}
$$

From Ref. [11], we find $a_{87} \sim -9.5\%$, $a_{27} \sim 1.06\%$, and $a_{28} \sim 0.16\%$. For the calculation of $A_{CP}(B \to X_S\gamma)$ in the SUSY model considered here, one just replaces $c^{\mathrm{SM}}_{11,12}$ by the total $c_{11,12}$ and adds a term $a_{87}\mathrm{Im}[c'_{11}c'^*_{12}]$ to the numerator and $|c'_{12}|^2$ to the denominator in the above equation.

Using the above, deviations of $c^{(')}_{11,12}$ from the SM values are severely constrained. In Fig. 1 we show the allowed ranges for the absolute values of $\delta^{bs}_{\mathrm{LR,RL}}$ and their phases τ for $m_{\tilde g} = 300$ GeV and $m_{\tilde q}$ in the range 100–1000 GeV at the one-σ level. We find that the constraints from $\mathrm{Br}(B \to X_S\gamma)$ are slightly more stringent than those from $A_{CP}(B \to X_S\gamma)$. Using the allowed parameters, one can obtain the

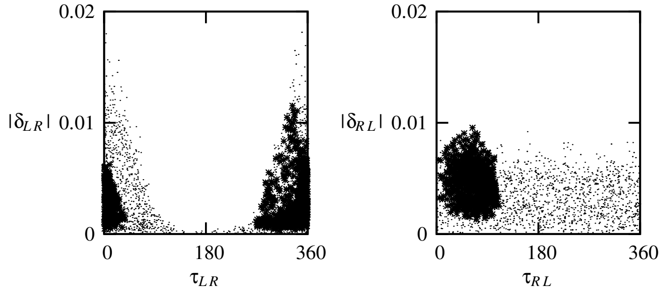

FIG. 1. The one-σ allowed ranges for the SUSY parameters $|\delta^{bs}_{\mathrm{LR,RL}}|$ and the phase τ taking $m_{\tilde g} = 300$ GeV and $m_{\tilde q}$ in the range 100–1000 GeV. The light-dark dotted areas are the allowed parameter spaces from $\mathrm{Br}(B \to X_s\gamma)$ and $A_{CP}(B \to X_S\gamma)$ constraints. The dark dotted areas are allowed ranges by the $A_{CP}(\bar B^0 \to K^-\pi^+)$ constraint. The left and right panels are for the dipole operators with $1 + \gamma_5$ and $1 - \gamma_5$, respectively.

allowed $c_{11}^{(\prime)}$ through Eq. (3) and study implications for other rare B decays. The allowed ranges for $\delta_{\rm LR}^{bs}(\tau_{\rm LR})$ and $\delta_{\rm RL}^{bs}(\tau_{\rm RL})$ are correlated, in general.

We now study whether after the constraint from $B \to X_S\gamma$, the observed CP asymmetry $A_{CP}(\bar{B}^0 \to K^-\pi^+)$ can be reproduced and analyze what constraint can be put on the SUSY parameters. For this purpose, we need to calculate the amplitudes for $B \to K\pi$ decays. We follow the QCD factorization approach in Ref. [6]. Since O_{12} is suppressed by a factor of α_{em}/α_s compared with O_{11}, we will neglect its contribution in our later discussions. We find that the gluonic dipole contributions to the decay amplitudes, $-\sqrt{2}A(\bar{B}^0 \to \bar{K}^0\pi^0)$, $A(\bar{B}^0 \to K^-\pi^+)$, $\sqrt{2}A(B^- \to K^-\pi^0)$, $A(B^- \to \bar{K}^0\pi^-)$, are the same, which are given by

$$i\frac{G_F}{\sqrt{2}} f_K m_B^2 F_0^{B\to\pi}(m_K^2) V_{tb}V_{ts}^* \frac{C_F\alpha_s}{2\pi N_c}(c_{11} - c'_{11})G_{K\pi}, \qquad (6)$$

where $G_{K\pi} = \int_0^1 \phi_K(x)dx/(1-x) + R_K$, $R_K = 2m_K^2/m_s m_b$, and $C_F = (N_c^2 - 1)/(2N_c)$ with the number of color $N_c = 3$. $\phi_K(x)$ is the light cone distribution amplitude.

In our numerical analysis we will take the CKM parameters to be known, with the standard parametrization $s_{12} = 0.2243$, $s_{23} = 0.0413$, $s_{13} = 0.0037$, $\delta_{13} = 1.05$, which is the central value given by the Particle Data Group [17]. With the SM amplitudes obtained and the default values for the hadronic parameters used in Ref. [6], we obtain the CP asymmetry $A_{CP}(\bar{B}^0 \to K^-\pi^+)$ in the SM to be 0.15. This is different in sign than the experimental value. When SUSY dipole interactions are included the experimental value can be reproduced. For example, when $m_{\tilde{g}} = m_{\tilde{q}} = 300$ GeV, $\delta_{\rm LR} = 2.62 \times 10^{-3}e^{0.238i}$, $\delta_{\rm RL} = 4.31 \times 10^{-3}e^{1.007i}$, the asymmetry $A_{CP}(\bar{B}^0 \to K^-\pi^+)$ is approximately -0.114. Using the same set of SUSY parameters, we have ${\rm Br}(B \to X_s\gamma) = 3.48 \times 10^{-4}$, $A_{CP}(B \to X_S\gamma) = 0.016$. It is clear that the CP asymmetry $A_{CP}(\bar{B}^0 \to K^-\pi^+)$ can be brought to be in agreement with data at one-σ level when SUSY gluonic dipole interactions are included.

To see how the CP asymmetry provides stringent constraint on the SUSY flavor changing parameters, we show in Fig. 1 the parameter space allowed from $A_{CP}(\bar{B}^0 \to K^-\pi^+)$ (the dark dotted areas) on top of the allowed ranges by a $B \to X_S\gamma$ constraint alone at the one-σ level. We see that the CP asymmetry in $\bar{B}^0 \to K^-\pi^+$ considerably reduces the allowed parameter space.

One should also check if other data already rule out the allowed range for relevant CP violating dipole parameters. We find that, at present, constraints from B decay considered here provide the most stringent constraints compared with other B decay processes. There are other processes which can constrain SUSY CP violating parameters, such as Kaon decays [18], and electric dipole moment of electron, neutron, and nuclei such as Mercury [19]. However, these processes involve different SUSY parameters which, in general, are not directly related to the parameters for $B \to K\pi$. In the following discussions we will use constraints from the above analysis.

Using the above allowed SUSY parameters, one can predict the branching ratios for all four $B \to K\pi$ branching ratios and also the unmeasured CP asymmetries. Since the branching ratios involve unknown $B \to K$ and $B \to \pi$ form factors, one cannot make precise predictions without a good understanding of these form factors. We therefore study just the CP asymmetries in which a large part of the form factor effects are canceled out. In Fig. 2, we show the direct CP asymmetries in $B^- \to \bar{K}^0\pi^-$, $B^- \to K^-\pi^0$, and $\bar{B}^0 \to \bar{K}^0\pi^0$ for the allowed parameter space in Fig. 1. We see that large CP asymmetries are allowed. In particular, the CP asymmetry in $B^- \to \bar{K}^0\pi^-$ can be as large as -0.3, whereas in the SM this asymmetry is very small. Near future experiments can test these predictions.

We finally study time-dependent CP asymmetries in $B \to K^*\gamma \to \pi^0 K_S\gamma$ and $B \to \phi K_S$. There are two CP violating parameters A_f and S_f which can be measured in time-dependent decays of B and $\bar{B}$ produced at e^+e^- colliders at the $\Upsilon(4S)$ resonance, $A^{CP}(t) = A_f\cos(\Delta t\Delta m_B) + S_f\sin(\Delta t\Delta m_B)$. The parameters A_f and S_f are related to the decay amplitudes as

$$A_f = \frac{|\lambda_f|^2 - 1}{|\lambda_f|^2 + 1}, \qquad S_f = -2\frac{{\rm Im}[(q_B/p_B)\lambda_f]}{|\lambda_f|^2 + 1}, \qquad (7)$$

where $\lambda_f = \bar{A}/A$, and $\bar{A}$ and A are the decay amplitudes of $\bar{B}^0 \to f_{CP}$ and $B^0 \to f_{CP}$, respectively. q_B/p_B is the mixing parameter in $B - \bar{B}$ mixing.

For $\bar{B}^0 \to \bar{K}^{*0}\gamma \to \pi^0 K_S\gamma$ and $B^0 \to K^{*0}\gamma \to \pi^0 K_S\gamma$, we have [11,14,20]

$$S_{K^*\gamma} = -2\frac{{\rm Im}[(q_B/p_B)(c_{12}c'_{12})]}{|c_{12}|^2 + |c'_{12}|^2}. \qquad (8)$$

To the leading order $A_{K^*\gamma}$ is the same as $A_{CP}(B \to X_S\gamma)$. Note that the hadronic matrix element $\langle K^*|\bar{s}\sigma^{\mu\nu}(1 \pm \gamma_5)b|B\rangle$ does not appear, which makes the calculation

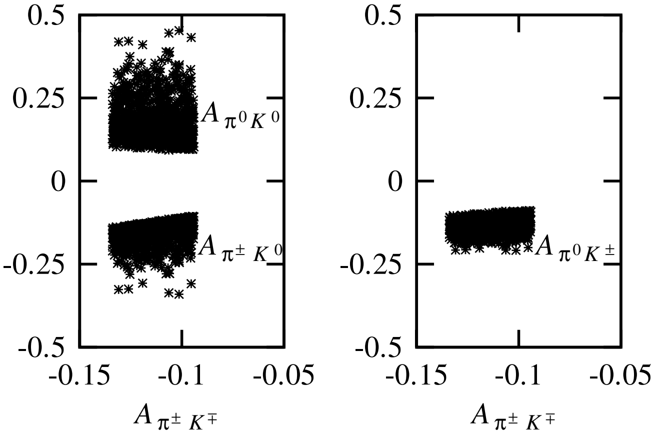

FIG. 2. The allowed CP asymmetries in $B^- \to \bar{K}^0\pi^-$, $B^- \to K^-\pi^0$, and $\bar{B}^0 \to \bar{K}^0\pi^0$.

simple and reliable. In order to have a nonzero $S_{K^*\gamma}$ neither c_{12} nor c'_{12} can be zero.

In the SM the asymmetries $A_{K^*\gamma}$ and $S_{K^*\gamma}$ are predicted to be small with $A^{\rm SM}_{K^*\gamma} \approx 0.5\%$, $S^{\rm SM}_{K^*\gamma} \approx 3\%$ [11,20]. With SUSY gluonic dipole interaction, the predictions for these *CP* asymmetries can be changed dramatically [14]. With the constraints obtained previously, we find that the parameter q_B/p_B is not affected very much compared with the SM calculation. To a good approximation $q_B/p_B = e^{-2i\beta}$.

A large gluonic dipole interaction also has a big impact on $B \to \phi K_S$ decays [21]. In the SM, $A_{\phi K_S}$ is predicted to be very small and $S_{\phi K_S}$ is predicted to be the same as $S_{J/\psi K_S} = \sin(2\beta)$. With SUSY gluonic dipole contribution, the decay amplitude for $B \to \phi K_S$ will be changed and the predicted value for both $A_{\phi K_S}$ and $S_{\phi K_S}$ can be very different from those in the SM [21]. To obtain concrete values, we again use QCD factorization to evaluate the amplitude. We obtain the contributions of c_{11} and c'_{11} to $B \to \phi K_s$ amplitude to be

$$\frac{G_F}{\sqrt{2}} m_\phi f_\phi F_1^{B\to K}(m_\phi^2)\epsilon_\phi^\mu \cdot (P_\mu^B + P_\mu^K)(c_{11} + c'_{11})G_{\phi,11}, \qquad (9)$$

where ϵ_ϕ^μ is the polarization vector of ϕ. $G_{\phi,11} = -\int_0^1 2\phi_\phi(x)dx/(1-x)$ with $\phi_\phi(x)$ being the light cone distribution function.

We are now ready to present the allowed ranges for the time-dependent parameters A_f and S_f for both the processes $\bar{B}^0 \to \bar{K}^*\gamma \to K_S\pi^0\gamma$ and $\bar{B}^0 \to \phi K_S$. The results are shown in Fig. 3. The current values of $S_{K^*\gamma}$ and $A_{K^*\gamma}$ from *BABAR* (Belle) are $0.57 \pm 0.32 \pm 009(-0.00 \pm 0.38)$, $0.25 \pm 0.63 \pm 0.14(-0.79^{+0.63}_{-0.50} \pm 0.09)$, respectively [22]. From Fig. 3, we see that the allowed ranges can cover the central values of $S_{K^*\gamma}$ from *BABAR* and Belle, but it is not possible to obtain the central value of $A_{K^*\gamma}$ by Belle. Future improved data can further restrict the parameter space. Both *BABAR* and Belle have also measured $A_{CP}(B^- \to K^{*-}\gamma)$ with ranges $-0.074 \sim 0.049$ (*BABAR*) and $-0.015 \pm 0.044 \pm 0.012$ (Belle) [23]. In the model we are considering, the *CP* asymmetries $A_{K^*\gamma}$ and $A_{CP}(B^- \to K^{*-}\gamma)$ are the same. The results for the charged *B CP* asymmetry are consistent with data.

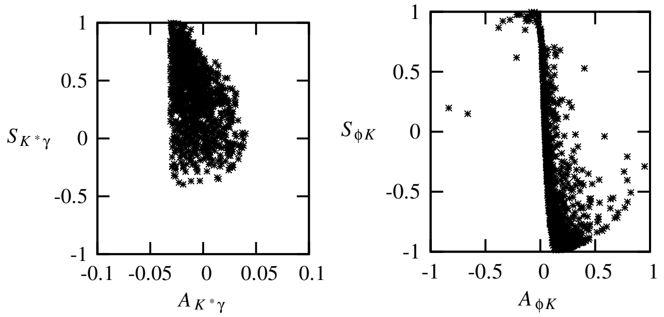

FIG. 3. The allowed time-dependent *CP* asymmetries in $\bar{B}^0 \to K^*\gamma \to K_S\pi^0\gamma$ and $\bar{B}^0 \to \phi K_S$.

The time-dependent asymmetry in $B \to \phi K_S$ is a very good test of *CP* violation in the SM. Experimental measurements have not converged with the current values of *BABAR* (Belle) given by $0.00 \pm 0.23 \pm 0.05(0.08 \pm 0.22 \pm 0.09)$, and $0.50 \pm 0.25^{+0.07}_{-0.04}(0.06 \pm 0.33 \pm 0.09)$ for $A_{\phi K_S}$ and $S_{\phi K_S}$ [4,24], respectively. These values are considerably different than the value reported by Belle last year of $S_{\phi K_S} = -0.96 \pm 0.50^{+0.09}_{-0.11}$ [25]. From Fig. 3 we see that the current data of $A_{\phi K_S}$ and $S_{\phi K_S}$ can be easily accommodated by the allowed ranges. We also note that the allowed ranges can cover last year's Belle data. Since the error bars on the data are large, no definitive conclusions can be drawn at present.

In summary we have studied the implications of the recently measured *CP* asymmetry in $\bar{B}^0 \to K^-\pi^+$ on SUSY flavor changing interactions. The experimental value for this asymmetry -0.114 ± 0.020 is substantially different than QCD factorization prediction. We have shown that SUSY FCNC interaction via gluonic dipole can explain this difference. The allowed SUSY parameter space is considerably reduced compared with constraint from $B \to X_s\gamma$ alone. *CP* asymmetries in other $B \to K\pi$ decays are predicted to be sizable. We also find that the allowed time-dependent *CP* asymmetries S_f in $\bar{B}^0 \to \bar{K}^{*0}\gamma \to \pi^0 K_S\gamma$ and $\bar{B}^0 \to \phi K_S$ are in the ranges of $-0.4 \sim 1$ and $-1 \sim 1$, respectively. These predictions are quite different from the ones in the SM and can be tested in the near future.

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