CP Asymmetry in $\bar{B}^0 \to K^-\pi^+$ from SUSY Flavor Changing Interactions

Xiao-Gang He,$^{1,2}$ Chong-Sheng Li,$^{1,3}$ and Li-Lin Yang$^1$

$^1$Department of Physics, Peking University, Beijing 100871, China
$^2$NCTS/IPE, Department of Physics, National Taiwan University, Taipei
(Dated: March 26, 2022)

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 QCD factorization prediction. We show that SUSY 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 sizeable. Taking this asymmetry as a constraint, we find that the allowed SUSY parameter space is considerably reduced compared with constraint from $B \to X_s \gamma$ alone. We also find that the allowed time dependent CP asymmetries $S_\gamma$ in $\bar{B}^0 \to K^{*+}\gamma \to \pi^0 K_S\gamma$ 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.

PACS numbers: 13.25.Hw, 11.30.Er, 12.60.Jv

Recently Babar and Belle collaborations have measured direct CP asymmetry $A_{CP}$ in $\bar{B}^0 \to K^-\pi^+$ with a value of $-0.114 \pm 0.020$\cite{1}. With also precision determinations of the branching ratios of $B \to X_s \gamma$, $B \to K\pi$, and other rare $B$ decays\cite{2,3,4}, 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\cite{5,6,7}. 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 for a set of favored hadronic parameters\cite{8,9,10}. Although at this stage one cannot conclude that there is the need of new physics beyond the SM, as there are also methods which can give a value close to the experimental data, such as pQCD calculations\cite{11}. We emphases that at present there is not a method which can explain all data, branching ratios and CP asymmetries in $B$ decays simultaneously. 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 SM can be extracted.

In this letter we take such an approach to study implications of the CP asymmetry in $\bar{B}^0 \to K^-\pi^+$ on supersymmetric (SUSY) flavor changing neutral current (FCNC) interaction via gluonic dipole term using QCD improved factorization. We combine more hadronic model independent process $B \to X_s \gamma$ to constrain the relevant parameters. Predictions for direct CP asymmetries in other $B \to K\pi$ decays, and time dependent CP asymmetries in $B \to K^+\gamma \to \pi^0 K_S\gamma$ and $\bar{B}^0 \to \phi K_S$ are also studied.

In the SM, the Hamiltonian for the $B$ decays to be considered is well known which is of the form\cite{12},

$$H = \frac{G_F}{\sqrt{2}}[V_{ub}V_{us}^*(c_1 O_1 + c_2 O_2) - \sum_{i=3}^{12} V_{ij} V_{jk}^* c_i^* O_i],$$ (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, values of which from NDR scheme will be used\cite{13}. 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

$$O_{11} = \frac{\alpha_s}{8\pi^2} \delta\sigma_{\mu\nu} G_a^{\mu\nu} T^a [m_b(1 + \gamma_5) + m_s(1 - \gamma_5)] b, \quad (2)$$
$$O_{12} = \frac{e}{8\pi^2} \delta\sigma_{\mu\nu} F_{\mu\nu} [m_b(1 + \gamma_5) + m_s(1 - \gamma_5)] b,$$

where $T^a$ is the color SU(3) generator normalized to $Tr(T^a T^b) = \delta^{ab}/2$. $G_{\mu\nu}$ and $F_{\mu\nu}$ are the gluon and photon field strengths. In the SM $c_{11} = -0.151$ and $c_{12} = -0.318\sqrt{2}$\cite{13,14,15}.

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\cite{16,17} 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\cite{16}. We will concentrate on the effects of this interaction, although there are also possible large contributions from other sources\cite{18}. In general exchange of squarks and gluinos can generate non-zero $c_{11,12}$ for dipole operators with $1 + \gamma_5$, as well as with non-zero $c'_{11,12}$ for dipole operators with $1 - \gamma_5$.

The Wilson coefficients $c_{11,12}$ from SUSY contributions obtained in the mass insertion approximation are given

*e-mail: hexg@phys.ntu.edu.tw
† e-mail: csli@pku.edu.cn
‡ e-mail: freewill@pku.edu.cn
by, for the case with $1 + \gamma_5$ \[1\],
\[c_{11}^{\text{susy}}(m_{\tilde{g}}) = \frac{\sqrt{2} \pi \alpha_s(m_{\tilde{g}})}{G_F m_{\tilde{g}}^2} \frac{\delta_{LR}^{bs}}{V_{tb}^* V_{ts}} m_{\tilde{g}} G_0(x_{qq}),
\]
\[c_{12}^{\text{susy}}(m_{\tilde{g}}) = \frac{\sqrt{2} \pi \alpha_s(m_{\tilde{g}})}{G_F m_{\tilde{g}}^2} \frac{\delta_{LR}^{bs}}{V_{tb}^* V_{ts}} m_{\tilde{g}} F_0(x_{qq}),
\]
\[G_0(x) = x [22 - 20 x - 2 x^2 + (16 x - x^2 + 9) \ln(x)] 3(1 - x)^4,
\]
\[F_0(x) = -4 x [1 + 4 x - 5 x^2 + (4 x + 2 x^2) \ln(x)] 9(1 - x)^4,
\]
where $\delta_{LR}^{bs}$ parameterizes the mixing of left and right squarks, $x_{qq} = m_3^2/m_\tilde{g}^2$ is the ratio of gluino mass $m_\tilde{g}$ and squark mass $m_3$. The Wilson coefficients $c_{11,12}^{\text{susy}}$ for the case with $1 - \gamma_5$ can be easily obtained by replacing the Left-Right mixing parameter $\delta_{LR}^{bs}$ by the Right-Left mixing parameter $\delta_{RL}^{bs}$.

At the energy scale relevant for $B$ decays, $\mu \approx m_b$, the coefficients $c_{11,12}^{\text{susy}}$ are modified to be\[2\], \[c_{11}^{\text{susy}}(\mu) = \eta^\prime c_{11}^{\text{susy}}(m_{\tilde{g}}), \quad c_{12}^{\text{susy}}(\mu) = \eta^\prime c_{12}^{\text{susy}}(m_{\tilde{g}}) + \frac{8}{3} (\eta^\prime - \eta) c_{11}^{\text{susy}}(m_{\tilde{g}}),\]
with $\eta = (\alpha_s(m_{\tilde{g}})/\alpha_s(m_b))^{2/21} (\alpha_s(m_b)/\alpha_s(m_{\tilde{g}}))^{2/23}$.

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 $(m_3/m_b)(m_{\tilde{g}}/m_\tilde{g})$ for the SUSY dipole interactions. In this case even a small $\delta_{LR,RL}^{bs}$, 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 constraint on the SUSY parameters $\delta_{LR,RL}^{bs}$ from $B \to X_S \gamma$. The branching ratio of this process has been measured to a good precision with $(3.54 \pm 0.28) \times 10^{-4}$ \[2\]. Theoretically the branching ratio has been evaluated to the next-to-leading order QCD corrections. The branching ratio with the photon energy cut to have $E_\gamma > (1 - \delta)E_{\gamma \text{max}}$ is given by \[11\]
\[2.57 \times 10^{-3} \times K_{NLO}(\delta) \times \frac{Br(B \to X_S \gamma)}{10.5\%}, \]
where the factor $K_{NLO}(\delta)$ related to the Wilson coefficients $c_i$ is given by, $K_{NLO}(\delta) = \sum_{i,j=2,11,12} k_{ij}(\delta)\left[c_i'^2 + c_i'^2\right] + k_{12,12}(\delta)\left[c_{11}^{(1)} c_{12} + c_{12}^{(1)} c_{11}^{(1)}\right]$. The values of $c_i'$ and $k_{ij}(\delta)$ can be obtained by using the expressions given in Ref. \[11\]. We use $\delta = 90\%$ which gives $Br(B \to X_S \gamma) \approx 3.5 \times 10^{-4}$, which is consistent with the data and the complete NLO QCD results in Ref. \[12\].

Although experimentally CP asymmetry in $B \to X_S \gamma$ has not been well established, there are constraints from experiments with $0.005 \pm 0.036$ \[2\]. 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
\[A_{X_S \gamma} = \frac{1}{|c_{12}^{SM}|^2} \left[a_{27} \text{Im}[c_2^{SM} c_{12}^{SM*}] + a_{28} \text{Im}[c_2^{SM} c_{11}^{SM*}] + a_{29} \text{Im}[c_1^{SM} c_{12}^{SM*}]\right]. \]

From Ref. \[11\], we find $a_{27} \sim -9.5\%, a_{27} \sim 1.06\%$, and $a_{28} \sim 0.16\%$. For the calculation of $A_{CP}(B \to X_S \gamma)$ in SUSY model considered here, one just replaces $c_{11,12}^{(1)}$ by the total $c_{11,12}$ and adds a term $a_{27} \text{Im}[c_{11}^{SM} c_{12}^{SM*}]$ to the numerator and $|c_{12}^{SM})^2$ to the denominator in the above equation.

Using the above, deviations of $c_{11,12}^{(1)}$ from the SM values are severely constrained. In Figure 1 we show the allowed ranges for the absolute values of $\delta_{LR,RL}^{bs}$ and their phases $\tau$ for $m_{\tilde{g}} = 300\text{GeV}$ and $m_3$ in the range $100 \sim 1000\text{GeV}$ at the one $\sigma$ level. We find that the constraints from $Br(B \to X_S \gamma)$ are slightly more stringent than those from $A_{CP}(B \to X_S \gamma)$. Using the allowed parameters, one can obtain the allowed $c_{11}^{(1)}$ through Eq. 4 and to study implications for other rare $B$ decays. The allowed ranges for $\delta_{LR}^{bs}(\tau R)$ and $\delta_{RL}^{bs}(\tau L)$ are correlated in general.

![FIG. 1: The one $\sigma$ allowed ranges for the SUSY parameters $\delta_{LR,RL}^{bs}$ and the phase $\tau$ taking $m_{\tilde{g}} = 300\text{GeV}$ and $m_3$ in the range $100 \sim 1000\text{GeV}$. The light-dark dotted areas are the allowed parameter spaces from $Br(B \to X_S \gamma)$ and $A_{CP}(B \to X_S \gamma)$ constraints. The dark dotted areas are allowed ranges by $A_{CP}(B^0 \to K^- \pi^0)$ constraint. Figure 1a (on the left) and Figure 1b (on the right) are for the dipole operators with $1 + \gamma_5$ and $1 - \gamma_5$, respectively.](image-url)
where $G_{K\pi} = \int_0^1 \phi_K(x) dx \big/ (1 - x) + R_K$. $R_K = 2m_K^2/m_{\pi} m_b$, 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 [1]. With the SM amplitudes obtained and the default values for the hadronic parameters used in Ref. [3], we obtain the CP asymmetry $A_{CP}(B^0 \rightarrow K^-\pi^+)$ in the SM to be 0.15. This is different in sign with the experimental value. When SUSY dipole interactions are included the experimental value can be reproduced. For example $m_\tilde{q} = m_\tilde{\bar{q}} = 300$GeV, $\delta_{LR} = 2.62 \times 10^{-3} e^{0.238i}$, $\delta_{RL} = 4.31 \times 10^{-3} e^{0.006i}$ the asymmetry $A_{CP}(B^0 \rightarrow K^-\pi^+)$ is approximately $-0.141$. Using the same set of SUSY parameters, we have $Br(B \rightarrow X_s\gamma) = 3.48 \times 10^{-4}$, $A_{CP}(B \rightarrow X_s\gamma) = 0.016$. It is clear that the CP asymmetry $A_{CP}(B^0 \rightarrow K^-\pi^+)$ can be brought to be in agreement with data at one $\sigma$ 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 Figure 1 the parameter space allowed from $A_{CP}(B^0 \rightarrow K^-\pi^+)$ (the dark dotted areas) on top of the allowed ranges by $B \rightarrow X_s\gamma$ constraint alone at the one $\sigma$ level. We see that the CP asymmetry in $B^0 \rightarrow K^-\pi^+$ considerably reduces the allowed parameter space.

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

![FIG. 2: The allowed CP asymmetries in $B^- \rightarrow \bar{K}^0\pi^-$, $B^- \rightarrow K^-\pi^0$ and $B^0 \rightarrow K^0\pi^0$.](image)

We finally study time dependent CP asymmetries in $B \rightarrow K^{*}\gamma \rightarrow \pi^0K_S\gamma$ and $B \rightarrow \phi K_S$. 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, $A_{CP}^{f_{\bar{B}}}(t) = A_f \cos(\Delta t m_B) + S_f \sin(\Delta t m_B)$. The parameters $A_f$ and $S_f$ are related to the decay amplitudes as

$$A_f = \frac{\left|\lambda_f\right|^2 - 1}{\left|\lambda_f\right|^2 + 1}, \quad S_f = -\frac{2Im[(q_{B}/p_B)\lambda_f]}{|\lambda_f|^2 + 1}, \quad (7)$$

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

For $B^0 \rightarrow K^{*}\pi^0 \rightarrow \pi^0K_S\gamma$ and $B^0 \rightarrow K^{*}\gamma \rightarrow \pi^0K_S\gamma$, we have

$$S_{K^*\gamma} = -\frac{2Im[(q_{B}/p_B)\lambda_f(c_{12}c_{12}')] }{c_{12}^2 + |c_{12}'|^2}. \quad (8)$$

To the leading order $A_{K^*\gamma}$, is the same as $A_{CP}(B \rightarrow X_s\gamma)$. Note that the hadronic matrix element $<K^*|\bar{s}_u\bar{}\mu^0(1 \pm \gamma_5)b|B>$ does not appear, which makes the calculation simple and reliable. In order to have a non-zero $S_{K^*\gamma}$ both $c_{12}$ and $c_{12}'$ cannot be zero.

In the SM the asymmetries $A_{K^*\gamma}$ and $S_{K^*\gamma}$ are predicted to be small with $A_{K^*\gamma}^{SM} \approx 0.5\%$, $S_{K^*\gamma}^{SM} \approx 3\%$ [11, 12]. With SUSY gluonic dipole interaction, the predictions for these CP asymmetries can be changed dramatically [12]. 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 $q_B/p_B = e^{-2\beta}$.

A large gluonic dipole interaction also has a big impact on $B \rightarrow \phi K_S$ decays [12]. 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 $B \rightarrow \phi K_S$ 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 [11]. To obtain concrete values, we again use QCD factorization to evaluate the amplitude. We obtain the contributions of $c_{11}$ and $c_{11}'$ to $B \rightarrow \phi K_S$ amplitude to be

$$G_F \frac{m_\phi f_\phi F_1^{B \rightarrow K^0}(m_\phi^2) e_{\phi}^\mu \cdot (P_B + P_K)(c_{11} + c_{11}')G_{\phi,11}(9)$$

where $e_{\phi}^\mu$ is the polarization vector of $\phi$. $G_{\phi,11} = -\int_0^1 2\phi(x) dx/(1 - x)$ with $\phi(x)$ 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 $B^0 \rightarrow K^{*}\gamma \rightarrow \pi^0K_S\gamma$ and $B^0 \rightarrow \phi K_S$. The results are shown in Figure 3. The current values of $S_{K^*\gamma}$ and $A_{K^*\gamma}$ from Babar (Belle) are: 0.57 $\pm$ 0.32 $\pm$ 0.09 $-0.00 \pm 0.38$, 0.25 $\pm$ 0.63 $\pm$ 0.14 $-0.79^{+0.63}_{-0.50}$ $\pm 0.09$, respectively [20]. From Figure 3, we see that the allowed ranges can cover the central values of $S_{K^*\gamma}$, from Babar and Bell, 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) \[22\]. In the model we are considering, the CP asymmetries \(A_{K_{\gamma}}\) and \(A_{CP}(B^\pm \to K^{\pm}\gamma)\) are the same. The results for the charged \(B\) CP asymmetry are consistent with data.

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 \(0.50 \pm 0.25 \pm 0.05 \pm 0.06 (0.06 \pm 0.33 \pm 0.09)\) for \(A_{\phi K_S}\) and \(S_{\phi K_S}\) \[1\] \[21\], respectively. These values are considerably different than the value reported by Belle last year of \(S_{\phi K_S} = -0.96 \pm 0.50 \pm 0.09\) \[23\]. From Figure 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 \(\bar{B}^0 \to K^0 \pi^+\) on SUSY flavour changing interactions. The experimental value for this asymmetry \(-0.114 \pm 0.020\) 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 \(B \to X_{\gamma}\) alone. CP asymmetries in other \(B \to K\pi\) decays are predicted to be sizeable. We also find that the allowed time dependent CP asymmetries \(S_f\) in \(B^\pm \to K^{*}\pi^0\gamma\) and \(B^0 \to \phi K_S\) 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.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China and Specialized Research Fund for the Doctoral Program of Higher Education.

\[\text{FIG. 3: The allowed time dependent CP asymmetries in } B^0 \to K^* \gamma \to K_S \pi^0\gamma \text{ and } B^0 \to \phi K_S.\]
