Electroweak Penguins, Final State Interaction Phases, and CP Violation in $B \longrightarrow K\pi$ Decays

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The recently observed $B^- \longrightarrow K^-\pi^0$, $\bar{K}^0\pi^-$ and $\bar{B}^0 \longrightarrow K^-\pi^+$ decay modes appear to have nearly equal branching ratios. This suggests that tree and electroweak penguins play an important role, and inclusion of the latter improves agreement between factorization calculation and experimental data. The value of γ in the range of $90°-130°$ and $220°-260°$ is favored, while the $\bar{B}^0 \longrightarrow \bar{K}^0\pi^0$ rate is suppressed. Direct CP violation for $B \longrightarrow K\pi$ modes can be large if final state interaction phases are large. [S0031-9007(99)08712-8]

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The CLEO Collaboration has recently made the first observation of the decay $B^- \longrightarrow K^-\pi^0$, with the branching ratio (BR) of $(1.5 \pm 0.4 \pm 0.3) \times 10^{-5}$ [1]. They have also remeasured $\mathcal{B}(\bar{B}^0 \longrightarrow K^-\pi^+) = (1.4 \pm 0.3 \pm 0.2) \times 10^{-5}$ and $\mathcal{B}(B^- \longrightarrow \bar{K}^0\pi^-) = (1.4 \pm 0.5 \pm 0.2) \times 10^{-5}$. Though confirming previous results [2], the central value for the latter has dropped by 40%. The three rates now appear remarkably close to one another. If they are dominated by the strong penguin interaction, then $\mathcal{B}(B^- \longrightarrow K^-\pi^0) \sim 1/2\ \mathcal{B}(B^- \longrightarrow K^-\pi^+)$ is expected. As errors further improve, if $K^-\pi^0 \simeq K^-\pi^+ \simeq \bar{K}^0\pi^-$ still persists, there would be important implications for the interference between the strong penguin, the tree, and especially the electroweak penguin (EWP) interactions [3,4], final state interaction (FSI) phases [4–8], and CP asymmetries (a_{CP}). The isospin related $\bar{B}^0 \longrightarrow \bar{K}^0\pi^0$ decay rate can also be inferred once the other three are precisely known [8,9]. In the following, we carry out an analysis in the standard model (SM). Our conclusions are suggestive and depend on the BRs being close to the present central values.

We decompose the decay amplitudes according to final state isospin [6]. For $B \longrightarrow K\pi$ decays, the $I = 1/2$ and $3/2$ amplitudes are generated in SM by the $\Delta I = 0$ strong penguin and the $\Delta I = 0$, 1 tree and EWP effective Hamiltonians H_0^S, $H_{0,1}^T$, and $H_{0,1}^W$. Denoting the $I = 1/2$ amplitudes generated by $H_{0,1}^j$ as a_1^j, b_1^j and the $I = 3/2$ amplitudes generated by H_1^j as b_3^j, we write the $A_{K\pi}$ amplitudes as

$$A_{K^-\pi^0} = \frac{2}{3}\, b_3 e^{i\delta_3} + \sqrt{\frac{1}{3}}\,(a_1 + b_1)e^{i\delta_1},$$

$$A_{\bar{K}^0\pi^-} = -\frac{\sqrt{2}}{3}\, b_3 e^{i\delta_3} + \sqrt{\frac{2}{3}}\,(a_1 + b_1)e^{i\delta_1},$$

$$A_{K^-\pi^+} = \frac{\sqrt{2}}{3}\, b_3 e^{i\delta_3} + \sqrt{\frac{2}{3}}\,(a_1 - b_1)e^{i\delta_1},$$

$$A_{\bar{K}^0\pi^0} = \frac{2}{3}\, b_3 e^{i\delta_3} - \sqrt{\frac{1}{3}}\,(a_1 - b_1)e^{i\delta_1}, \tag{1}$$

where $a_1 = \sum a_1^j$ with j summed over T, S, and W, and likewise for b_i. Since the dominant strong penguin contributes to a_1 only, one expects $A_{K^-\pi^0} \simeq 1/\sqrt{2}\, A_{K^-\pi^+}$ hence $K^-\pi^0 \simeq 1/2\ K^-\pi^+$. Since the tree amplitude is no more than 20% of the strong penguin amplitude, to account for $K^-\pi^0 \simeq K^-\pi^+$, which violates isospin in the a_1-dominance limit, additional amplitudes such as EWP are called for.

We have made explicit the elastic $K\pi \longrightarrow K\pi$ rescattering phases $\delta_{1,3}$ in Eq. (1), where only $\delta = \delta_3 - \delta_1$ is physically relevant. There are additional phases in a_1^j and $b_{1,3}^j$, such as the CP violating weak phases in Kobayashi-Maskawa (KM) matrix elements, and absorptive parts due to rescattering between different flavored intermediate states with associated KM factors, such as charmless and charmed states, which cannot be absorbed into $\delta_{1,3}$ [3,5,8]. It has been pointed out that FSI phases in B decays do not necessarily decrease with large m_B [7], and inelastic phases may play a more important role. However, these phases cannot be calculated. Lacking reliable calculations, we make the usual approximation of retaining the absorptive part from quark level calculation [10], ignore long distance inelastic phases, and take only the phase δ to model long distance effects [11]. Theoretical estimates for δ have been attempted [7], but we will treat it as a free parameter and try to obtain information from data.

In SM the effective Hamiltonian relevant for Eq. (1) is [12,13]

$$H_{\rm eff} = \frac{G_F}{\sqrt{2}}\Big[V_{ub}V_{us}^*(c_1O_1 + c_2O_2) - \sum_{i=3}^{10}(V_{ub}V_{us}^*c_i^u + V_{cb}V_{cs}^*c_i^c + V_{tb}V_{ts}^*c_i^t)O_i\Big] + \text{H.c.}, \tag{2}$$

where the superscripts u, c, t are for internal quarks. The operators O_i and the Wilson coefficients (WC) c_i^j are given explicitly in Ref. [13]. To obtain exclusive decay amplitudes, one has to evaluate relevant hadronic matrix elements. We use the factorization approximation to estimate the magnitudes, then insert the FSI phases $\delta_{1,3}$ as in Eq. (1). We find

$$\begin{aligned}
a_1^T &= i\,\frac{\sqrt{3}}{4}\,V_{ub}V_{us}^*\;r\left[\frac{c_1}{N}+c_2\right],\\
b_1^T &= i\,\frac{1}{2\sqrt{3}}\,V_{ub}V_{us}^*\;r\left[-\frac{1}{2}\left(\frac{c_1}{N}+c_2\right)+\left(c_1+\frac{c_2}{N}\right)X\right],\\
b_3^T &= i\,\frac{1}{2}\,V_{ub}V_{us}^*\;r\left[\left(\frac{c_1}{N}+c_2\right)+\left(c_1+\frac{c_2}{N}\right)X\right],\\
a_1^S &= -i\,\frac{\sqrt{3}}{2}\,V_{ib}V_{is}^*\;r\left[\frac{c_3^i}{N}+c_4^i+\left(\frac{c_5^i}{N}+c_6^i\right)Y\right],\quad b_1^S=b_3^S=0\\
a_1^W &= -i\,\frac{\sqrt{3}}{8}\,V_{ib}V_{is}^*\;r\left[\left(\frac{c_7^i}{N}+c_8^i\right)Y+\frac{c_9^i}{N}+c_{10}^i\right],\\
b_1^W &= i\,\frac{\sqrt{3}}{4}\,V_{ib}V_{is}^*\;r\left\{\frac{1}{2}\left[\left(\frac{c_7^i}{N}+c_8^i\right)Y+\frac{c_9^i}{N}+c_{10}^i\right]+\left(c_7^i+\frac{c_8^i}{N}-c_9^i-\frac{c_{10}^i}{N}\right)X\right\},\\
b_3^W &= -i\,\frac{3}{4}\,V_{ib}V_{is}^*\;r\left\{\left[\left(\frac{c_7^i}{N}+c_8^i\right)Y+\frac{c_9^i}{N}+c_{10}^i\right]-\left(c_7^i+\frac{c_8^i}{N}-c_9^i-\frac{c_{10}^i}{N}\right)X\right\},
\end{aligned}\tag{3}$$

where $r = G_F f_K F_0^{B\pi}(m_K^2)(m_B^2 - m_\pi^2)$, $X = (f_\pi/f_K)[F_0^{BK}(m_\pi^2)/F_0^{B\pi}(m_K^2)](m_B^2 - m_K^2)/(m_B^2 - m_\pi^2)$, $Y = 2m_K^2/[(m_s + m_q)(m_b - m_q)]$ with $q = u, d$ for $\pi^{\pm,0}$ final states, respectively, and N is the number of effective colors. We have neglected small annihilation contributions. Setting $\delta = 0$, we obtain the usual factorization result where the tree contribution to $A_{\bar{K}^0\pi^-}$ vanish.

For our numerical calculations we use [14] $f_\pi = 133$ MeV, $f_K = 158$ MeV, $F_0^{B\pi}(0) = 0.36$, $F_0^{BK}(0) = 0.41$, assume monopole dependence for $F_0(k^2)$, and use the c_i^j values obtained in Ref. [13]. The WC's are scheme dependent, which should be compensated by hadronic matrix elements evaluated in the same scheme. Unfortunately, there is no reliable way to calcualte the hadronic matrix elements at present. The uncertainties are large for absolute BRs, mainly from form factors, while we have little control of nonfactorizable effects. But rather than aiming at precise predictions, we wish to demonstrate that the measured BRs can be accommodated within uncertainties.

There is an additional uncertainty in a_{CP} from the value q^2 of the momentum squared carried by the virtual gluon, which is not well defined for exclusive processes [5]. Care also has to be taken to include absorptive parts from the gluon propagator. Although the BRs are not very sensitive to the specific value of q^2, the a_{CP}s are sensitive to q^2 when δ is small. Two configurations need to be distinguished. When the pion comes off from the $q'\bar{q}'$ current in the penguin, q^2 should take the value of m_π^2. In case of Fierz transformed operators, the kaon contains the s quark and the $\bar{q}'$ quark. We assume that the two light quarks share the kaon momentum equally, then q^2 is approximately given by $m_b^2/2$, which is favorable for large a_{CP}s when the FSI phase is small. The a_{CP}s obtained this way should be viewed as an upper limit for $\delta = 0$. But for large δ, the choice of q^2 becomes unimportant.

Our results are given in Figs. 1–3, where BRs are averaged over B and $\bar{B}$ decays. We shall first explore the case without EWP contributions. Although the value of γ is still not well determined and is a topic we shall study, we use $\gamma = 64°$ obtained in Ref. [15] for illustration. In Fig. 1(a) we show the dependence of BRs on FSI phase δ. We see that $K^-\pi^0/K^-\pi^+ \sim \bar{K}^0\pi^0/\bar{K}^0\pi^- \sim 1/2$ for all δ, which clearly indicates strong penguin dominance. This is a general feature without EWPs which was pointed out in Ref. [16]. For large δ, the $\bar{K}^0\pi^-$ and $K^-\pi^+$ rates approach each other.

As pointed out some time ago, electroweak penguins are important in some $B \longrightarrow K\pi$ decay modes [3]. Adding the EWP effect, the results are given in Fig. 1(b). The impact is quite visible. Not only the δ dependence is different, but the most salient is that the $K^-\pi^0$ and $K^-\pi^+$ rates become much closer to each other. However, they lie considerably below the $\bar{K}^0\pi^-$ mode, and the splitting reaches maximum at $\delta = 180°$. Clearly the data prefer smaller δ, but larger δ is not ruled out within the errors. For small δ, the $\bar{K}^0\pi^0$ mode is about two to three times smaller than the other three, which agrees with some other estimates [8,9].

It is clear that the branching ratios in Fig. 1 cannot give $K^-\pi^0 \simeq K^-\pi^+ \simeq \bar{K}^0\pi^-$. Can they be brought closer to one another? The BRs depend strongly on γ, which offers an extra handle. We give the result without EWP

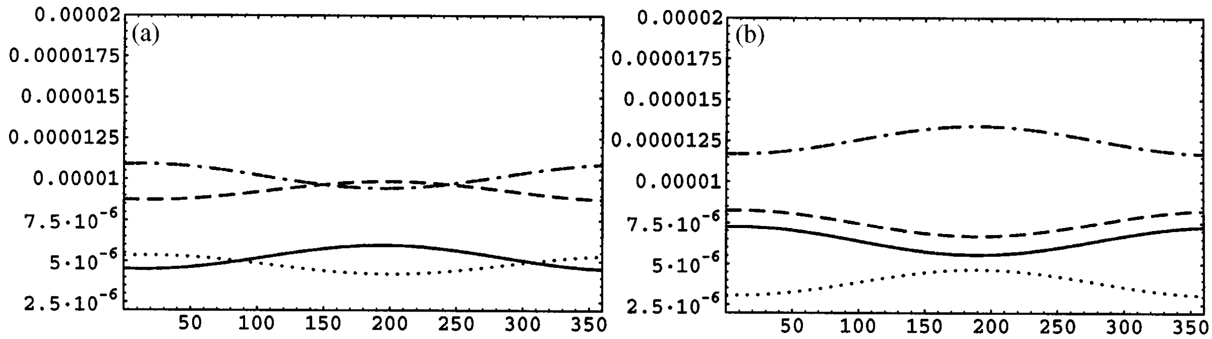

FIG. 1. $\mathcal{B}(B \longrightarrow K\pi)$ vs δ for $\gamma = 64°$ (a) without or (b) with electroweak penguin contributions. In all the figures we use $N = 3$ and $m_s = 200$ MeV. Solid, dot-dashed, dashed, and dotted lines are for $B^- \longrightarrow K^-\pi^0$, $\bar{K}^0\pi^-$ and $\bar{B}^0 \longrightarrow K^-\pi^+$, $\bar{K}^0\pi^0$, respectively.

in Fig. 2(a) for $\delta = 0$. Both $K^-\pi^+$ and $K^-\pi^0$ modes exhibit similar strong dependence on γ. However, they remain widely separated, and $K^-\pi^0 \simeq K^-\pi^+ \simeq \bar{K}^0\pi^-$ still cannot be realized. Turning on EWP contributions, the γ dependence is given in Fig. 2(b). Remarkably, it combines both the nice features of Figs. 1(b) and 2(a): $K^-\pi^0$ and $K^-\pi^+$ rates are close to each other in value. To have the three branching ratios within one standard deviation of the experimental central values, γ is preferred to be in the ranges of 90°–130° and 220°–260°. The branching ratios are large enough such that there is no need to scale up the form factors, but $K^-\pi^0$ is never larger than $K^-\pi^+$. The corresponding $\bar{K}^0\pi^0$ rate is typically three times smaller. Note that the method proposed to constrain γ from $K^-\pi^+/\bar{K}^0\pi^-$ [17] is no longer useful since the ratio is now almost one. However, the near equality of the three observed BRs favors [18] γ in the range of 90°–130° and 220°–260° when EWP effects are included.

A direct way of measuring the strength of the electroweak penguin is to observe modes such as $B \longrightarrow K^{(*)}\ell^+\ell^-$ [19] or $\bar{B}_s \longrightarrow \pi(\eta, \phi)$ [20], but these rates are small and not yet measured. The study of $B \longrightarrow K\pi$ modes thus provide a more practical method of probing EWP effects through interference.

Direct CP violating partial rate asymmetries are of great interest. In Fig. 3(a) we show the γ dependence with $\delta = 0$, where we now always include EWPs. The a_{CP}s can be as large as 13% for $K^-\pi^+$ and 8% for $K^-\pi^0$, but they are small for both $\bar{K}^0\pi^-$ and $\bar{K}^0\pi^0$ because the tree contribution to the former is zero and the latter is color suppressed. In Fig. 3(b) we show the dependence of the a_{CP}s on δ for $\gamma = 120°$, a typical value in the preferred range suggested by $K\pi$ data. Results for $\gamma = 64°$ and 240° are qualitatively similar. For δ around 10°–20° as suggested by some theoretical calculations [7], the a_{CP}s vary considerably. If the phase δ turns out to be large, a_{CP}s can be as large as –20% to 40%, with charged and neutral kaon modes typically having opposite sign. However, large δ values would again split the $\bar{K}^0\pi^-$ mode upwards from the other two observed modes, although $|\delta| < 60°$ is still allowed.

To see how nonfactorizable effects may affect our results, we vary the effective number of colors N. We find that a smaller N lowers the BRs but brings them closer to each other. Since the value of m_s is not well known, we note that a smaller m_s enhances the strong penguin contribution and tends to enforce $K^-\pi^0 \sim 1/2\ K^-\pi^+$ [16]. At present $1/N$ between $1/2$ to zero and m_s between 100 to 200 MeV are allowed by data.

The a_{CP}s discussed above depend strongly on δ. If the rate differences for all $K\pi$ modes are measured, one can observe CP violation involving only $I = 1/2$ amplitudes. This is in contrast with the kaon system where, in order to have rate asymmetry, there must be at least two isospin amplitudes [21]. Let us define

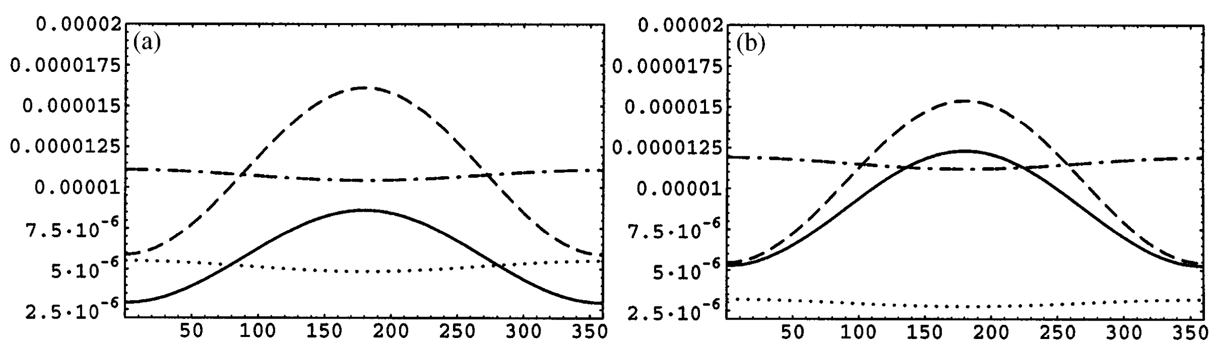

FIG. 2. As in Fig. 1 but vs γ for $\delta = 0$.

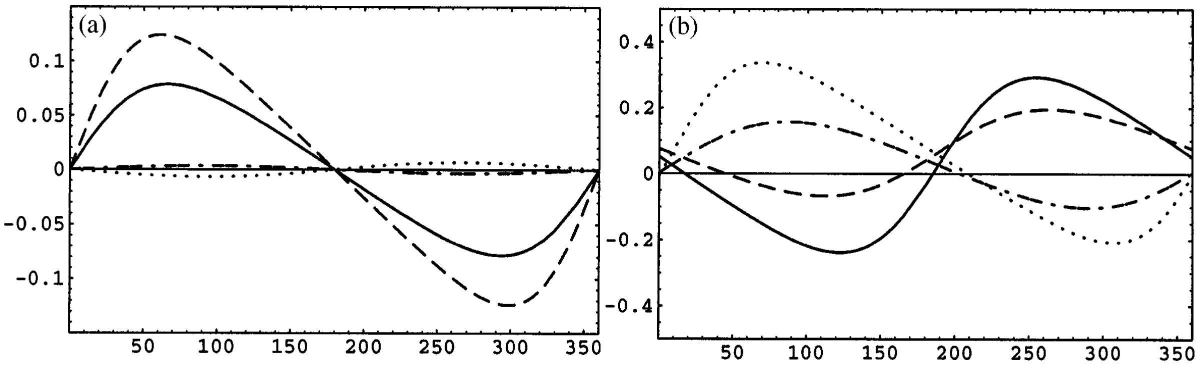

FIG. 3. $a_{CP}(B \longrightarrow K\pi)$ with EWP contributions (a) vs γ for $\delta = 0$ and (b) vs δ for $\gamma = 120°$.

$$\Delta = \Delta_{K^-\pi^0} + \Delta_{\bar{K}^0\pi^-} - \Delta_{K^-\pi^+} - \Delta_{\bar{K}^0\pi^0} \sim |a_1 + b_1|^2 - |\bar{a}_1 + \bar{b}_1|^2 - |a_1 - b_1|^2 + |\bar{a}_1 - \bar{b}_1|^2, \quad (4)$$

where Δ_{ij} is the rate difference between B and $\bar{B}$ decays, and barred amplitudes refer to antiparticles. Note that Δ is free from δ. Normalizing to $\Gamma \equiv (\bar{B}^0 \longrightarrow K^-\pi^+)$, we find that the quark level calculation gives Δ/Γ around -5% (-3%) for $\gamma = 64°(120°)$. This measurement also serves as a test for any additional relative phase between a_1 and b_1 as could arise from long distance inelastic FSI. For example, putting an additional CP conserving phase [11] of $20°, 70°, -20°, -70°$ in a_1, the value Δ/Γ is about -12%, -19%, 4%, 18% $(-8\%, -18\%, 2.4\%, 14\%)$ for $\gamma = 64°(120°)$.

In conclusion, the present data on $B \longrightarrow K\pi$ decay modes suggest that the electroweak penguins are important. Without them the $\bar{B} \longrightarrow \bar{K}^0\pi^-$ or $K^-\pi^+$ rates would be considerably higher than that of $K^-\pi^0$. The present experimental data still allow a FSI phase δ up to $60°$. CP violation in $\bar{B} \longrightarrow K^-\pi^0$, $\bar{K}^0\pi^-$, $K^-\pi^+$, and $\bar{K}^0\pi^0$ modes can be as large as 30%, 15%, 25%, and 40%, respectively, with characteristic sign correlations.

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