Prospects for Direct $CP$ Violation in Exclusive and Inclusive Charmless $B$ decays

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Abstract

Within the Standard Model, $CP$ rate asymmetries for $B \to K^-\pi^+\pi^0$ could reach 10%. With strong final state phases, they could go up to 20-30%, even for $\bar{K}^0\pi^-$ mode which would have opposite sign. We can account for $K^-\pi^+$, $\bar{K}^0\pi^-$ and $\phi K$ rate data with new physics enhanced color dipole coupling and destructive interference. Asymmetries could reach 40-60% for $K\pi$ and $\phi K$ modes and are all of the same sign. We are unable to account for $K^-\pi^0$ rate.

Our inclusive study supports our exclusive results.

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Half a dozen charmless two body $B$ decays appeared in 1997 \cite{1}, suggesting that loop induced $b \to s$ penguin processes are prevalent. Recently, the $\bar{K}^0\pi^-$ rate has come down, and the $K^-\pi^0$ mode has just been observed \cite{2}. Together with $K^-\pi^+$, all three modes are now $\simeq 1.4 \times 10^{-5}$, with error bars of order 30\%. The limit on the pure penguin mode $B \to \phi K < 0.5 \times 10^{-5}$, however, is rather stringent. At present, one has $\mathcal{O}(10)$ events per observed mode. As B Factories turn on at SLAC and KEK and with the CLEO III upgrade at Cornell, these numbers should increase to $\mathcal{O}(10^2)$ per experiment in two years, and to $\mathcal{O}(10^3)$ within five years at the B Factories. Many new modes would also emerge. Equally crucial, one would finally have event by event $K/\pi$ separation. Thus, direct CP violating rate asymmetries ($a_{CP}$) at 30\% and down to 10\% levels can be probed in the above time frame. It is of importance to know whether such large $a_{CP}$s are possible, and, if observed, whether they would signal the presence of new physics.

Within the Standard Model (SM), $a_{CP}$ for $b \to s$ modes are suppressed by \cite{3}

$$\text{Im}(V_{us}V_{ub}^*)/(V_{cs}V_{cb}^*) \simeq \eta \lambda^2 < 1.7\%,$$

where $\lambda \equiv |V_{us}|$ and $\eta < 0.36$ is the single CP violating parameter in the Wolfenstein parametrization of the Kobayashi-Maskawa (KM) matrix. Asymmetries need not be small, however, when both tree and penguins contribute, such as for $\bar{B}^0 \to K^-\pi^+$ mode, where destructive interference could lead to $a_{CP} \sim 10\%$. If final state interaction (FSI) phases are present, $a_{CP}$s could even reach beyond 20\%. But, as we will show, a combined study of several modes can distinguish between FSI phases or the presence of new physics. In contrast, pure penguin $b \to s\bar{s}s$ modes have only one single amplitude, and within SM the $\sim \eta \lambda^2$ suppression cannot be evaded. They are hence sensitive probes of new physics phases. The observation of $a_{CP}$ above the 10\% level in these modes would be striking evidence for physics beyond SM.

We shall study both exclusive and inclusive $a_{CP}$s for charmless $b(p_b) \to s(p_s)\bar{q}(p_q)q(p_q)$ decays, starting from the effective Hamiltonian

$$H_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \left[ V_{ub}V_{us}^*(c_1O_1 + c_2O_2) - V_{ib}V_{is}^* c_j^j O_j \right],$$

where $i$ is summed over $u, c, t$ and $j$ is summed over 3 to 8, with operators defined as
\[ O_1 = \bar{u}_\alpha \gamma_\mu L b_\beta \bar{s}_\beta \gamma^\mu L u_\alpha, \quad O_2 = \bar{w}_\mu Lb \bar{s}_\gamma \gamma^\mu Lu, \quad O_{3,5} = \bar{s}_\mu Lb \bar{q}_\gamma \gamma^\mu L(R)q, \]
\[ O_{4,6} = \bar{s}_\alpha \gamma_\mu L b_\beta \bar{q}_\beta \gamma^\mu L(R)q_\alpha, \quad \hat{O}_8 = \frac{\alpha_s}{4\pi} \bar{s}_i \sigma_\mu \Sigma q b q'^\nu \frac{m_b q'^\nu}{q^2} Rb \bar{q'} T^\alpha T^q q, \]

where \( \hat{O}_8 \) arises from the dimension 5 color dipole \( O_8 \) operator, and \( q = p_b - p_s \). We have neglected electroweak penguins for simplicity. The Wilson coefficients \( c_j \) are evaluated to NLO order in regularization scheme independent way, for \( m_t = 174 \text{ GeV}, \alpha_s(m_Z^2) = 0.118 \) and \( \mu = m_b = 5 \text{ GeV} \). Numerically \([3]\), \( c_{1,2} = -0.313, 1.150, c_{3,4,5,6} = 0.017, -0.037, 0.010, -0.045 \), and \( c_8^{\text{SM}} = c_8^t - c_8^c = -0.299 \). For absorptive parts, we add \( c_4^{u,c}(q^2) = -N c_3^{u,c}(q^2) = -P^{u,c}(q^2) \) for \( c \) and \( u \) quarks in the loop, where \( 8\pi P^{u,c}(q^2) = \alpha_s c_2(10/9 + G(m_{u,c}^2, q^2)) \), and \( G(m^2, q^2) = 4 \int x(1 - x) dx \ln (m^2/\mu^2 - x(1 - x)q^2/\mu^2) \). To respect CPT and unitarity at \( \mathcal{O}(\alpha_3^2) \), one must properly \([3]\) include the absorptive part of the gluon propagator for the \( b \rightarrow s\bar{u}u \) mode. Hence, for \( c_{3-8} \) at \( \mu \) below \( m_b \), we substitute \( 4\pi \text{ Im } c_3(q^2) = \alpha_s c_8 \sum_{u,d,s,c} \text{ Im } G(m_t^2, q^2) \), and \( 8\pi \text{ Im } c_4^{u,c} = -8\pi N \text{ Im } c_{3,5}^{u,c} = \alpha_s[c_3^{u,c} \text{ Im } G(m_s^2, q^2) + (c_4^{u,c} + c_6^{u,c}) \sum_{u,d,s,c} \text{ Im } G(m_t^2, q^2)] \), but only when these interfere with the tree amplitude.

We use the \( \hat{O}_8 \) operator to illustrate the possibility of new physics induced \( a_{CP} \). Although \( b \rightarrow s g \) (with \( g \) “on-shell” or jet-like) is only \( \sim 0.2\% \) in SM, data actually still allows \([3]\) it to be \( \sim 5\%-10\% \), which would help alleviate \([3]\) the long-standing low charm counting and semileptonic branching ratio problems. The recent discovery of \([7]\) a surprisingly large semi-inclusive charmless \( B \rightarrow \eta' + X_s \) decay could also be \([3]\) hinting at \( |c_8| \sim 2 \). Such a large dipole coupling would naturally carry a \( KM\text{-independent } \)CP violating phase, \( c_8 = |c_8| e^{i\sigma} \), and \( a_{CP} \sim 10\% \) in the \( m_{X_s} \) spectrum of \( B \rightarrow \eta' + X_s \) is possible. It is clear that such a new phase could lead to large \( a_{CP} \) in a plethora of \( b \rightarrow sqq \) modes \([3]\).

The theory of exclusive rates is far from clean. One needs to evaluate all possible hadronic matrix elements of products of currents. Faced with recent CLEO data, many theorists have advocated \([8]\) the use of \( N_{\text{eff}} \neq 3 \) as a process dependent measure of deviation from factorization, which becomes a mode by mode fit parameter. One still has to assume form factors and pole values, and, for \( a_{CP} \) evaluation, the \( q^2 \) value to take. The latter is further clouded by FSI phases. Even with such laxity, there are problems \([10]\) already in accounting
for observed rates. The $\eta'K$ and $\omega K$ modes appear to be high, while the yet to be observed $\phi K$ mode seems too low and hard to reconcile with large $\eta'K$. We refrain from studying $B \to \eta'K$ as it probably has much to do with the anomaly mechanism.

Our central theme is whether large $a_{CP}$ is possible in $b \to s$ modes, and, if so, how would they signal the presence of new physics, such as enhanced $c_8$. We find that SM alone allows for sizable $a_{CP}$ in $K\pi$ type of modes. This is important for the early observability of $a_{CP}$s, so let us first investigate the $K\pi$ modes.

The $K^−\pi^+$ mode receives both tree and penguin $b \to s\bar{u}u$ contributions, hence we separate into two isospin amplitudes, $A = A_{1/2} + A_{3/2}$. Since color allowed amplitudes dominate, we take $N_{eff} \simeq N = 3$. Assuming factorization we find,

$$A_{1/2} = \frac{G_F}{\sqrt{2}} f_K F_0 (m_B - m_\pi^2) \left\{ V_{us}^* V_{ub} \left[ \frac{2}{3} \left( \frac{c_1}{N} + c_2 \right) - r \left( \frac{c_1}{N} + \frac{c_2}{N} \right) \right] ight. - V_{js}^* V_{jb} \left[ \frac{c_3^2}{N} + c_4^2 \right. + \frac{2m_K^2}{(m_b - m_u)(m_d + m_u)} \left( \frac{c_5^2}{N} + c_6^2 \right) + \frac{\delta_{ij} \alpha_s m_b^2}{4\pi q^2} c_8 \tilde{S}_{\pi K} \right\},$$

(2)

and for $A_{3/2}$ one sets $c_{3,8} \to 0$ and 2/3, $-r/3 \to 1/3, r/3$. Here, $F_0 = F_{B\pi}^0 (m_K^2)$ is a BSW form factor, $\tilde{S}_{\pi K} \sim -0.76$ is a complicated form factor normalized to $F_0$ coming from the matrix element of $\tilde{O}_8$ (with further assumptions), and $r = f_\pi F_0^{B\pi} (m_\pi^2)(m_B - m_\pi^2)/f_K F_0^{B\pi} (m_\pi^2)(m_B - m_\pi^2)$. The $K^−\pi^0$ mode is similar, with changes in $A_{3/2}$ and an overall factor of $1/\sqrt{2}$. Since penguins contribute only to $A_{1/2}$, for $B^- \to \bar{K}^0\pi^-$ one has just Eq. (2) with $c_{1,2} \to 0$. Note that the $c_{5,6}$ terms are sensitive to current quark masses because of effective density-density interaction. The impact of the $c_8$ term is small in SM.

The absorptive parts for $c_{3-8}$ is evaluated at some $q^2$ for the virtual gluon. We take $q^2 \approx m_b^2/2$ which favors large $a_{CP}$, but it could be as low as $m_b^2/4 \ [3]$. In usual convention, the dispersive part of second term of Eq. (2) is negative, while the sign of first term depends on $\cos \gamma$ (or, Wolfenstein’s $\rho$) where $\gamma = \arg (V_{ub}^* V_{us})$. For $\cos \gamma > 0$ which is now favored, $a_{CP}$ is enhanced by destructive interference, but for $\cos \gamma < 0$ the effect is opposite [3]. This can be seen in Fig. 1(a) and (b) where we plot the branching ratio ($B_r$) and $a_{CP}$ vs. $\gamma$. For $K^-\pi^{+0}$, $a_{CP}$ peaks at the sizable $\sim 10\%$ just at the currently favored $[12]$ value of $\gamma \approx 64^\circ$. But for $\bar{K}^0\pi^-$, $a_{CP} \sim \eta\lambda^2$ is very small. We have used $m_s(\mu = m_b) \approx 120$ MeV [13] since
it enhances the rates. With \( m_s (\mu = 1 \text{ GeV}) \simeq 200 \text{ MeV} \), the rates would be a factor of 2 smaller. We find \( K^-\pi^+, \bar{K}^0\pi^- \), \( K^-\pi^0 \sim 1.4, 1.6, 0.7 \times 10^{-5} \), respectively. The first two numbers agree well with experiment [4], but \( K^-\pi^0/\bar{K}^0\pi^- \sim (1/\sqrt{2})^2 \) seems too small.

As noted some time ago [3], the \( K\pi \) modes are sensitive to FSI phases of the two isospin amplitudes. If the FSI phase difference \( \delta \) is large, it could easily overwhelm the meager perturbative absorptive parts controlled by “\( q^2 \)”.

Neglecting an overall phase, we write \( A = A_1/2 + A_3/2 e^{i\delta} \) and plot in Fig. 1(c) and (d) the \( B_r \) and \( a_{CP} \) vs. \( \delta \) for \( \gamma = 64^\circ \). The rate is not sensitive to \( \delta \) which reflects penguin dominance over tree, but \( a_{CP} \) can now reach 20%, even reaching 30% for \( K^-\pi^0 \). We stress that the \( \bar{K}^0\pi^- \) mode is in fact also quite susceptible to FSI phases, as it is the isospin partner of \( K^-\pi^0 \) which does receive tree contributions. When \( \delta \neq 0 \), tree contributions enter \( B^- \to \bar{K}^0\pi^- \) through FSI rescattering. Comparing Fig. 1(b) and (d), \( a_{CP} \) in this mode can be much larger than naive expectations. However, being out of phase with \( K^-\pi^+ \), comparing the two cases can give information on \( \delta \).

To illustrate physics beyond SM, we keep \( N = 3 \) but set \( c_8 = 2 e^{i\sigma} \). Since the \( c_8 \) term now dominates, the results are not very sensitive to the FSI phase \( \delta \). We plot in Fig. 1(e) and (f) the \( B_r \) and \( a_{CP} \) vs. the new physics phase \( \sigma \), for \( \gamma = 64^\circ \) and \( \delta = 0 \). The \( K^-\pi^+ \) and \( \bar{K}^0\pi^- \) modes are very close in rate for \( \sigma \sim 45^\circ - 180^\circ \), but the \( K^-\pi^0 \) mode is still a factor of 2 too low. However, the \( a_{CP} \) can now reach 50% for \( K^-\pi^+/\bar{K}^0\pi^- \) and 40% for \( K^-\pi^0 \)!

These are truly large asymmetries and would be easily observed soon. They are in strong contrast to the SM case with FSI phase \( \delta \), Fig. 1(d), and can be distinguished.

Genuine pure penguin processes arising from \( b \to s\bar{s}s \) give cleaner probes of new physics \( CP \) violation effects. The amplitude for \( B^- \to \phi K^- \) decay is

\[
A(B \to \phi K) \simeq -i G_F f_\phi m_\phi \sqrt{2} p_B \cdot \epsilon_\phi F_1 (m_\phi^2) V_{js}^* V_{jb} \left\{ \left( c^j_3 + c^j_4/N + c^j_5 \right) \right|_{q_2^2} + \left( c^j_3/N + c^j_4 + c^j_6/N \right) \right|_{q_1^2} + \delta_{jt} \alpha_s m_b^2 c_8 \tilde{S}_\phi /4\pi q_1^2 \right. \right)
\]

The annihilation contributions which we have neglected are small, and the tree annihilation contributions are further suppressed by the KM factor. We have also dropped the color octet contributions and have checked that they are small. The relevant \( q^2 \) is determined by
kinematics: \( q_1^2 = m_b^2 / 2 \) as before, but for amplitudes without Fierzing \( q_2^2 = m_\phi^2 \). Since the amplitude is now basically pure penguin, \( c_8 \) should have no absorptive part. As seen from Fig. 1(a) and (b), the SM rate of \( \sim 1 \times 10^{-5} \) is a bit high while \( a_{CP} \) is unmeasurably small. For \( c_8 = 2e^{i\sigma} \), the results are plotted in Fig. 1(e) and (f) vs. \( \sigma \). The rate is lower than the \( \bar{K}^0\pi^-/K^-\pi^+ \) modes because it is not sensitive to \( 1/m_s \). The \( a_{CP} \) could be as large as 60% when \( c_8 \) and the SM amplitude interfere destructively.

One can now construct an attractive picture. As commented earlier, recent studies cannot explain the low \( B \to \phi K \) upper limit. If \( c_8 \) is enhanced and interferes destructively with SM, \( B \to \phi K \) can be brought down to below \( 5 \times 10^{-6} \). The experimentally observed \( \bar{K}^0\pi^- \simeq K^-\pi^+ \) follows from \( c_8 \) dominance, and the \( B_r \) value \( \simeq 1.4 \times 10^{-5} \) which is 2–3 times larger than the \( \phi K \) mode suggests a low \( m_s \) value and slight tunings of BSW form factors. Around \( \sigma \sim 145^\circ \), the rates are largely accounted for, but \( a_{CP} \) for \( \phi K, K^-\pi^+/K^-\pi^0 \) and \( \bar{K}^0\pi^- \) could be enhanced to the dramatic values of 55%, 45% and 35% respectively. We do fail to account for the \( K^-\pi^0 \) rate, which is comparable to the \( \phi K \) mode. We note that, with recalibration of CLEO II data and adding similar amount of CLEO II.5 data, the \( \bar{K}^0\pi^- \) rate came down by 40% [2]! Thus, a \( K^-\pi^0 \) rate lower than the present preliminary result cannot be excluded. If the current result of \( \bar{K}^0\pi^- \simeq K^-\pi^+ \simeq K^-\pi^0 \simeq 1.4 \times 10^{-5} \) persists down to errors of say 15%, the enhanced \( c_8 \) model would be in trouble. From Fig. 1(a) and (c) we see that SM with Eq. (1) also does not suffice, even with FSI phases, and other effective interactions such as electroweak penguins have to be included.

We are barely able to accommodate \( B \to \omega K \). Within SM \( 1/N_{eff} \sim 1 \) is needed to account for \( B \to \omega K \simeq 1.5 \times 10^{-5} \), while for \( 1/N_{eff} \sim 0 \) one accounts for at most only half. With \( c_8 = 2e^{i\sigma} \), we can account for \( B_r \) for both large and small \( N_{eff} \), but not for \( N = 3 \). However, \( a_{CP} \) is never more than a few % and not very interesting.

To gain better understanding, we discuss briefly inclusive \( b \to s\bar{q}q \) decays, where the theory is cleaner. The existence of \( b \to sg \) at lower order implies a \( \log q^2 \) pole for the \( |c_8|^2 \) term, which we simply cut off at \( q^2 \simeq 1 \text{ GeV}^2 \). The pure penguin \( b \to s\bar{d}d \) case is the simplest since \( c_{1,2} \) do not contribute. The results for SM and several \( |c_8| = 2 \) cases
are given in Fig. 2(a) and Table 1. The low $q^2$ pole is not prominent and $a_{CP}$ is indeed small in SM, arising mostly from below $\bar{c}c$ threshold. For enhanced $c_8$, however, both the low $q^2$ pole and the $a_{CP}$ above $\bar{c}c$ threshold become significant. The overall $a_{CP}$ is not much larger than SM case, since the $\bar{u}u$ cut and hence the asymmetry below $\bar{c}c$ threshold is still suppressed by $V^*_{us} V_{ub}$. However, above the $\bar{c}c$ threshold $a_{CP}$ is of order 10–30%, which confirms our exclusive findings, and perhaps can be probed by the partial reconstruction technique developed in Ref. [14]. We note that for the destructive interference case of $\sigma = 3\pi/4$, the rate is comparable to SM and $a_{CP}$ is the largest.

The $b \to s\bar{u}u$ process receives tree contributions also. Keeping $c_1$ and $c_2$ in the calculation, the results are given in Fig. 2(b) and Table 1. We now have to include gluon propagator absorptive parts for $c_{3-8}^t$ terms when they interfere with tree amplitude. As noted in Ref. [3], in SM the $a_{CP}$ tends to cancel between $q^2$ below and above $\bar{c}c$ threshold, but in each domain the $a_{CP}$ could be of order 10%, supporting our $B \to K^-\pi^+\pi^0$ studies. For $|c_8| = 2$, rather large $a_{CP}$ can arise above the $\bar{c}c$ threshold. For $b \to s\bar{s}s$ (Fig. 2(c)) mode, interference with exchange graphs from identical particle effects leads to peculiar shapes and smears out the rate asymmetry to all $q^2$, but the qualitative features are similar to the $b \to s\bar{d}d$ case. Our inclusive results therefore provide qualitative support of our exclusive studies.

We conclude that the prospects are rather bright for observing large $CP$ violating asymmetries in charmless $b \to s$ decays in the near future. Within SM, $a_{CP} \sim 10\%$ for $K^-\pi^+$ and $K^-\pi^0$ for $\gamma \sim 64^\circ$ which is currently favored, but $< 1\%$ for $\bar{K}^0\pi^-$ and $\phi K$. With large FSI phase $\delta$, $a_{CP}$ in $K\pi$ modes can be enhanced to 20–30%, even for the naively pure penguin $\bar{K}^0\pi^-$, but the latter would typically have sign opposite to $K^-\pi^+/K^-\pi^0$. Enhanced color dipole $c_8 \sim 2e^{i\sigma}$ could explain $\bar{K}^0\pi^- \sim K^-\pi^+$, which are split upwards from the $\phi K$ mode by a low $m_s$ value. Destructive interference with $\sigma \sim 145^\circ$ seems to be favored by present data on $K^-\pi^+$, $\bar{K}^0\pi^-$ and $\phi K$. The corresponding $a_{CP}$ would be $\sim 35$–45% for $K\pi$ modes and 55% for $\phi K$, which should be easily observed and rather distinct from SM case with or without FSI phase. We are unable to account for the newly observed $K^-\pi^0$ rate. Noting that the $\bar{K}^0\pi^-$ rate came down recently, we wait for further confirmation of present data.
Our inclusive study of rates and asymmetries support our exclusive findings. Our results on large $a_{CP}$ in charmless $b \to s$ decays can be tested soon at the B Factories.

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TABLE I. Inclusive $B_r$ (in $10^{-3}$)/$a_{CP}$ (in %) for SM and for $c_S = 2e^{i\sigma}$.

|       | SM    | $\sigma = 0$ | $i\pi/4$ | $i\pi/2$ | $i\pi/4$ | $i\pi$ |
|-------|-------|--------------|-----------|-----------|-----------|-------|
| $b \rightarrow s\bar{d}d$ | 2.6/0.8 | 8.5/0.4 | 7.6/3.4 | 5.2/6.5 | 2.9/8.1 | 1.9/0.5 |
| $b \rightarrow s\bar{u}u$ | 2.4/1.4 | 8.1/-0.2 | 7.5/2.6 | 5.5/5.6 | 3.2/8.1 | 2.0/3.5 |
| $b \rightarrow s\bar{s}s$ | 2.0/0.9 | 6.9/0.4 | 6.2/3.2 | 4.4/6.0 | 2.6/7.1 | 1.8/0.4 |
FIG. 1. $Br$ and $a_{CP}$ vs. (a), (b) SM unitarity angle $\gamma$, (c), (d) FSI phase $\delta$ for $\gamma = 64^\circ$, and (e), (f) new physics phase $\sigma$ for $\gamma = 64^\circ$ and $\delta = 0$. Solid, dotted, dashed and dotdashed lines are for $K^-\pi^+$, $\bar{K}^0\pi^-$, $K^-\pi^0$ and $\phi K$ respectively.
FIG. 2. Inclusive branching ratios vs. $y = q^2/m_b^2$ for (a) $b \rightarrow sdd$, (b) $b \rightarrow s\bar{u}u$ and (c) $b \rightarrow s\bar{s}s$ decays (solid) and $\bar{b}$ decays (dashed). The curves with prominent small $y$ tail are for $c_8 = 2e^{i\sigma}$ with $\sigma = \pi/4$ (top), $\pi/2$ (middle), $3\pi/4$ (bottom), while the other is the SM result.