Prospects for Direct *CP* Violation in Exclusive and Inclusive Charmless *B* Decays

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(Received 8 September 1998)

Within the standard model, *CP* rate asymmetries for $B \to K^-\pi^{+,0}$ could reach 10%. With strong final state phases, they could go up to 20%–30%, even for the $\bar{K}^0\pi^-$ mode which would have the opposite sign. We can account for $K^-\pi^+$, $\bar{K}^0\pi^-$, and ϕK rate data with new physics enhanced color dipole coupling and destructive interference. Asymmetries could reach 40%–60% for $K\pi$ and ϕK modes and are all of the same sign. We are unable to account for the $K^-\pi^0$ rate. Our inclusive study supports our exclusive results. [S0031-9007(98)08019-3]

PACS numbers: 13.25.Hw, 11.30.Er, 12.38.Bx, 12.60.–i

Half a dozen charmless two-body B decays appeared in 1997 [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 [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 $\mathcal{O}(10^3)$ in five years. Many new modes would also emerge. Equally crucial, one would finally have event by event K/π 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 important 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 [3] $\mathrm{Im}(V_{us}V_{ub}^*)/(V_{cs}V_{cb}^*) \simeq \eta\lambda^2 < 1.7\%$, where $\lambda \cong |V_{us}|$ 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 the $\bar{B}^0 \to K^-\pi^+$ 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 $b(p_b) \to s(p_s)\bar{q}(p_{\bar{q}})q(p_q)$ decays, starting from the effective Hamiltonian

$$H_{\mathrm{eff}} = \frac{4G_F}{\sqrt{2}}\left[V_{ub}V_{us}^*(c_1O_1 + c_2O_2) - V_{ib}V_{is}^*c_j^iO_j\right], \tag{1}$$

where i is summed over u, c, t and j is summed over 3 to 8, with operators defined as

$$O_1 = \bar{u}_\alpha\gamma_\mu Lb_\beta\bar{s}_\beta\gamma^\mu Lu_\alpha, \qquad O_2 = \bar{u}\gamma_\mu Lb\bar{s}\gamma^\mu Lu,$$
$$O_{3,5} = \bar{s}\gamma_\mu Lb\bar{q}\gamma^\mu L(R)q,$$
$$O_{4,6} = \bar{s}_\alpha\gamma_\mu Lb_\beta\bar{q}_\beta\gamma^\mu L(R)q_\alpha,$$
$$\tilde{O}_8 = \frac{\alpha_s}{4\pi}\,\bar{s}i\sigma_{\mu\nu}T^a\,\frac{m_bq^\nu}{q^2}\,Rb\bar{q}\gamma^\mu T^aq,$$

where $\tilde{O}_8$ 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^i are evaluated to next-to-leading order in a regularization scheme independent way, for $m_t = 174$ GeV, $\alpha_s(m_Z^2) = 0.118$, and $\mu = m_b = 5$ GeV. Numerically [4], $c_{1,2} = -0.313, 1.150$, $c_{3,4,5,6}^t = 0.017, -0.037, 0.010, -0.045$, and $c_8^{\mathrm{SM}} = c_8^t - c_8^c = -0.299$. For absorptive parts, we add $c_{4,6}^{u,c}(q^2) = -Nc_{3,5}^{u,c}(q^2) = -P^{u,c}(q^2)$ for c and u quarks in the loop, where $8\pi P^{u,c}(q^2) = \alpha_sc_2[10/9 + G(m_{u,c}^2, q^2)]$, and $G(m^2, q^2) = 4\int x(1-x)\,dx \times \ln[m^2/\mu^2 - x(1-x)q^2/\mu^2]$. To respect CPT symmetry and unitarity at $\mathcal{O}(\alpha_S^2)$, one must properly [3] include the absorptive part of the gluon propagator for the $b \to s\bar{u}u$ mode. Hence, for c_{3-8}^t at μ below m_b, we substitute $4\pi\,\mathrm{Im}\,c_8(q^2) = \alpha_sc_8\sum_{u,d,s,c}\mathrm{Im}\,G(m_i^2, q^2)$, and $8\pi\,\mathrm{Im}\,c_{4,6}^t = -8\pi N\,\mathrm{Im}\,c_{3,5}^t = \alpha_s[c_3^t\,\mathrm{Im}\,G(m_s^2, q^2) + (c_4^t + c_6^t)\sum_{u,d,s,c}\mathrm{Im}\,G(m_i^2, q^2)]$, but only when these interfere with the tree amplitude.

We use the $\tilde{O}_8$ operator to illustrate the possibility of new physics induced a_{CP}. Although $b \to sg$ (with g "on-shell" or jetlike) is only $\sim 0.2\%$ in SM, data still allow [5] it to be $\sim 5\%$–10%, which would help alleviate [6] the long-standing low charm counting and semileptonic branching ratio problems. The

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recent discovery of [7] a surprisingly large charmless $B \to \eta' + X_s$ decay could also be [8] hinting at $|c_8| \sim 2$. Such a large dipole coupling would naturally carry a KM-independent CP violating phase, $c_8 = |c_8|e^{i\sigma}$, and $a_{CP} \sim 10\%$ in the m_{X_s} spectrum of $B \to \eta' + X_s$ is possible. Clearly, *such a new phase could lead to large a_{CP} in a plethora of $b \to s\bar{q}q$ modes* [9].

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 [10] the use of $N_{\rm eff} \neq 3$ 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 ωK modes appear to be high, while the yet to be observed ϕK 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 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, $A = A_{1/2} + A_{3/2}$. We take $N_{\rm eff} \simeq N = 3$, assume factorization and find

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

and for $A_{3/2}$ [11] one sets $c_{3-8}^j \to 0$ and $2/3, -r/3 \to 1/3, r/3$. Here, $F_0 = F_0^{B\pi}(m_K^2)$ is a form factor, $\tilde{S}_{\pi K} \sim -0.76$ is a form factor normalized to F_0 coming from the matrix element of $\tilde{O}_8$ (with further assumptions), and $r = f_\pi F_0^{BK}(m_\pi^2)(m_B^2 - m_K^2)/f_K F_0^{B\pi}(m_K^2)(m_B^2 - m_\pi^2)$. 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 $c_{1,2} \to 0$. 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}^j are evaluated at some q^2. 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 the usual convention, the dispersive part of the second term of Eq. (2) is negative, while the sign of the first term depends on $\cos\gamma$ 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 Figs. 1(a) and 1(b) where we plot the branching ratio (B_r) and a_{CP} vs γ. For $K^-\pi^{+,0}$, a_{CP} peaks at the sizable $\sim$10% just at the currently favored [12] value of $\gamma \simeq 64°$. But for $\bar{K}^0\pi^-$, $a_{CP} \sim \eta\lambda^2$ is very small. We have used $m_s(\mu = m_b) \simeq 120$ MeV [13] since it enhances the rates. With $m_s(\mu = 1\ \text{GeV}) \simeq 200$ 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, 0.7×10^{-5}, respectively. The first two numbers agree well with experiment [2], but $K^-\pi^0/K^-\pi^+ \sim (1/\sqrt{2})^2$ 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 δ 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 Figs. 1(c) and 1(d) the B_r and a_{CP} vs δ for $\gamma = 64°$. The rate is not sensitive to δ which reflects penguin dominance over tree, but a_{CP} can now reach 20%, even 30% for $K^-\pi^0$. We stress that the $\bar{K}^0\pi^-$ mode is in fact also 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 Figs. 1(b) and 1(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 δ.

To illustrate physics beyond SM, we keep $N = 3$ but set $c_8 = 2e^{i\sigma}$. Since the c_8 term now dominates, the results are not sensitive to the FSI phase δ. We plot in Figs. 1(e) and 1(f) the B_r and a_{CP} vs the new physics phase σ, for $\gamma = 64°$ and $\delta = 0$. The $K^-\pi^+$ and $\bar{K}^0\pi^-$ modes are close in rate for $\sigma \sim 45°$–$180°$, but the $K^-\pi^0$ mode is still a factor of 2 too low. However, a_{CP} can now reach 50% for $K^-\pi^+/\bar{K}^0\pi^-$ and 40% for $K^-\pi^0$. Such large asymmetries would be easily observed soon. They are in strong contrast to the SM case with the FSI phase δ, Fig. 1(d), and distinguishable.

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

$$A(B \to \phi K) \simeq -\,iG_F f_\phi m_\phi \sqrt{2}\, p_B \cdot \varepsilon_\phi F_1(m_\phi^2) V_{js}^* V_{jb}$$
$$\times \{(c_3^j + c_4^j/N + c_5^j)|_{q_2^2} + (c_3^j/N + c_4^j + c_6^j/N)|_{q_1^2} + \delta_{jt}\alpha_s m_b^2 c_8 \tilde{S}_{\phi K}/4\pi q_1^2\}. \tag{3}$$

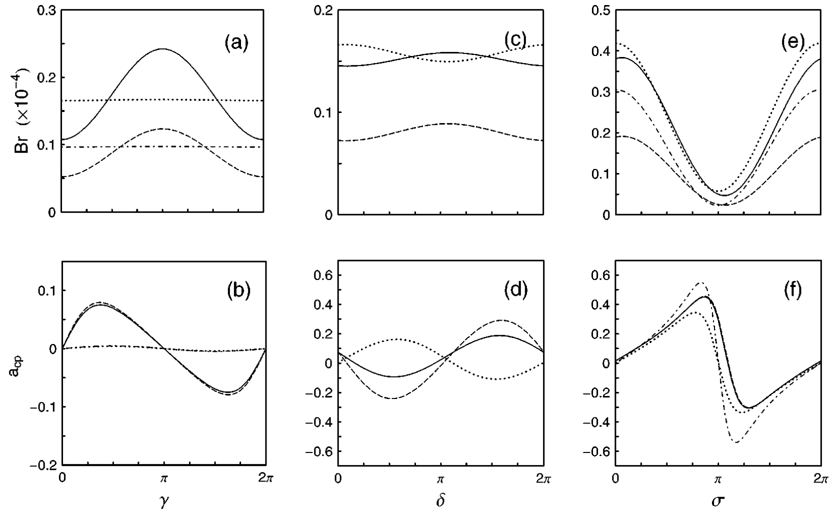

FIG. 1. Br and a_{CP} [(a) and (b)] vs SM unitarity angle γ; (c),(d) FSI phase δ for $\gamma = 64°$; and (e),(f) new physics phase σ for $\gamma = 64°$ and $\delta = 0$. Solid, dotted, dashed, and dot-dashed lines are for $K^-\pi^+$, $\bar{K}^0\pi^-$, $K^-\pi^0$, and ϕK, respectively.

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 Figs. 1(a) and 1(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 Figs. 1(e) and 1(f) vs σ. 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 5×10^{-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 ϕK mode suggests a low m_s value and slight tunings of form factors. Around $\sigma \sim 145°$, the rates are largely accounted for, but a_{CP} for ϕK, $K^-\pi^+/K^-\pi^0$, 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 ϕK mode. We note that, with recalibration of CLEO II data and adding a 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 Figs. 1(a) and 1(c) we see that SM with

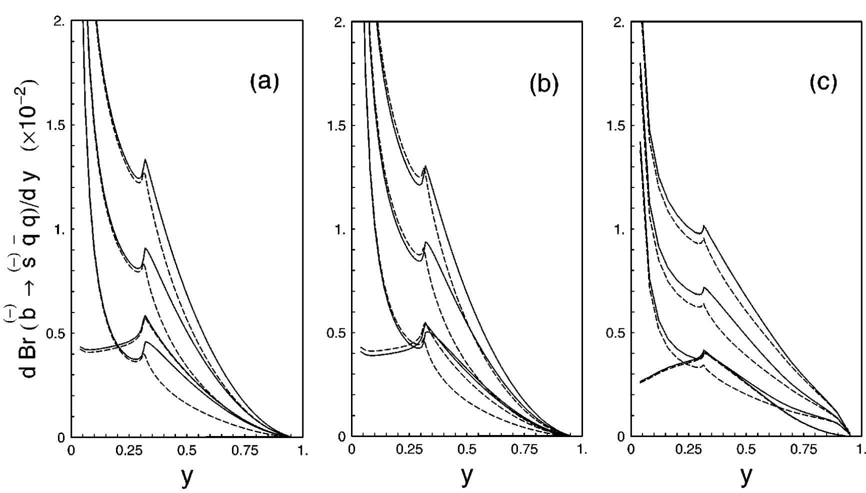

FIG. 2. Inclusive branching ratios vs $y = q^2/m_b^2$ for (a) $b \to s\bar{d}d$, (b) $b \to s\bar{u}u$, and (c) $b \to s\bar{s}s$ decays (solid) and $\bar{b}$ decays (dashed). The curves with prominent small y tail are for $c_8 = 2e^{i\sigma}$ with $\sigma = \pi/4$ (top), $\pi/2$ (middle), and $3\pi/4$ (bottom), while the other is the SM result.

TABLE I. Inclusive B_r (in 10^{-3})/a_{CP} (in %) for SM and for $c_8 = 2e^{i\sigma}$.

SM	$\sigma =$	0	$\frac{i\pi}{4}$	$\frac{i\pi}{2}$	$\frac{i3\pi}{4}$	$i\pi$
$b \to s\bar{d}d$ 2.6/0.8		8.5/0.4	7.6/3.4	5.2/6.5	2.9/8.1	1.9/0.5
$b \to s\bar{u}u$ 2.4/1.4		8.1/−0.2	7.5/2.6	5.5/5.6	3.2/8.1	2.0/3.5
$b \to s\bar{s}s$ 2.0/0.9		6.9/0.4	6.2/3.2	4.4/6.0	2.6/7.1	1.8/0.4

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 $1/N_{\rm eff} \sim 1$ is needed to account for $B \to \omega K \simeq 1.5 \times 10^{-5}$, while for $1/N_{\rm eff} \sim 0$ one accounts for at most only half. With $c_8 = 2e^{i\sigma}$, we can account for B_r for both large and small $N_{\rm eff}$, but not for $N = 3$. However, a_{CP} is never more than a few percent 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 $q^2 \simeq 1$ 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 I. 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 the 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 I. 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 $B \to K^-\pi^{+,0}$ 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 $\gamma \sim 64°$ which is currently favored, but <1% for $\bar{K}^0\pi^-$ and ϕK. With large FSI phase δ, 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 a 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 ϕK mode by a low m_s value. Destructive interference with $\sigma \sim 145°$ seems to be favored by present data on $K^-\pi^+$, $\bar{K}^0\pi^-$, and ϕK. The corresponding a_{CP} would be ~35%–45% for $K\pi$ modes and 55% for ϕK, which should be easily observed and rather distinct from the 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 supports our exclusive findings. Our results on large a_{CP} in charmless $b \to s$ decays can be tested soon at the B Factories.

This work is supported in part by Grants No. NSC 88-2112-M-002-033 and No. NSC 88-2112-M-001-006 of the Republic of China, and by Australian Research Council.

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