What can we learn from $B \to \rho(\omega) K$ decays?

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Abstract

We show that in the PQCD approach the $B \to \rho(\omega) K$ decays display not only the dynamical penguin enhancement, the mechanism responsible for the large branching ratios (BRs) of $B \to \phi K$ decays, but also the importance of annihilation contributions. We find that the CP asymmetries (CPAs) of $B \to \rho^\pm K^{\mp}$, $B^\mp \to \rho^0(\omega) K^{\mp}$ (class I) are all over 50%.

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The study of charmless $B$ meson decays has an enormous progress, since many modes, such as $B \rightarrow \pi \pi$ and $B \rightarrow \pi K$, were measured by CLEO [7], as well as by BABAR [8] and BELLE [9]. Via the search of $B$ decays, we can not only test the origin of CP violation in standard model (SM), which is the consequence of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [10], but also verify various QCD approaches, proposed to deal with hadronic effects in exclusive decays. Recently, the BRs of the modes involving a vector ($V$) meson, such as $B \rightarrow \rho(\omega)\pi$ measured by CLEO [7] and $B^\pm \rightarrow \phi K^\pm$ by the $B$ factories,

$$B^\pm \rightarrow \phi K^\pm = \begin{cases} (5.5^{+2.1}_{-1.8} \pm 0.6) \times 10^{-6} & \text{(CLEO [8])}, \\
(7.7^{+1.6}_{-1.4} \pm 0.8) \times 10^{-6} & \text{(BABAR [9])}, \\
(11.2^{+2.2}_{-2.0} \pm 1.4) \times 10^{-6} & \text{(BELLE [9])} \end{cases}$$

have been also observed. Although the present results of $B^\pm \rightarrow \phi K^\pm$ among the $B$ factories do not match well each other, more accurate measurements will be obtained in the near future. Nevertheless, the theoretical predictions are not consistent either; for instance, the modified perturbative QCD (MPQCD) predicts $(10.2^{+3.9}_{-2.1}) \times 10^{-6}$ [3, 10], but QCD factorization (QCDF) [11] gives $(4.3^{+3.0}_{-1.4}) \times 10^{-6}$ [12]. Therefore, an interesting question is raised: besides $B \rightarrow \phi K$ decays, can we find other processes, that distinguish which QCD approach is proper and correct? or what processes can support either of them? Following the speculation of $B \rightarrow VP$ decays, $P$ being a pseudoscalar meson, we find that it is important to investigate $B \rightarrow V'K$ decays ($V' = \rho$ and $\omega$), because many properties, such as CPAs of over 50% and essential annihilation contributions, are remarkable. Although the $V'$ meson carries spin degrees of freedom, only the longitudinal component contributes. Thus, in order to understand the properties of $B \rightarrow V'K$, it is useful to combine the analysis of $B \rightarrow \pi^-K^+$ and $B^+ \rightarrow \phi K^+$ decays, all of which are described by the $b \rightarrow s$ transition. Note that the pion can be regarded as the longitudinal component of a $\rho$ meson.

The effective Hamiltonian for decays with the $b \rightarrow s$ transition is given by

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{q'=u,c} v_{q'} \left[ C_1(\mu) O_1^{(q')} + C_2(\mu) O_2^{(q')} + \sum_{i=3}^{10} C_i(\mu) O_i \right]$$

(1)

where $V_{q'} = V_{q's} V_{q'b}$ are the products of the CKM matrix elements, $C_i(\mu)$ are the Wilson coefficients (WCs) and $O_i$ correspond to the four-quark operators. The explicit expressions of $C_i(\mu)$ and $O_i$ can be found in Ref.[13]. We can define the evolution variables as

$$a_1 = C_1 + \frac{C_2}{N_c}, \quad a_2 = C_2 + \frac{C_1}{N_c}, \quad a'_1 = \frac{C_2}{N_c}, \quad a'_2 = \frac{C_1}{N_c},$$

$$a_{3,4}^{(q)} = C_{3,4} + \frac{3e_q}{2} C_{9,10} + a^{(q)}_{3,4}, \quad a^{(q)}_{3,4} = \frac{C_{4,3}}{N_c} + \frac{3e_q}{2} C_{10,9},$$

$$a_{5,6}^{(q)} = C_{5,6} + \frac{3e_q}{2} C_{7,8} + a^{(q)}_{5,6}, \quad a^{(q)}_{5,6} = \frac{C_{6,5}}{N_c} + \frac{3e_q}{2} C_{8,7}$$

(2)

where the superscripts $q$ represent the light u, d and s quarks. Note that $a_2$ is larger than $a_1$ and nonfactorizable effects are only associated with the color suppressed variables $a_j^{(q)}$.

For a simple analysis, we first concentrate on $B \rightarrow \rho^-K^+$ decay, because it contains the common properties of $B \rightarrow V'K$ decays. Hence, based on Eq. (1), the decay amplitudes for $B \rightarrow \pi^-K^+$, $B^+ \rightarrow \phi K^+$ and $B \rightarrow \rho^-K^+$ are written as

$$A(B \rightarrow \pi^-K^+) = f_K \left[ V_{t}^{*} \left( a_4^{(u)} + 2r_K a_6^{(u)} \right) - V_{u}^{*} a_2 \right]$$
\[ A(B^+ \rightarrow \phi K^+) = \times F^{B \pi}_e + 2 f_B V^*_t a_6^{(d)} F^{\tau \phi K}_{a6} + \ldots, \tag{3} \]

\[ A(B \rightarrow \rho^- K^+) = f_K \left[ V^*_t \left( a_3^{(s)} + a_4^{(s)} + a_5^{(s)} \right) F^{B \rho K}_e \right. \]
\[ \left. + 2 f_B V^*_t a_6^{(u)} F^{\phi K}_{a6} + \ldots, \tag{4} \right. \]

\[ A(B \rightarrow \rho^- K^+) = f_K \left[ V^*_t \left( a_4^{(u)} - 2 r_K a_6^{(u)} \right) - V^*_u a_2 \right] \times F^{B \rho}_e + 2 f_B V^*_t a_6^{(d)} F^{\rho \phi K}_{a6} + \ldots \tag{5} \]

with \( r_K = m_K^0 / M_B, m_K^0 \) being the chiral symmetry breaking (CSB) parameter associated with the kaon. We present only the dominant and subdominant effects with nonfactorizable effects neglected. However, the complete effects will be included in our numerical calculations. \( f_K, f_\phi \) and \( f_B \) are the decay constants of \( K, \phi \) and \( B \) mesons, respectively. \( F^{B \pi(V)}_e \) denote the \( B \rightarrow P(V) \) form factors, and \( F^{P(V)P}_{a6} \) are the time-like form factors induced by the annihilation contributions from the \((S - P)(S + P)\) four-quark operators. As for \( F^{P(V)P}_{a6} \) generated by the \((V - A)(V - A)\) operators, due to helicity suppression, we do not discuss them. We emphasis that the expressions of \( a_i^{(q)} F^{P(V)P}_{e[a]} \) in Eqs. (3)-(5) are given only for the short-hand convenience. In the MPQCD approach, they are convolutions of \( a_i^{(q)} \) and \( F^{P(V)P}_{e[a]} \) actually. If we apply the idea of QCDF to MPQCD, in the viewpoint of numerical estimation, the \( \mu \) scale of \( a_i^{(q)}(\mu) \) could be fixed at around the scale of 1.7 GeV. The scale is around 2.7 GeV in QCDF.

Although \( C_2 \) is one order of magnitude larger than \( C_4 \) and \( C_6 \), which are the first two largest WCs of QCD penguin, the penguin emission topologies in the \( \pi^- K^+ \) and \( \phi K^+ \) modes are the dominant effects due to the suppression of CKM matrix element \( V_u \approx 1.6 A_\lambda^5 e^{-i\tau} \). The tree and penguin annihilation are subdominant. If taking \( \gamma \approx 90^0 \), the numerical value of Eq. (3) is larger than that of Eq. (1) by an approximate factor of \( \sqrt{1.8} \) and \( \sqrt{3.1} \) with \( \mu \) being fixed at the different scales in MPQCD and QCDF, respectively. As known, the world average BR of \( B \rightarrow \pi^+ K^\pm \) is \( (17.2 \pm 1.5) \times 10^{-6} \). Following the above analysis, we expect the BR of \( \phi K^\pm \) mode is around \( 9.5 \times 10^{-6} \) \((\mu = 1.7 \text{ GeV}) \) and \( 5.5 \times 10^{-6} \) \((\mu = 2.7 \text{ GeV}) \). Clearly, with the information of \( B \rightarrow \pi^\pm K^\pm \) in the present experimental status, we cannot determine the typical QCD scale for heavy-to-light decays, unless more precision measurements on \( B \rightarrow \phi K \) are given.

Different from \( B \rightarrow \pi^- K^+ \) and \( B^+ \rightarrow \phi K^+ \), in terms of Eq. (4), we see that due to the cancellation between the two terms in \( a_4^{(q)} - 2 r_K a_6^{(q)} \), the penguin emission contributions of \( B \rightarrow \rho^- K^+ \) decay are no longer leading. Instead, tree diagram may be the main effects. It is known that \( a_2(\mu) \) is a flat function in \( \mu \). However, \( a_4^{(q)}(\mu) \) and \( a_6^{(q)}(\mu) \) have an enormous enhancement at \( \mu \ll M_B / 2 \). If \( F^{\rho \phi K}_a \) is only few times smaller than \( F^{B \rho}_e \), with the penguin enhancement from \( a_6^{(q)}(\mu) \), the annihilation contributions could possibly become the essential parts in \( B \rightarrow \rho^- K^+ \) decay. Recently, the estimation of annihilation topologies has been proposed by MPQCD and QCDF. Although the basic idea is originated from the Lepage and Brodsky (LB) formalism, in which a transition amplitude can be factorized into the convolution of nonperturbative parts, described by hadron wave functions, and a hard amplitude of valence quarks, dictated by perturbative hard gluon exchanges, both approaches have different description on factorization scale.

It has been known that the original LB formalism suffers singularities from the endpoint region with a momentum fraction \( x \rightarrow 0 \). In the QCDF approach, it is claimed that heavy \( B \) meson decays at the fast recoil region are still dominated by soft gluons, which
are uncalculable perturbatively. As a result, the decay amplitudes for $B$ meson decays are written as $A \sim C(t_0) f_{M_1} F^{BM_2}$ with $t_0 \approx M_B \sim M_B/2$, where $C(t_0)$, $f_{M_1}$ and $F^{BM_2}$ are the relevant wilson coefficient, decay constant of $M_1$ meson and $B \to M_2$ form factor respectively. However, following the concept of PQCD, if the spectator quark of inside $B$ meson, carrying the momentum of order of $\Lambda$ with $\Lambda = M_B - M_b$ and $M_b$ being $b$ quark mass, wants to catch up with the outgoing quark, which is the daughter of $b$ quark decay, to form a hadron, it should need to obtain a large energy from $b$ quark or the daughter of $b$ quark. That is, in contrast to the conclusion of QCF approach, hard gluons actually play an essential role in $B$ meson decays. Therefore, the relevant decay amplitude should be calculable perturbatively and the order of magnitude of typical scale is similar to the momentum of hard gluon approximately, denoted by $\sqrt{\Lambda M_B}$ [23, 24].

Now, how to deal with the problem of singularities is the main part of PQCD. In order to handle these singularities, the strategy of including $k_T$, the transverse momentum of the valence quark, and threshold resummation has been proposed [15]. It has been shown that the singularities do not exist in a self-consistent MPQCD analysis [15]. Additionally, MPQCD gives many interesting results: for example, the $B \to P(V)$ form factors are dominated by perturbative dynamics with $\alpha_s/\pi < 0.2$, the formalism involves less theoretical uncertain parameters that arise from the shape parameter $\omega_B$ in the $B$ meson wave function, CSB parameter $m^0_\rho$ and the parametrization of Sudakov factor from threshold resummation, the penguin contribution is enhanced at a lower typical scale and annihilation topologies contribute large absorptive parts. Especially, according to our power counting rules, the ratios of the transition form factor ($F^{BM_2}$) to the annihilation contributions and to the nonfactorizable contributions are found to be $= 1 : r_K : \Lambda/M_B$ [10]. For $M_B \sim 5.0 \text{ GeV}$, the magnitude of the annihilation amplitude is only less than that of $F^{BM_2}$ by a factor of 3. In the literature, the applications of the MPQCD to the processes of $B \to PP$, such as $B \to K\pi$ [16], $B \to \pi\pi$ [17], $B \to KK$ [18], $B \to K\eta(0)$ [19] and $B \to \rho\eta$ [20], have been studied and found that they are consistent with the experimental data or limits.

Hence, the $B \to \rho$ and time-like form factors, defined as

$$< \rho^- (p_\rho, \epsilon_\rho)|\bar{b} \gamma_5 u|B(p_B)> = 2m_\rho \epsilon_\rho \cdot q F^{BM_2}_\rho,$$

$$< \rho^- (p_\rho)K_+^+(p_K)|\bar{u}\gamma_5 s|0> = 2m_\rho \epsilon_\rho \cdot q F^{OK}_\rho$$

with $q = p_B - p_\rho$, can be explicitly written as

$$F^{BM_2}_\rho = 8\pi C_F M_B^2 \int_0^1 dx_1dx_2 \int_0^\infty b_1 db_1 b_2 db_2$$

$$\phi_B (x_1, b_1) \left\{ [(1 + x_2) \phi_\rho (x_2) + r_\rho (1 - 2x_2) \phi_\rho^\prime (x_2)] E_e \left( t_e^{(1)} \right) h_e (x_1, x_2, b_1, b_2) \right.$$

$$+ [2r_\rho \phi_\rho^\prime (x_2)] E_e \left( t_e^{(2)} \right) h_e (x_2, x_1, b_1, b_2) \left. \right\}$$

$$F^{OK}_\rho = -8\pi C_F M_B^2 \int_0^1 dx_2dx_3 \int_0^\infty b_2 db_2 b_3 db_3$$

$$\left\{ [x_3 r_K \phi_\rho (x_2) \phi_K (x_3) - \phi_\rho^\prime (x_3)] \right.$$

$$+ 2r_\rho \phi_\rho^\prime (x_2) \phi_K (x_3) \left. \right\} E_a \left( t_a^{(1)} \right) h_a (x_2, x_3, b_2, b_3)$$

$$+ [ - r_\rho x_3 \phi_K (x_3)] \left\{ \phi_\rho^\prime (x_2) - \phi_\rho^\prime (x_3) \right.$$

$$+ 2r_\rho \phi_\rho^\prime (x_2) \phi_K (x_3) \left. \right\} E_a \left( t_a^{(2)} \right) h_a (x_3, x_2, b_3, b_2)$$
where \( r_\rho = m_\rho/M_B \), \( m_\rho \) is the \( \rho \) meson mass, \( C_F = 4/3 \) is the color factor, \( x_i \) (\( i = 1, 2, 3 \)) are the momentum fractions carried by the spectator quarks inside the \( B, \rho \) and \( K \) mesons, and the variables \( b_i \) are conjugate to parton transverse momenta \( k_{iT} \). \( \phi_{P(V)}(x) \) denote the twist-2 P(V) meson wave functions, and \( \phi_{P(V)}^{(t)}(x) \) and \( \phi_{P(V)}^{(s)}(x) \) correspond to the pseudoscalar (tensor) and pseudotensor (scalar) twist-3 wave functions, respectively \([10, 23]\). The wave functions are pure nonperturbative effects and universal. In our numerical calculations, we will adopt the results of Refs. \([24, 27]\) derived from QCD sum rules. The explicit expressions of hard functions \( h_e(a) \) are shown as

\[
\begin{align*}
  h_e(x_1, x_2, b_1, b_2) &= K_0 \left( \sqrt{x_1 x_2} M_B b_1 \right) S_t(x_2) \\
  &\times \left[ \theta(b_1 - b_2) K_0 \left( \sqrt{x_2 M_B b_1} \right) I_0 \left( \sqrt{x_2 M_B b_2} \right) \\
  &+ \theta(b_2 - b_1) K_0 \left( \sqrt{x_2 M_B b_2} \right) I_0 \left( \sqrt{x_2 M_B b_1} \right) \right], \\
  h_a(x_2, x_3, b_2, b_3) &= \left( \frac{i\pi}{2} \right)^2 H_0^{(1)}(\sqrt{x_2 x_3 M_B b_2}) S_t(x_3) \\
  &\times \left[ \theta(b_2 - b_3) H_0^{(1)}(\sqrt{x_3 M_B b_2}) J_0(\sqrt{x_3 M_B b_3}) \\
  &+ \theta(b_3 - b_2) H_0^{(1)}(\sqrt{x_3 M_B b_3}) J_0(\sqrt{x_3 M_B b_2}) \right],
\end{align*}
\]

where \( S_t(x) \) is the evolution function from threshold resummation parametrized by \( S_t \approx N_t [x(1-x)]^c \) \([15]\), and \( K_0, I_0, H_0 \) and \( J_0 \) are the Bessel functions. The evolution factors are given by

\[
E_{e(a)}(t) = \alpha_s(t) \exp\left[ -S_{B(K)}(t, x_{1(3)}) - S_\rho(t, x_2) \right],
\]

which contain the Sudakov factor from \( k_T \) resummation \([20, 27]\).

Adopting \( f_B = 0.19, f_\rho = 0.20, f_K = 0.16 \) GeV and with the allowed values of parameters, we obtain \( F_{eB_\rho} = 0.37^{+0.03}_{-0.02} \). Via the same procedure, we get \( F_{eB_K} = 0.35^{+0.04}_{-0.02} \) \([10]\) and \( F_{eB}\pi = 0.3^{+0.03}_{-0.02} \) \([14, 23]\). All of these form factors are consistent with those from light-cone QCD sum rules (LCSR) \([23]\) and quark model (QM) \([23]\). Similarly, the time-like form factor is given by \( F_{a6K} = (-0.46 + 7.4i) \times 10^{-2} \), in which the large absorptive part arises from the on-shell condition of internal light quarks. As expected, the magnitude of \( F_{B_\rho} \) is only larger than that of \( F_{a6K} \) by a factor of 5 in the MPQCD approach. In terms of the above results, from Eq. \( (8) \), if choosing \( \gamma \approx 90^0 \), the contributions of tree and penguin annihilation are comparable but are opposite in sign, such that the BR of \( B \to \rho^- K^+ \) is small. However, via \( V_u \) instead of \( V_{ts} \), we find immediately that the CP conjugate mode \( B \to \rho^+ K^- \) is enhanced. It is interesting to question how large the BR can be pushed up by such enhancement. For estimation, we assume \( F_{a6K} \approx F_{a6K}^{(t)} \) and use the above obtained values, from Eqs. \( (9) \) and \( (10) \), the relation \( |A(B^+ \to \phi K^+)| \sim 1.17 |A(B \to \rho^+ K^-)| \) for \( \gamma \approx 90^0 \) and for \( \mu \approx 1.7 \) GeV is obtained. With \( BR(B^+ \to \phi K^+) \approx 10 \times 10^{-6} \), we get \( BR(B \to \rho^+ K^-) \approx 7 \times 10^{-6} \). Furthermore, due to the destruction between the tree and penguin amplitudes in \( B \to \rho^- K^+ \) decay, one also expects the CPA in \( B \to \rho^+ K^- \) is large.

We have studied the properties of \( B \to \rho^+ K^- \) and found that by the constructive interference between the tree and penguin annihilation topologies, the BR and CPA estimated in the MPQCD are not as small as those expected in Ref. \([30]\). As mentioned before, basically all the modes in \( B \to \rho(\omega) K \) have the similar properties. In addition, for those decays involving \( \rho^0 \) and \( \omega \) mesons that are composed by \( (\bar{u}u - \bar{d}d)/\sqrt{2} \) and \( (\bar{u}u + \bar{d}d)/\sqrt{2} \), respectively, the new terms \( (a_{35}^{(a)} - a_{35}^{(d)}) F_{eB_\rho}^{BK} \) and \( (a_{35}^{(a)} + a_{35}^{(d)}) F_{eB_\rho}^{BK} \) with \( a_{35}^{(a)} = a_3^{(a)} + a_5^{(a)} \) will be induced. Because the values of \( a_3^{(a)} \) and \( a_5^{(a)} \) are much smaller than those of \( a_{4,6}^{(a)} \), the
The properties discussed before will not change. Furthermore, we can separate these decays into two classes. Class I consists of $B \to \rho^\mp K^{\mp}$, $B^+ \to \rho^0 K^+$ and $B^0 \to \omega K^+$, while $B \to \rho^0 K^0$, $B \to \omega K^0$ and $B^\mp \to \rho^\mp K^0$ are in class II. We find that the tree contributions in class I are related to $a_2 F_{e}^{B\rho}$, but in class II they are associated with $a_1 F_{c}^{B\rho K}$ or $a_2 F_{a_4}^{fK}$. As shown, $a_1$ is one order of magnitude less than $a_2$ and $F_{a_4}^{fK}$ is much smaller than $F_{a_6}^{fK}$, so that the tree effects associated with $V_u a_1 F_{c}^{B\rho K}$ and $V_u a_2 F_{a_4}^{fK}$ are quite small. Thus, we expect that the large CPAs and BRs exist only in the modes of class I. We emphasize that the dynamical effects associated with $\omega K$ decay modes much larger than that of its CP conjugate mode. For illustration, they are shown in Table 1. Note that the CPAs in class I are large. That means the BR of one of the BRs as a function of $\gamma$ in Figure 1. It is worth of pointing out that except tree effects, the $B^\pm \to \rho^\mp K^0$ and $B \to \rho^- K^+$ decays have the similar contributions from the penguin topologies. According to our estimation, the effect of penguin emission associated with $(a_4^{(d)} - 2 r_K a_6^{(d)}) F_{e}^{B\rho}$ on the BR is only around 19%. Therefore, the value of $BR(B^\pm \to \rho^\mp K^0)$ in Table 1 almost indicates the effects of annihilation contributions. In MPQCD, the uncertainties of hadronic effects can be from the power factor $c$ for the parametrization of threshold resummation, $\omega_B$ and $m_0^K$. With the allowed regions [1], we find that the uncertainties of power factor $c$ and $\omega_B$ are below 10% and the error of $m_0^K$ is 20%. The most challenge contributions are from higher order corrections. In order to estimate their size, we fix all free parameters to specific values, shown in the beginning of this paragraph, and then change the chosen condition of $t$ scale by a deviation of 30%. We find that the influence on BRs is also around 30%.

We now give a brief discussion on the nonfactorizable effects. It is known that besides contributions from $a_4^{(q)}$ to the nonfactorizable diagrams of the hard gluon exchanges between the valence quarks in $\rho$ and $B$ mesons, those from $a_{35}^{(u)} - a_{35}^{(d)}$ and $a_{35}^{(u)} + a_{35}^{(d)}$ for $\rho^0$ and $\omega$ modes will also be introduced. According to Eq. (2), the former is only associated with the small WCs of $C_{7,10}(\mu)$ but the latter is related to $C_{4,6}$. Thus, we expect that the influence of nonfactorizable effects on $\omega K$ modes is extraordinary. From our estimations, by neglecting all nonfactorizable contributions, we find that the BRs of $B \to \omega K^+(K^0)$ are reduced about 50%, while the influence on $BR(\rho K^+)$ and $BR(\rho K^0)$ are around 35% and 18%, respectively.

Finally, we give a remark on the QCDF approach. According to the analysis of Ref. [1], the BR of $B^\pm \to \phi K^\pm$ can reach $7.3 \times 10^{-6}$, if the included annihilation effects are almost real. If taking this value as the common result of MPQCD and QCDF, with the similar procedure, the values of the CP-averaged BR for $B \to \rho(\omega) K$ in QCDF can be estimated as $(B \to \rho^\mp K^{\mp}, B^+ \to \rho^0 K^+, B^0 \to \omega K^+) \sim (2.51, 0.62, 1.28) \times 10^{-6}$ and $(B^\mp \to \rho^\mp K^0, B \to \rho^0 K^0) \sim (1.63, 1.99, 0.64) \times 10^{-6}$ for $\gamma \approx 72^\circ$. The results in MPQCD are 35% smaller than those in Table 1. Though some results are similar in both approaches, the CPAs from QCDF for class I are found to be only at the few percent level. If the considered annihilation effects are almost imaginary, the CPAs from QCDF for class I can be as large as those from MPQCD. However, the BRs from QCDF become much smaller than those from
MPQCD. Altogether, even if MPQCD and QCDF have the common prediction for $B \to \phi K$, it is clear that $B \to \rho(\omega)K$ can distinguish the different QCD approaches.

In summary, we have performed the analysis of the $B \to \rho(\omega)K$ decays. Although the unique dynamical penguin enhancement in MPQCD can be verified by the measurements of $B \to \phi K$, which distinguish MPQCD from QCDF, $B \to \rho(\omega)K$ can display not only such an enhancement but also the importance of annihilation topologies, especially their absorptive parts. We also show that nonfactorizable effects play an important role in $B \to \omega K$ decays. Moreover, due to the cancellation in $a_4^{(q)} - 2r_K a_6^{(q)}$ for penguin emission topologies, any sizable new physics, with or without new weak CP violating phases contributing to the penguin operators $O_3 \sim O_{10}$, will have a remarkable influence on the BRs and CPAs of the modes in class I and II. $B \to \rho(\omega)K$ are also sensitive to physics beyond standard model. Recently, CLEO has reported results of $B \to \rho(\omega)K$, such as $BR(B \to \rho^\pm K^\mp) = (16.0^{+7.6}_{-6.4} \pm 2.8) \times 10^{-6}$ and $BR(B^\pm \to \omega K^\mp) = (3.2^{+2.4}_{-1.9} \pm 0.8) \times 10^{-6}$. It is obvious that the central value of $BR(B^\pm \to \omega K^\mp)$ is the same as our prediction. The further confirmation will be made, when the data from the B factories are announced in the near future.

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References

[1] CLEO Collaboration, D. Cronin-Hennessy, Phys. Rev. Lett. 85, 515 (2000).

[2] BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 87, 151802 (2001).

[3] BELLE Collaboration, K. Abe et al., Phys. Rev. Lett. 87, 101801 (2001).

[4] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).

[5] CLEO Collaboration, C.P. Jessop et al., Phys. Rev. Lett. 85, 2881 (2000).

[6] CLEO Collaboration, A. Lyon, talk presented at the 4th International Workshop on B Physics and CP violation, Ise-Shima, Japan, Feb. 19-23, 2001.

[7] BABAR Collaboration, G. Cavoto, talk presented at XXXVI Rencontres de Moriond, Mar. 17-24, 2001.

[8] Belle Collaboration, H. Tajima, Contributed to the Proceedings of the XX International Symposium on Lepton and Photon Interactions at High Energies, July 23–28, 2001, Rome, Italy, hep-ex/0111037.

[9] S. Mishima, hep-ph/0107163; Phys. Lett. B521, 252 (2001).

[10] C.H. Chen, Y.Y. Keum and H.N. Li, Phys. Rev. D64, 112002 (2001).

[11] M. Beneke, G. Buchalla, M. Neubert and C.T. Sachrajda, Nucl. Phys. B591, 313 (2000); ibid B606, 245 (2001).

[12] H.Y. Cheng and K.C. Yang, Phys. Rev. D64, 074004 (2001).

[13] G. Buchalla, A.J. Buras and M.E. Lautenbacher, Rev. Mod. Phys. 68, 1230 (1996).

[14] G.P. Lepage and S.J. Brodsky, Phys. Lett. B87, 359 (1979); Phys. Rev. D22, 2157 (1980).

[15] H.N. Li, Phys. Rev. D64, 014019 (2001); H.N. Li, hep-ph/0102013.

[16] Y.Y. Keum, H.N. Li, and A.I. Sanda, Phys. Lett. B504, 6 (2001); Phys. Rev. D63, 054008 (2001).

[17] C.D. Lü, K. Ukai, and M.Z. Yang, Phys. Rev. D63, 074009 (2001).

[18] C.H. Chen and H.N. Li, Phys. Rev. D63, 014003 (2001).

[19] E. Kou and A.I. Sanda, hep-ph/0106159.

[20] C.H. Chen, Phys. Lett. B520, 33 (2001).

[21] B. Melic, Phys. Rev. D59, 074005 (1999).

[22] C.D. Lü and M.Z. Yang, hep-ph/0011238.

[23] T. Kurimoto, H.N. Li, and A.I. Sanda, hep-ph/0105003.
[24] P. Ball, V.M. Braun, Y. Koike, and K. Tanaka, Nucl. Phys. B\textbf{529}, 323 (1998).

[25] P. Ball, JHEP \textbf{01}, 010 (1999).

[26] J.C. Collins and D.E. Soper, Nucl. Phys. B\textbf{193}, 381 (1981).

[27] J. Botts and G. Sterman, Nucl. Phys. B\textbf{325}, 62 (1989).

[28] A. Ali, \textit{et. al.} Phys. Rev. D\textbf{61}, 074024 (2000).

[29] D. Melikhov and B. Stech, Phys. Rev. D\textbf{62}, 014006 (2000).

[30] A. Ali \textit{et. al.}, Phys. Rev. D\textbf{58}, 094009 (1998); Y.H. Chen \textit{et. al.} Phys. Rev. D60, 094014 (1999).
Figure 1: BRs of the $B \to \rho(\omega)K$ decays as a function of the angle $\gamma$. The solid, dashed and dash-dotted lines are for (a) $B_d \to \rho^\pm K^\mp$, $B^\mp \to \rho^0 K^\mp$, and $B^\mp \to \omega K^\mp$, and for (b) $B_d \to \rho^0 K^0$, $B^\pm \to \rho^\pm K^0$, and $B_d \to \omega K^0$, respectively.

Table 1: BRs (in units of $10^{-6}$) with CP average for class I and II respectively and CP asymmetries (%) in the $B \to \rho(\omega)K$ decays for $\gamma \simeq 72^0$. Nonfactorizable effects are included.

|                | Class I |                |                |                |
|----------------|---------|----------------|----------------|----------------|
| **Mode**       | $B \to \rho^\pm K^\mp$ | $B^\mp \to \rho^0 K^\mp$ | $B^\mp \to \omega K^\mp$ |
| **BR**         | 5.42    | 2.18           | 3.22           |
| **CPA**        | -60.76  | -74.95         | -58.21         |

|                | Class II |                |                |                |
|----------------|----------|----------------|----------------|----------------|
| **Mode**       | $B^\pm \to \rho^\pm K^0$ | $B \to \rho^0 K^0$ | $B \to \omega K^0$ |
| **BR**         | 2.96     | 2.49           | 2.07           |
| **CPA**        | -3.74    | -6.18          | 6.39           |