On Measuring $CP$ Violation in Neutral $B$-meson Decays at the $\Upsilon(4S)$ Resonance

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Abstract

Within the standard model we carry out an analysis of $CP$-violating observables in neutral $B$-meson decays at the $\Upsilon(4S)$ resonance. Both time-dependent and time-integrated $CP$ asymmetries are calculated, without special approximations, to meet various possible measurements at symmetric and asymmetric $e^+e^-$ $B$ factories. We show two ways to distinguish between direct and indirect $CP$-violating effects in the $CP$-eigenstate channels such as $B^0_d/\bar{B}^0_d \rightarrow \pi^+\pi^-$ and $\pi^0 K_S$. Reliable knowledge of the Cabibbo-Kobayashi-Maskawa phase and angles can in principle be extracted from measurements of some non-$CP$-eigenstate channels, e.g., $B^0_d/\bar{B}^0_d \rightarrow D^\pm\pi^\mp$ and $D^{(*)0}\pi K_S$, even in the presence of significant final-state interactions.

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1. Introduction

Observing $CP$ violation in the $B$-meson system and confronting it with the predictions of the standard model is a challenging task in particle physics. On the experimental side, a sample of at least $10^9$ $B$ mesons is required before meaningful measurements of $CP$ asymmetries can be carried out. On the theoretical side, there are two obstacles to reliable numerical predictions for $CP$ asymmetries in exclusive non-leptonic $B$ decays. First, the present knowledge of some of the underlying electroweak parameters such as the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements is insufficient. Second, intrinsic uncertainties due to the impact of strong interactions exist. While the former awaits more accurate measurements, the latter needs a deeper understanding of the dynamics of the non-leptonic weak decays.

It is well known that large $CP$ asymmetries may arise in many exclusive decay channels of neutral $B$ mesons, either from $B^0\bar{B}^0$ mixing or via final-state strong interactions, or by a combination of the two. However, many of the previous quantitative predictions are problematic because they have ignored or injudiciously simplified final-state interactions. In the long run, a great improvement of these calculations is possible to yield reliable results. It is more instructive at present to explore various available measurements of $CP$ asymmetries at $B$ factories, in order to test the unitarity of the CKM matrix and study the impact of final-state interactions in neutral $B$ decays in a model-independent way.

In this letter we present a non-trivial analysis of $CP$-violating observables in correlated decays of $B^0\bar{B}^0_\epsilon$ pairs at the $\Upsilon(4S)$ resonance, a clean basis of the future symmetric and asymmetric $e^+e^-$ $B$ factories. Two categories of interesting transitions are focused on: (1) $B^0_d$ and $\bar{B}^0_d$ decays to $CP$ eigenstates, in which significant QCD-loop-induced (penguin) contributions may exist; and (2) $B^0_d$ and $\bar{B}^0_d$ decays to common non-$CP$ eigenstates, whose amplitudes depend only on a single weak phase. To meet various possible measurements proposed for a new generation of $e^+e^-$ colliders running at the $\Upsilon(4S)$, we calculate both the time-dependent and time-integrated decay probabilities and $CP$ asymmetries by taking final-state interactions into account. Some useful relations between the observables and the weak and strong transition phases are obtained. We show two ways to distinguish between direct and indirect $CP$-violating effects in the $CP$-eigenstate decays such as $B^0_d/\bar{B}^0_d \to \pi^+\pi^-$ and $\pi^0K_S$. In principle, reliable knowledge of the CKM phase and angles can be extracted from measurements of some non-$CP$-eigenstate decays, e.g. $B^0_d/\bar{B}^0_d \to D^\pm\pi^\mp$ and $D^{(*)}\pi K_S$, even in the presence of significant final-state strong interactions. We also point out that measurements of...
a few pure penguin modes such as $B_d^0/\bar{B}_d^0 \to \phi K_S$ should serve as a good test of the existing
calculations for the strong penguin diagrams.

2. Decay probabilities of $B_d^0\bar{B}_d^0$ pairs at the $\Upsilon(4S)$

The unique experimental advantages of studying $b$-quark physics at the $\Upsilon(4S)$ are well
known. For either symmetric or asymmetric $e^+e^-$ collisions, the detectors required to measure
$CP$ violation in correlated decays of $B_d^0\bar{B}_d^0$ events are sophisticated, but within the limits of
the present technology [4,5]. On the $\Upsilon(4S)$ resonance, the $B$'s are produced in a two-body
($B_d^+ B_d^-$ or $B_d^0\bar{B}_d^0$) state with definite charge parity $C = \pm$. The two neutral $B$ mesons mix
coherently until one of them decays. Thus one can use the semileptonic decays of one meson
to tag the flavour of the other meson decaying to a flavour-non-specific hadronic final state.
At a centre-of-mass beam energy above $m_B + m_{\bar{B}}$, but below $2m_{B}$, the $e^+e^-$ annihilation can produce $B\bar{B}$ or $B^*\bar{B}$ pairs, which dominate the $b\bar{b}$ final states [5]. The $B^*$ ($\bar{B}^*$) will decay
radiatively to the $B$ ($\bar{B}$), leaving $B\bar{B}\gamma$ with the $B\bar{B}$ in a $C = +$ state. At a $B$ factory, both
the $B_d^0\bar{B}_d^0$ decays in the $C = -$ and $C = +$ states are worth studying in order to search for
large $CP$-violating effects.

Supposing one neutral $B$ meson decaying to a semileptonic state $|l^\pm X^\mp\rangle$ at (proper) time
time $t_1$ and the other to a non-leptonic state $|f\rangle$ at time $t_2$, the time-dependent probabilities for
such a joint decay can be given by [2]

$$Pr(l^\pm X^\mp,t_1; f,t_2)_C \propto |A_l|^2 |A_f|^2 \epsilon^{-\Gamma(t_1+t_2)} \left[ \frac{1+|\xi_f|^2}{2} \right. \\
\left. \pm \frac{1-|\xi_f|^2}{2} \cos[\Delta m(t_2+Ct_1)] \pm Im \xi_f \sin[\Delta m(t_2+Ct_1)] \right], \tag{1}$$

where $C (= \pm)$ is the charge parity of the $B_d^0\bar{B}_d^0$ pair. Here we have defined $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$
and $\Delta m \equiv m_2 - m_1$, where $\Gamma_{1,2}$ and $m_{1,2}$ are the widths and masses of the $B_d$ mass eigenstates,
$B_{1,2}$. In obtaining Eq. (1), two good approximations $\Delta \Gamma \equiv \Gamma_1 - \Gamma_2 \ll \Gamma$ and $\Delta \Gamma \ll \Delta m$
have been used [6]. In addition,

$$A_l \equiv \langle l^\pm X^- |H|B_d^0 \rangle \quad \text{CFP} \quad \text{CPP} \quad \langle l^- X^+ |H|\bar{B}_d^0 \rangle, \quad A_f \equiv \langle f|H|B_d^0 \rangle, \quad \bar{A}_f \equiv \langle f|H|\bar{B}_d^0 \rangle, \quad \xi_f \equiv e^{-2i\phi_B} \frac{\bar{A}_f}{A_f}, \tag{2}$$

where $\phi_B \equiv \text{arg}(V_{tb}V_{td}^*)$ is the phase of $B_d^0\bar{B}_d^0$ mixing [2,6]. For the case that one neutral $B$
meson decays to $|l^\pm X^\mp\rangle$ at time $t_1$ and the other decays to $|\bar{f}\rangle$ (the $CP$-conjugate state of $|f\rangle$)
at time $t_2$, the corresponding decay probabilities $Pr(l^\pm X^\mp, t_1; f, t_2)_C$ can be obtained from Eq. (1) by the replacements $A_f \to \bar{A}_f$ and $\xi_f \to \bar{\xi}_f$, where

$$\bar{A}_f \equiv \langle \bar{f}|H|B^0_d \rangle, \quad A_f \equiv \langle f|H|B^0_d \rangle, \quad \bar{\xi}_f \equiv e^{2\phi_f} \frac{A_f}{\bar{A}_f}. \quad (3)$$

The difference between the decay probabilities associated with $B^0_d \to f$ and $\bar{B}^0_d \to \bar{f}$ is a basic signal for $CP$ violation. In practice, one has to consider the possibility of an $e^+ e^-$ collider to measure the time development of the decay rates and $CP$ asymmetries. For a symmetric collider running at the $\Upsilon(4S)$ resonance, the mean decay length of $B^0$'s is insufficient for the measurement of $(t_2 - t_1)$ [4]. On the other hand, the quantity $(t_2 + t_1)$ cannot be measured in a symmetric or asymmetric storage ring operating at the $\Upsilon(4S)$, unless the bunch lengths are much shorter than the decay lengths [4,5]. Therefore, only the time-integrated measurements are available at a symmetric $B$ factory. Integrating $Pr(l^\pm X^\mp, t_1; f, t_2)_C$ over $t_1$ and $t_2$, we obtain

$$Pr(l^\pm X^\mp, f)_- \propto |A_i|^2 |A_f|^2 \left[ \frac{1 + |\kappa_f|^2}{2} \mp \frac{1 - |\kappa_f|^2}{2} \right], \quad (4)$$

and

$$Pr(l^\pm X^\mp, f)_+ \propto |A_i|^2 |A_f|^2 \left[ \frac{1 + |\kappa_f|^2}{2} \mp \frac{1 - |\kappa_f|^2}{2} \right] \left[ \frac{1 - x_d^2}{2} \mp \frac{1 - x_d^2}{2} \right] \pm \frac{2x_d}{(1 + x_d^2)^2} Im \xi_f, \quad (5)$$

where $x_d \equiv \Delta m/\Gamma \sim 0.7$ is a measurable of $B^0_d - \bar{B}^0_d$ mixing [7]. For an asymmetric collider running in this energy region, one might want to integrate Eq. (1) only over $(t_2 + t_1)$ in order to measure the development of decay probabilities with $\Delta t \equiv (t_2 - t_1)$ [4,5]. In this case, we obtain

$$Pr(l^\pm X^\mp, f; \Delta t)_- \propto |A_i|^2 |A_f|^2 e^{-|\Delta t|} \left[ \frac{1 + |\kappa_f|^2}{2} \mp \frac{1 - |\kappa_f|^2}{2} \cos(\Delta m \Delta t) \pm Im \xi_f \sin(\Delta m \Delta t) \right] \quad (6)$$

and

$$Pr(l^\pm X^\mp, f; \Delta t)_+ \propto |A_i|^2 |A_f|^2 e^{-|\Delta t|} \left[ \frac{1 + |\kappa_f|^2}{2} \mp \frac{1 - |\kappa_f|^2}{2} \right] \left[ \frac{1 - x_d^2}{2} \mp \frac{1 - x_d^2}{2} \right] \pm \frac{2x_d}{(1 + x_d^2)^2} Im \xi_f \sin(\Delta m \Delta t + \phi_{x_d})$$

$$\pm \frac{1}{\sqrt{1 + x_d^2}} \frac{Im \xi_f \sin(\Delta m \Delta t + \phi_{x_d})}{\sqrt{1 + x_d^2}}, \quad (7)$$

where $\phi_{x_d} \equiv \tan^{-1} x_d \sim 35^\circ$. 

From Eqs. (4)-(7) one can straightforwardly obtain the decay probabilities associated with $B^0_d \to f$ and $\bar{B}^0_d \to \bar{f}$. Corresponding to the possible measurements for joint $B^0_d \bar{B}^0_d$ decays at
symmetric (S) and asymmetric (A) B factories, we define the CP-violating asymmetries as

$$A_C^S = \frac{Pr(l^{-}X^{+}, f)}{Pr(l^{-}X^{+}, f) + Pr(l^{+}X^{-}, \bar{f})}.$$  

and

$$A_C^A(\Delta t) = \frac{Pr(l^{-}X^{+}, f; \Delta t) - Pr(l^{+}X^{-}, \bar{f}; \Delta t)}{Pr(l^{-}X^{+}, f) + Pr(l^{+}X^{-}, \bar{f}; \Delta t)}.$$  

In the following, we shall calculate $A_C^S$ and $A_C^A(\Delta t)$ for two categories of interesting neutral $B$ decays and explore relations between the observables and the weak and strong transition phases in them.

3. CP asymmetries in $B_d$ decays to CP eigenstates

We first consider the $B^0_d$ and $\bar{B}^0_d$ decays to CP eigenstates (i.e. $|\bar{f}| = n_{CP}|f|$ with $n_{CP} = \pm 1$), such as $J/\psi K_S$, $\pi^+\pi^-$, and $\pi^0 K_S$. With the phase convention $CP|B^0_d) = |\bar{B}^0_d)$, we have $A_f = n_{CP}A_f$, $\bar{A}_f = n_{CP}\bar{A}_f$, and $\xi_f = 1/\xi_f$. For symmetric and asymmetric $e^+e^-$ collisions at the $\Upsilon(4S)$, the corresponding CP asymmetries in $(B^0_d \bar{B}^0_d) \rightarrow (l^\pm X^\mp) f$ are given by

$$A_C^S = \frac{1}{1 + x^2_d} U_f,$$

$$A_C^S = \frac{1}{1 + x^2_d} U_f + \frac{2x_d}{(1 + x^2_d)^2} V_f;$$

and

$$A_C^A(\Delta t) = U_f \cos(\Delta m \Delta t) + V_f \sin(\Delta m \Delta t),$$

$$A_C^A(\Delta t) = \frac{1}{\sqrt{1 + x^2_d}} [U_f \cos(\Delta m \Delta t + \phi_{x_d}) + V_f \sin(\Delta m \Delta t + \phi_{x_d})],$$

where

$$U_f = \frac{1 - |\xi_f|^2}{1 + |\xi_f|^2}, \quad V_f = \frac{-2i m \xi_f}{1 + |\xi_f|^2}.$$  

Non-vanishing $U_f$ and $V_f$ imply the CP asymmetry in the decay amplitude (i.e. $|\xi_f| \neq 1$) and the one from interference between decay and mixing, respectively. From the above equations one can observe a few interesting features.

1. $A_C^S$ is a pure measure of direct CP violation, while $A_C^A$ contains both direct and indirect CP asymmetries. A combination of the measurements for $A_C^S$ can in principle distinguish between direct and indirect CP-violating effects in neutral $B$-meson decays [8]. From Eqs. (10) and (12), we obtain

$$U_f = (1 + x^2_d) A_C^S,$$

$$V_f = \frac{(1 + x^2_d)^2}{2x_d} \left[A_C^S - \frac{1 - x^2_d}{1 + x^2_d} A_C^S\right].$$
(2) Compared with the time-integrated $CP$ asymmetry in incoherent $B_d^0$ and $\bar{B}_d^0$ decays to $CP$ eigenstates \cite{9} (e.g. in a hadronic production environment or in high energy $e^+e^-$ reactions \cite{10}):

$$\mathcal{A} = \frac{1}{1 + x_d^2} U_f + \frac{x_d}{1 + x_d^2} V_f,$$

the direct and indirect parts of $\mathcal{A}_\pm^S$ have the additional dilution factors $(1 - x_d^2)/(1 + x_d^2) \sim 0.34$ and $2/(1 + x_d^2) \sim 1.34$, respectively.

(3) Both $\mathcal{A}_\pm^A(\Delta t)$ are composed of direct and indirect $CP$ violation and have the following relation:

$$\mathcal{A}_\pm^A(\Delta t) = \frac{1}{\sqrt{1 + x_d^2}} \mathcal{A}_\pm A^A \left( \frac{n \pi}{\Delta m} - \frac{\phi_{x_d}}{\Delta m} \right).$$

In contrast with $\mathcal{A}_\pm(\Delta t)$, the asymmetry $\mathcal{A}_\pm^A(\Delta t)$ has a dilution factor in its magnitude $1/\sqrt{1 + x_d^2} \sim 0.82$, and a positive shift in its phase $\phi_{x_d} \sim 35^\circ$.

(4) If $|\xi_f| = 1$, only the asymmetries via mixing remain in $\mathcal{A}_\pm^A(\Delta t)$. As a signal of the existence of direct $CP$ violation, the deviation of $|\xi_f|$ from unity can also be probed by measuring the time development of the asymmetries. In particular, one can extract the information on direct $CP$ violation with the help of

$$\mathcal{A}_\pm^A \left( \frac{n \pi}{\Delta m} \right) = \sqrt{1 + x_d^2} \mathcal{A}_\pm A^A \left( \frac{n \pi}{\Delta m} - \frac{\phi_{x_d}}{\Delta m} \right) = (-1)^n U_f,$$

where $n = 0, \pm 1, \pm 2$, and so on.

From the measurements of $\mathcal{A}_\pm^S$ or $\mathcal{A}_\pm^A(\Delta t)$ one can obtain the information on $|A_f|, |\xi_f|$, and $Im \xi_f$ for the decays $B_d^0 \rightarrow f$ and $\bar{B}_d^0 \rightarrow n_{CP}f$. At the quark level, most of the neutral $B$ decays to $CP$ eigenstates occur through the transitions $b \rightarrow (Q\bar{Q})q$ (with $Q = u, c, t$ and $q = d, s$) and their flavour-conjugate processes. With the help of the CKM unitarity $V_{ub}V_{us}^* + V_{cb}V_{cs}^* + V_{tb}V_{ts}^* = 0$, the decay amplitudes $A_f$ and $\bar{A}_f$ can be symbolically expressed as

$$A_f = \left[ A_u e^{i(\phi_u + \delta_u)} + A_c e^{i(\phi_c + \delta_c)} \right] e^{-i\phi_K},$$

$$\bar{A}_f = n_{CP} \left[ A_u e^{i(\phi_u + \delta_u)} + A_c e^{i(\phi_c + \delta_c)} \right] e^{i\phi_K},$$

where $\phi_u \equiv \arg(V_{ub}V_{us})$ and $\phi_c \equiv \arg(V_{cb}V_{cs})$ are the $b$-decay (weak) phases, $\delta_{u,c}$ are the corresponding strong phases, $A_{u,c}$ are the full (real) amplitudes calculated to first order in the weak interactions and (in principle) to all orders in the strong interactions, and $\phi_K$ is a weak phase associated with the possible $K^0 - \bar{K}^0$ mixing in the final state ($\phi_K = \arg(V_{cs}V_{cd}^*)$ when $|f|$ contains a single $K_S$ or $K_L$, and $\phi_K = 0$ when $|f|$ is of zero strangeness). Defining $h = A_c/A_u,$
\[ \delta \equiv \delta_c - \delta_u, \text{ and } \phi_M \equiv \phi_B - \phi_K, \text{ one obtains} \]
\[
|A_f|^2 = A_u^2 \left[ 1 + 2h \cos(\delta + \phi_u - \phi_c) + h^2 \right],
\]
\[
|\xi_f|^2 = \frac{1 + 2h \cos(\delta - \phi_u + \phi_c) + h^2}{1 + 2h \cos(\delta + \phi_u - \phi_c) + h^2},
\]
\[
Im \xi_f = n_{CP} \frac{\sin 2(\phi_u - \phi_M) + 2h \cos \delta \sin(\phi_u + \phi_c - 2\phi_M) + h^2 \sin 2(\phi_c - \phi_M)}{1 + 2h \cos(\delta + \phi_u - \phi_c) + h^2}.
\]  

In Eq. (18), three relations are given between the observables (\(|A_f|\), \(|\xi_f|\), and \(Im \xi_f\)) and the weak and strong transition parameters (\(\phi_u, \phi_M, A_{u,c}, \text{ and } \delta\)). If the relevant weak phases have been well determined elsewhere, one may use these relations to probe \(A_{u,c}\) and \(\delta\), in order to obtain the information on final-state interactions. In principle, the decay amplitudes \(A_f\) and \(\tilde{A}_f\) can be evaluated with the help of effective weak Hamiltonians [11] and QCD [12]. The experimental determination of \(A_{u,c}\) and \(\delta\) will provide a test of the theoretical calculations.

There are two categories of interesting decay modes, in which no significant entanglement exists between the tree-level and penguin contributions:

1. For the decay modes with dominant tree-level amplitudes such as \(B_d^0/\bar{B}_d^0 \rightarrow J/\psi K_S\) and \(D^+ D^-\), one can safely neglect the component \(A_u\) in \(A_f\) and \(\tilde{A}_f\). As a result, Eq. (18) is simplified as
\[
|A_f| = A_c, \quad |\xi_f| = 1, \quad Im \xi_f = n_{CP} \sin 2(\phi_c - \phi_M),
\]
where only the \(CP\) violation from mixing remains. Taking \(B_d^0\) versus \(\bar{B}_d^0 \rightarrow J/\psi K_S\) for example, we show the relative size between \(A_c^+(\Delta t)\) and \(A_c^+(\Delta t)\) as well as between \(A_s^+\) and \(A_s^+\) in Fig. 1. Obviously one of the angles of the CKM unitarity triangle, \(\beta \equiv \arg(-V_{cb}^* V_{cd}/V_{ub}^* V_{ud})\), can be reliably determined from the measurements of \(A_c^+(\Delta t)\) or \(A_s^+\) with the help of the relation\(^4\)
\[
Im \xi_{J/\psi K_S} = \sin(2\beta).
\]

2. For the pure penguin transitions such as \(B_d^0/\bar{B}_d^0 \rightarrow \phi K_S\) and \(K^0 \bar{K}^0\), \(A_{u,c}\) contain no tree-level components and may be more easily calculated. Using perturbative QCD and simplifying final-state hadronization, the quantities \(A_{u,c}\) and \(\delta_{u,c}\) have been estimated for some charmless exclusive decay modes [13]. Those rough results can give one a feeling of ballpark numbers to be expected. Since the electromagnetic penguin transitions such as \(B_d^0 \rightarrow \gamma K^{*0}\) have been observed recently [14], a further study of the pure strong penguin decays would be very useful. In such decays a comparison between the theoretical and experimental results of \(h\) and \(\delta\) will provide a good test of the understanding of the strong penguin diagrams. In

\(^4\)Note that here \(n_{CP} = -1\) since \(J/\psi K_S\) is a \(CP\)-odd state.
practice, $B_d^0$ versus $\bar{B}_d^0 \to \phi K_S$ might be most promising, since their branching ratios are on the order of $10^{-5}$ [15], a level at which current $B$ experiments start to observe rare decays [16].

4. \textit{CP} asymmetries in $B_d$ decays to non-\textit{CP} eigenstates

Now we consider the case that $B_d^0$ and $\bar{B}_d^0$ decay to a common non-\textit{CP} eigenstate (i.e. $|\bar{f}\rangle \neq n_{CP}|f\rangle$), but their amplitudes $A_f$ ($A_{\bar{f}}$) and $\bar{A}_f$ ($\bar{A}_{\bar{f}}$) contain only a single weak phase. Most of such decays occur through the quark transitions $b \to u\bar{c}$ and $c\bar{u}$ (with $q = d, s$), and a typical example is $B_d^0/\bar{B}_d^0 \to (\bar{f})^{(s)}K_S$ as illustrated in Fig. 2. In this case, no measurable direct \textit{CP} violation arises in the decay amplitudes since $|\bar{A}_f| = |A_{\bar{f}}|$, $|\bar{A}_{\bar{f}}| = |A_f|$, and $|\bar{\xi}_f| = |\xi_f|$ (see Eq. (23)). For symmetric and asymmetric $e^+e^-$ collisions at the $\Upsilon(4S)$ resonance, the corresponding \textit{CP} asymmetries in such decay modes are given by

$$A^S = 0,$$
$$A^S_+ = \frac{-2x_d Im(\xi_f - \bar{\xi}_f)}{2 + x_d^2 + x_d^4 + x_d^2(3 + x_d^2)|\xi_f|^2 - 2x_d Im(\xi_f + \bar{\xi}_f)};$$

and

$$A_4^S(\Delta t) = \frac{-Im(\xi_f - \bar{\xi}_f) sin(\Delta m \Delta t)}{(1 + |\xi_f|^2) + F(\xi_f, \bar{\xi}_f, \Delta m \Delta t)};$$
$$A_4^S(\Delta t) = \frac{-Im(\xi_f - \bar{\xi}_f) sin(\Delta m \Delta t + \phi_{x_d})}{\sqrt{1 + x_d^2(1 + |\xi_f|^2) + F(\xi_f, \bar{\xi}_f, \Delta m \Delta t + \phi_{x_d})}},$$

where $F$ is a function defined as

$$F(x, y, z) \equiv (1 - |x|^2) cos z - Im(x + y) sin z.$$
Symbolically the decay amplitudes \( A_f \) (\( \bar{A}_f \)) can be written as

\[
A_f = A_\xi e^{i(-\phi+\delta)}e^{-i\phi_K}, \quad \bar{A}_f = A_\xi e^{i(\phi+\delta)}e^{i\phi_K};
\]

\[
A_f = A_\tilde{\xi} e^{i(-\bar{\delta}+\tilde{\delta})}e^{-i\phi_K}, \quad \bar{A}_f = A_\tilde{\xi} e^{i(\bar{\delta}+\tilde{\delta})}e^{i\phi_K},
\]

where \( \phi \equiv \arg(V_{cb}V_{ub}^*) \) and \( \bar{\phi} \equiv \arg(V_{ub}V_{cb}^*) \) (with \( q = d, s \)) are the \( b \)-decay (weak) phases, \( \delta \) and \( \tilde{\delta} \) are the corresponding strong phases, \( A_\xi \) and \( A_{\tilde{\xi}} \) are the real (positive) hadronic amplitudes, and \( \phi_K \) is the possible \( K^0-\bar{K}^0 \) mixing phase in the final states as defined in Eq. (17). With the notation \( \Delta \delta \equiv \tilde{\delta} - \delta \), we obtain

\[
Im \xi_f = \frac{A_{\tilde{\xi}}}{A_\xi} \sin(\Delta \delta + \phi + \bar{\phi} - 2\phi_M),
\]

\[
Im \bar{\xi}_f = \frac{A_\xi}{A_{\tilde{\xi}}} \sin(\Delta \delta - \phi - \bar{\phi} + 2\phi_M).
\]

Or equivalently,

\[
Im(\xi_f + \bar{\xi}_f) = 2|\xi_f| \sin \Delta \delta \cos(\phi + \bar{\phi} - 2\phi_M),
\]

\[
Im(\xi_f - \bar{\xi}_f) = 2|\xi_f| \cos \Delta \delta \sin(\phi + \bar{\phi} - 2\phi_M).
\]

From these relations one can reliably determine \( \Delta \delta \) and \( (\phi + \bar{\phi} - 2\phi_M) \), once \( |\xi_f|, Im \xi_f, \) and \( Im \bar{\xi}_f \) have been measured in experiments. This is really interesting because we do not need to ignore the presence of significant final-state interactions in these decays. In Ref. [17], \( B^0_s \to \pi^0 D^{0(*)} K \) and their \( CP \)-conjugate processes have been considered to probe the angles of the CKM unitarity triangle \( \alpha \) and \( \beta \) with the help of an approximate form of Eq. (24). Certainly one can also apply Eq. (24) or (25) to some other related decay modes such as \( f = D^{(*)0} \pi^\pm, D^{(*)0} \pi^0, F^{(*)0} K^\mp, \) and \( \bar{D}^{(*)0} J/\psi \). On the experimental side, to detect such charmed channels should be a little easier than to detect those without charm.

5. Discussion and conclusion

To meet various possible measurements at symmetric and asymmetric \( e^+e^- B \) factories, we have analysed both time-dependent and time-integrated \( CP \)-violating asymmetries in correlated decays of \( B^0_s \) and \( \bar{B}^0_s \) mesons at the \( \Upsilon(4S) \) resonance. A parallel discussion can be given for joint \( B^0_s \bar{B}^0_s \) decays at the \( \Upsilon(5S) \). Because of the very large \( B^0_s-\bar{B}^0_s \) mixing predicted by the standard model \( (x_s \sim O(10) \) [18]), the observable size of time-integrated \( CP \) asymmetries at the \( \Upsilon(5S) \) will be considerably diluted. On the other side, the time-dependent measurements are also difficult for \( B^0_s \) and \( \bar{B}^0_s \) decays due to the expected rapid rate of oscillation. In fact,
it is almost impossible to accumulate sufficient $B_s$ events at the $\Upsilon(5S)$ for the study of $CP$-violating effects. Using hadron collisions or high energy $e^+e^-$ reactions (e.g. at the Z peak) for producing beauty mesons, one might be able to measure the proper time evolution of some $B_s$ decays in the future. Then Eqs. (18) and (24) remain useful for analysing the weak and strong transition phases in them. As an independent test of the CKM picture of $CP$ violation, the study of incoherent $B_s$ decays such as $B_s^0/\bar{B}_s^0 \rightarrow J/\psi\phi$ and $\phi (^{(1)}D_0)$ is quite helpful.

It is worthwhile at this point to remark that in Eq. (17) (or Eq. (23)) the decay amplitudes $A_f$ and $\tilde{A}_f$ are parametrized in terms of their weak phases, where all the strong interaction contributions are included in $A_{uc}$ and $\delta_{uc}$ (or $A_\delta$, $A_\tilde{\delta}$, $\delta$ and $\tilde{\delta}$). Reliably evaluating these strong-interaction quantities is a serious theoretical challenge. In the literature most of the numerical calculations are done with the help of effective weak Hamiltonians and factorization approximations, where all the long-distance strong interactions are incorporated in the hadronic matrix elements of local four-quark operators. However, the quark final states are not uniquely related to the physical states, and the overlap between them could be very complicated. In order to give reliable predictions of $CP$ asymmetries in $B$-meson decays, a deeper study of the dynamics of non-leptonic weak transitions, especially at the hadron level, becomes more urgent today [19].

In conclusion, measurements of neutral $B$ decays at the $\Upsilon(4S)$ supply a valuable opportunity to probe the sources of $CP$ violation beyond the $K$-meson system and to advance our understanding of final-state strong interactions in exclusive weak decays. In view of recent development in building high-luminosity $B$ factories [4,5], we believe that the work done here should be useful for experimental studies of $CP$ violation and $B$-meson decays in the near future.

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References


Fig. 1  $CP$ asymmetries in $B^0_d$ versus $\bar{B}^0_d \to J/\psi K_S$ at the $\Upsilon(4S)$. Here $x_d \equiv \Delta m/\Gamma$ is a measurable of $B^0_d$-$\bar{B}^0_d$ mixing, and $\phi_{x_d} = \tan^{-1} x_d$; $\beta \equiv \arg(-V^*_{cb} V_{cd}/V^*_{tb} V_{td})$ is an angle of the CKM unitarity triangle; $L_1 = |\sin(2\beta)|/\sqrt{1 + x_d^2}$, and $L_2 = 2x_d |\sin(2\beta)|/(1 + x_d^2)^2$.

Fig. 2  Quark diagrams for $B^0_d$ versus $\bar{B}^0_d$ decays to $\bar{D}^{(*)0} K_S$ and $D^{(*)0} K_S$. 