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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 $\overset{(-)}{D}{}^{(*)0} K_S$, 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 10^8 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 [1] 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 [2]. However, many of the previous quantitative predictions are problematic because they have ignored or injudiciously simplified final-state interactions [3]. 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 $B^0_d\bar{B}^0_d$ pairs at the $\Upsilon(4S)$ resonance, a clean basis of the future symmetric and asymmetric e^+e^- B factories [4]. 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 $\Upsilon(4S)$ [4,5], 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 $B^0_d/\bar{B}^0_d \rightarrow \pi^+\pi^-$ and π^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. $B^0_d/\bar{B}^0_d \rightarrow D^\pm\pi^\mp$ and $\overset{(-)}{D}{}^{(*)0}K_S$, even in the presence of significant final-state strong interactions. We also point out that measurements of a few pure penguin modes such as $B^0_d/\bar{B}^0_d \rightarrow \phi K_S$ should serve as a good test of the existing calculations for the strong penguin diagrams.

2. Decay probabilities of $B^0_d\bar{B}^0_d$ 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 $B^0_d\bar{B}^0_d$ 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 ($B^+_u B^-_u$ or $B^0_d\bar{B}^0_d$) state with definite charge parity $C = -$. 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 $m_B + m_{B^*}$ 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 $B^0_d\bar{B}^0_d$ 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 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]

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

where C $(= \pm)$ is the charge parity of the $B^0_d\bar{B}^0_d$ 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 $\Delta\Gamma \equiv \Gamma_1 - \Gamma_2 << \Gamma$ and $\Delta\Gamma << \Delta m$ have been used [6]. In addition,

$$
\begin{aligned}
A_l \;\; & \equiv \;\; \langle l^+X^-|H|B^0_d\rangle \;\stackrel{CPT}{=\!=}\; \langle l^-X^+|H|\bar{B}^0_d\rangle \; , \\
A_f \;\; & \equiv \;\; \langle f|H|B^0_d\rangle \; , \quad \bar{A}_f \;\equiv\; \langle f|H|\bar{B}^0_d\rangle \; , \quad \xi_f \;\equiv\; e^{-2i\phi_B}\frac{\bar{A}_f}{A_f} \; ,
\end{aligned}
\tag{2}
$$

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

$$\bar{A}_{\bar{f}} \;\equiv\; \langle \bar{f}|H|\bar{B}^0_d\rangle \;, \quad A_{\bar{f}} \;\equiv\; \langle \bar{f}|H|B^0_d\rangle \;, \quad \bar{\xi}_{\bar{f}} \;\equiv\; e^{2i\phi_B}\frac{A_{\bar{f}}}{\bar{A}_{\bar{f}}} \;. \tag{3}$$

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'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

$$Pr(l^{\pm}X^{\mp},f)_- \;\propto\; |A_l|^2|A_f|^2\left[\frac{1+|\xi_f|^2}{2} \mp \frac{1}{1+x_d^2}\frac{1-|\xi_f|^2}{2}\right] \;, \tag{4}$$

and

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

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

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

and

$$\begin{aligned} Pr(l^{\pm}X^{\mp},f;\Delta t)_+ \;\;\propto\;\; & |A_l|^2|A_f|^2 e^{-\Gamma|\Delta t|}\left[\frac{1+|\xi_f|^2}{2} \mp \frac{1}{\sqrt{1+x_d^2}}\frac{1-|\xi_f|^2}{2}\cos(\Delta m\Delta t + \phi_{x_d})\right. \\ & \left. \pm \frac{1}{\sqrt{1+x_d^2}} Im\xi_f \sin(\Delta m\Delta t + \phi_{x_d})\right] \;, \end{aligned} \tag{7}$$

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

From Eqs. (4)-(7) one can straightforwardly obtain the decay probabilities associated with $B^0_d \to \bar{f}$ 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

$$\mathcal{A}_C^S \equiv \frac{Pr(l^-X^+, f)_C - Pr(l^+X^-, \bar{f})_C}{Pr(l^-X^+, f)_C + Pr(l^+X^-, \bar{f})_C} , \tag{8}$$

and

$$\mathcal{A}_C^A(\Delta t) \equiv \frac{Pr(l^-X^+, f; \Delta t)_C - Pr(l^+X^-, \bar{f}; \Delta t)_C}{Pr(l^-X^+, f; \Delta t)_C + Pr(l^+X^-, \bar{f}; \Delta t)_C} . \tag{9}$$

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

$$\begin{aligned} \mathcal{A}_-^S &= \frac{1}{1+x_d^2}\mathcal{U}_f , \\ \mathcal{A}_+^S &= \frac{1-x_d^2}{(1+x_d^2)^2}\mathcal{U}_f + \frac{2x_d}{(1+x_d^2)^2}\mathcal{V}_f ; \end{aligned} \tag{10}$$

and

$$\begin{aligned} \mathcal{A}_-^A(\Delta t) &= \mathcal{U}_f \cos(\Delta m \Delta t) + \mathcal{V}_f \sin(\Delta m \Delta t) , \\ \mathcal{A}_+^A(\Delta t) &= \frac{1}{\sqrt{1+x_d^2}}\left[\mathcal{U}_f \cos(\Delta m \Delta t + \phi_{x_d}) + \mathcal{V}_f \sin(\Delta m \Delta t + \phi_{x_d})\right] , \end{aligned} \tag{11}$$

where

$$\mathcal{U}_f = \frac{1-|\xi_f|^2}{1+|\xi_f|^2} , \qquad \mathcal{V}_f = \frac{-2Im\xi_f}{1+|\xi_f|^2} . \tag{12}$$

Non-vanishing $\mathcal{U}_f$ and $\mathcal{V}_f$ 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) $\mathcal{A}_-^S$ is a pure measure of direct CP violation, while $\mathcal{A}_+^S$ contains both direct and indirect CP asymmetries. A combination of the measurements for $\mathcal{A}_\pm^S$ can in principle distinguish between direct and indirect CP-violating effects in neutral B-meson decays [8]. From Eqs. (10) and (12), we obtain

$$\begin{aligned} \mathcal{U}_f &= (1+x_d^2)\mathcal{A}_-^S , \\ \mathcal{V}_f &= \frac{(1+x_d^2)^2}{2x_d}\left[\mathcal{A}_+^S - \frac{1-x_d^2}{1+x_d^2}\mathcal{A}_-^S\right] . \end{aligned} \tag{13}$$

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

$$\mathcal{A} \;=\; \frac{1}{1+x_d^2}\mathcal{U}_f + \frac{x_d}{1+x_d^2}\mathcal{V}_f \;, \tag{14}$$

the direct and indirect parts of $\mathcal{A}_+^S$ 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:

$$\mathcal{A}_+^A(\Delta t) \;=\; \frac{1}{\sqrt{1+x_d^2}}\mathcal{A}_-^A\left(\Delta t + \frac{\phi_{x_d}}{\Delta m}\right) \;. \tag{15}$$

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

(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

$$\mathcal{A}_-^A\left(\frac{n\pi}{\Delta m}\right) \;=\; \sqrt{1+x_d^2}\mathcal{A}_+^A\left(\frac{n\pi}{\Delta m} - \frac{\phi_{x_d}}{\Delta m}\right) \;=\; (-1)^n\mathcal{U}_f \;, \tag{16}$$

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 $V_{ub}V_{uq}^* + V_{cb}V_{cq}^* + V_{tb}V_{tq}^* = 0$, the decay amplitudes A_f and $\bar{A}_{\bar{f}}$ can be symbolically expressed as

$$\begin{aligned} A_f &= \left[A_u e^{i(-\phi_u+\delta_u)} + A_c e^{i(-\phi_c+\delta_c)}\right] e^{-i\phi_K} \;, \\ \bar{A}_{\bar{f}} &= n_{CP}\left[A_u e^{i(\phi_u+\delta_u)} + A_c e^{i(\phi_c+\delta_c)}\right] e^{i\phi_K} \;, \end{aligned} \tag{17}$$

where $\phi_u \equiv \arg(V_{ub}V_{uq}^*)$ and $\phi_c \equiv \arg(V_{cb}V_{cq}^*)$ 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 ϕ_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 $|f\rangle$ contains a single K_S or K_L, and $\phi_K = 0$ when $|f\rangle$ is of zero strangeness). Defining $h \equiv A_c/A_u$,

$\delta \equiv \delta_c - \delta_u$, and $\phi_M \equiv \phi_B - \phi_K$, one obtains

$$\begin{aligned}
|A_f|^2 &= A_u^2 \left[1 + 2h\cos(\delta + \phi_u - \phi_c) + h^2\right] , \\
|\xi_f|^2 &= \frac{1 + 2h\cos(\delta - \phi_u + \phi_c) + h^2}{1 + 2h\cos(\delta + \phi_u - \phi_c) + h^2} , \\
Im\xi_f &= n_{CP} \frac{\sin 2(\phi_u - \phi_M) + 2h\cos\delta\sin(\phi_u + \phi_c - 2\phi_M) + h^2\sin 2(\phi_c - \phi_M)}{1 + 2h\cos(\delta + \phi_u - \phi_c) + h^2} .
\end{aligned} \tag{18}$$

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 ($\phi_{u,c}$, ϕ_M, $A_{u,c}$, and δ). If the relevant weak phases have been well determined elsewhere, one may use these relations to probe $A_{u,c}$ and δ, in order to obtain the information on final-state interactions. In principle, the decay amplitudes A_f and $\bar{A}_{\bar{f}}$ can be evaluated with the help of effective weak Hamiltonians [11] and QCD [12]. The experimental determination of $A_{u,c}$ and δ 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 $\bar{A}_{\bar{f}}$. As a result, Eq. (18) is simplified as

$$|A_f| = A_c , \qquad |\xi_f| = 1 , \qquad Im\xi_f = n_{CP}\sin 2(\phi_c - \phi_M) , \tag{19}$$

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 $\mathcal{A}_-^A(\Delta t)$ and $\mathcal{A}_+^A(\Delta t)$ as well as between $\mathcal{A}_-^S$ and $\mathcal{A}_+^S$ in Fig. 1. Obviously one of the angles of the CKM unitarity triangle, $\beta \equiv \arg(-V_{cb}^* V_{cd}/V_{tb}^* V_{td})$, can be reliably determined from the measurements of $\mathcal{A}_\pm^A(\Delta t)$ or $\mathcal{A}_+^S$ 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 δ 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 $\bar{B}_d^0 \rightarrow \phi K_S$ 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. CP asymmetries in B_d decays to non-CP eigenstates

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

$$
\begin{aligned}
\mathcal{A}_-^S &= 0 \, , \\
\mathcal{A}_+^S &= \frac{-2x_d Im(\xi_f - \bar{\xi}_{\bar{f}})}{2 + x_d^2 + x_d^4 + x_d^2(3 + x_d^2)|\xi_f|^2 - 2x_d Im(\xi_f + \bar{\xi}_{\bar{f}})} \, ;
\end{aligned}
\tag{20}
$$

and

$$
\begin{aligned}
\mathcal{A}_-^A(\Delta t) &= \frac{-Im(\xi_f - \bar{\xi}_{\bar{f}}) \sin(\Delta m \Delta t)}{(1 + |\xi_f|^2) + F(\xi_f, \bar{\xi}_{\bar{f}}, \Delta m \Delta t)} \, , \\
\mathcal{A}_+^A(\Delta t) &= \frac{-Im(\xi_f - \bar{\xi}_{\bar{f}}) \sin(\Delta m \Delta t + \phi_{x_d})}{\sqrt{1 + x_d^2}(1 + |\xi_f|^2) + F(\xi_f, \bar{\xi}_{\bar{f}}, \Delta m \Delta t + \phi_{x_d})} \, ,
\end{aligned}
\tag{21}
$$

where F is a function defined as

$$
F(x, y, z) \equiv (1 - |x|^2) \cos z - Im(x + y) \sin z \, . \tag{22}
$$

Compared with the CP asymmetries in neutral B decays to CP eigenstates, here $\mathcal{A}_+^S$ is a pure measure of CP violation via B_d^0-$\bar{B}_d^0$ mixing. Note that the evolution of $\mathcal{A}_\pm^A(\Delta t)$ slightly deviates from the harmonic oscillation. From the above equations we see that the quantities $|\xi_f|$, $Im\xi_f$, and $Im\bar{\xi}_{\bar{f}}$ can be determined if the measurements of $\mathcal{A}_+^S$ or $\mathcal{A}_\pm^A(\Delta t)$ are carried out at future B factories. It should be noted that in some previous studies, $\bar{\xi}_{\bar{f}} = \xi_f^*$ was taken in order to simplify final-state interactions and allow numerical estimates. Certainly this is a very special condition and only valid for a few decay modes. The processes shown in Fig. 2 provide an example where $\bar{\xi}_{\bar{f}} \neq \xi_f^*$, since the final states $\overset{(-)}{D}{}^{(*)0} K_S$ contain both $I = 0$ and $I = 1$ isospin configurations.

Symbolically the decay amplitudes A_f ($A_{\bar{f}}$) and $\bar{A}_{\bar{f}}$ ($\bar{A}_f$) can be written as

$$
\begin{aligned}
A_f &= A_\delta e^{i(-\phi+\delta)} e^{-i\phi_K} , \quad & \bar{A}_{\bar{f}} &= A_\delta e^{i(\phi+\delta)} e^{i\phi_K} ; \\
A_{\bar{f}} &= A_{\tilde{\delta}} e^{i(-\tilde{\phi}+\tilde{\delta})} e^{-i\phi_K} , \quad & \bar{A}_f &= A_{\tilde{\delta}} e^{i(\tilde{\phi}+\tilde{\delta})} e^{i\phi_K} ,
\end{aligned}
\tag{23}
$$

where $\phi \equiv \arg(V_{cb}V^*_{uq})$ and $\tilde{\phi} \equiv \arg(V_{ub}V^*_{cq})$ (with $q = d, s$) are the b-decay (weak) phases, δ and $\tilde{\delta}$ are the corresponding strong phases, A_δ and $A_{\tilde{\delta}}$ are the real (positive) hadronic amplitudes, and ϕ_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

$$
\begin{aligned}
Im\xi_f &= \frac{A_{\tilde{\delta}}}{A_\delta} \sin(\Delta\delta + \phi + \tilde{\phi} - 2\phi_M) , \\
Im\bar{\xi}_{\bar{f}} &= \frac{A_{\tilde{\delta}}}{A_\delta} \sin(\Delta\delta - \phi - \tilde{\phi} + 2\phi_M) .
\end{aligned}
\tag{24}
$$

Or equivalently,

$$
\begin{aligned}
Im(\xi_f + \bar{\xi}_{\bar{f}}) &= 2|\xi_f| \sin\Delta\delta \cos(\phi + \tilde{\phi} - 2\phi_M) , \\
Im(\xi_f - \bar{\xi}_{\bar{f}}) &= 2|\xi_f| \cos\Delta\delta \sin(\phi + \tilde{\phi} - 2\phi_M) .
\end{aligned}
\tag{25}
$$

From these relations one can reliably determine $\Delta\delta$ and $(\phi + \tilde{\phi} - 2\phi_M)$, once $|\xi_f|$, $Im\xi_f$, and $Im\bar{\xi}_{\bar{f}}$ 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], $B^0_d \rightarrow \overset{(-)}{D}{}^{0(*)} K_S$ and their CP-conjugate processes have been considered to probe the angles of the CKM unitarity triangle α and β 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 $f = D^{(*)\pm}\pi^\mp$, $\overset{(-)}{D}{}^{(*)0}\pi^0$, $F^{(*)\pm}K^\mp$, and $\overset{(-)}{D}{}^{(*)0}J/\psi$. 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_d and $\bar{B}^0_d$ 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 $B^0_s/\bar{B}^0_s \rightarrow J/\psi\phi$ and $\phi \overset{(-)}{D}{}^0$ is quite helpful.

It is worth while at this point to remark that in Eq. (17) (or Eq. (23)) the decay amplitudes A_f and $\bar{A}_{\bar{f}}$ are parametrized in terms of their weak phases, where all the strong interaction contributions are included in $A_{u,c}$ and $\delta_{u,c}$ (or A_δ, $A_{\tilde{\delta}}$, δ 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

[1] N. Cabibbo, Phys. Rev. Lett. 10 (1963) 531; M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49 (1973) 652.

[2] M. Bander, D. Silverman, and A. Soni, Phys. Rev. Lett. 43 (1979) 242; A.B. Carter and A.I. Sanda, Phys. Rev. Lett. 45 (1980) 952; I.I. Bigi and A.I. Sanda, Nucl. Phys. B193 (1981) 85; L. Wolfenstein, Nucl. Phys. B246 (1984) 45; L.L. Chau and H.Y. Cheng, Phys. Rev. Lett. 53 (1984) 1037; I. Dunietz and J.L. Rosner, Phys. Rev. D34 (1986) 1404; D. Du, I. Dunietz, and D. Wu, Phys. Rev. D34 (1986) 3414; for a review, see: I.I. Bigi, V.A. Khoze, N.G. Uraltsev, and A.I. Sanda, in *CP Violation*, ed. C. Jarlskog (World Scientific, Singapore, 1988), p. 175.

[3] L. Wolfenstein, Phys. Rev. D43 (1991) 151.

[4] *The Proceedings of the ECFA Workshop on the Physics of a B Meson Factory*, eds. R. Aleksan and A. Ali, DESY 93-053 (1993); *Conceptual Design for a B Factory Based on CESR*, CESR/CLEO Collaboration, CLNS 91-1050 (1991); *Task Force Report on Asymmetric B Factory at KEK*, KEK report, 1990; *Feasibility Study for an Asymmetric B Factory Based on PEP*, SLAC-352 (1989); a complete reference on all the considered B factories can be found in: T. Nakada, CERN 90-02 (1990).

[5] G.J. Feldman et al., in *High Energy Physics in the 1990's*, ed. S. Jensen (World Scientific, Singapore, 1988), p. 561; S. Stone, Mod. Phys. Lett. A3 (1988) 541; R. Aleksan et al., Phys. Rev. D39 (1989) 1283.

[6] Y. Nir and H.R. Quinn, Annu. Rev. Nucl. Part. Sci. 42 (1992) 211; Y. Nir, SLAC-PUB-5874/WIS-92/67/PH (1992).

[7] ALEPH Collaboration, D. Buskulic et al., Phys. Lett. B313 (1993) 498; CLEO Collaboration, M. Artuso et al., Phys. Rev. Lett. 62 (1989) 2233; ARGUS Collaboration, H. Albrecht et al., Phys. Lett. B192 (1987) 245.

[8] Z. Xing and D. Du, Phys. Lett. B276 (1992) 511.

[9] M. Gronau, Phys. Rev. Lett. 63 (1989) 1451; B. Grinstein, Phys. Lett. B229 (1989) 280; D. London and R.D. Peccei, Phys. Lett. B223 (1989) 257.

[10] M. Gronau and J.L. Rosner, Phys. Rev. Lett. 72 (1994) 191; Phys. Rev. D49 (1994) 254.

[11] A.J. Buras et al., Nucl. Phys. B370 (1992) 69; and references therein.

[12] H. Fritzsch, Summary talk given at the workshop on *QCD 20 Years Later*, June 1992, Aachen, Germany.

[13] See, for example, J.-M. Gerard and W.S. Hou, Phys. Rev. D43 (1991) 2909; H. Simma and D. Wyler, Phys. Lett. B272 (1991) 395.

[14] CLEO Collaboration, R. Ammar et al., Phys. Rev. Lett. 71 (1993) 674.

[15] N.G. Deshpande and J. Trampetic, Phys. Rev. D41 (1990) 895.

[16] CLEO Collaboration, M. Battle et al., Phys. Rev. Lett. 71 (1993) 3922.

[17] M. Gronau and D. London, Phys. Lett. B253 (1991) 483; I.I. Bigi, Z. Phys. C51 (1991) 267.

[18] A. Ali, CERN-TH.7123/93 (1993); A. Ali and D. London, DESY 93-022/UdeM-LPN-TH138 (1993).

[19] For a review of recent developments in this direction, see: *B Decays*, ed. S. Stone (World Scientific, Singapore, 1992); *Review Volume on Heavy Flavours*, eds. A.J. Buras and M. Lindner (World Scientific, Singapore, 1992).

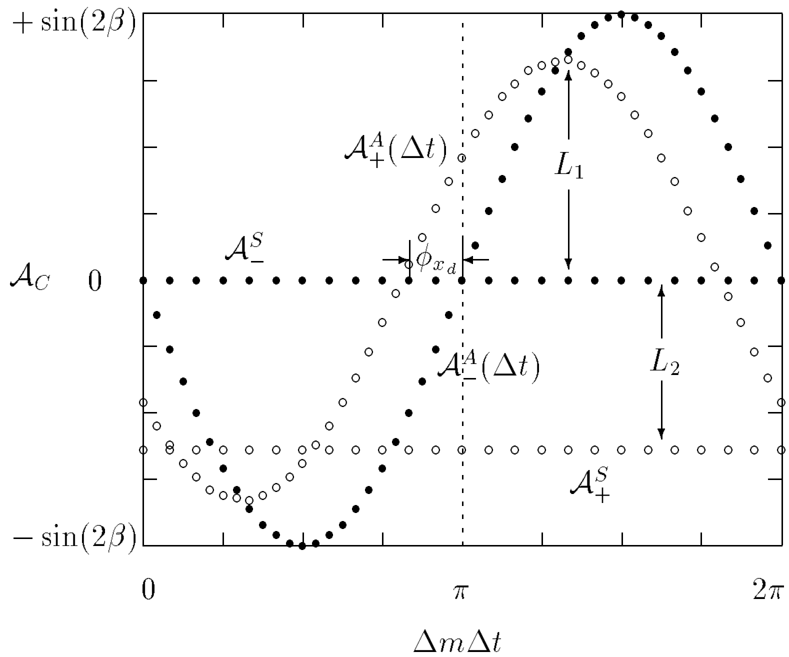

Fig. 1 CP asymmetries in B_d^0 versus $\bar{B}_d^0 \rightarrow J/\psi K_S$ at the $\Upsilon(4S)$. Here $x_d \equiv \Delta m/\Gamma$ is a measurable of B_d^0-$\bar{B}_d^0$ mixing, and $\phi_{x_d} = \tan^{-1} x_d$; $\beta \equiv \arg(-V_{cb}^* V_{cd}/V_{tb}^* V_{td})$ is an angle of the CKM unitarity triangle;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

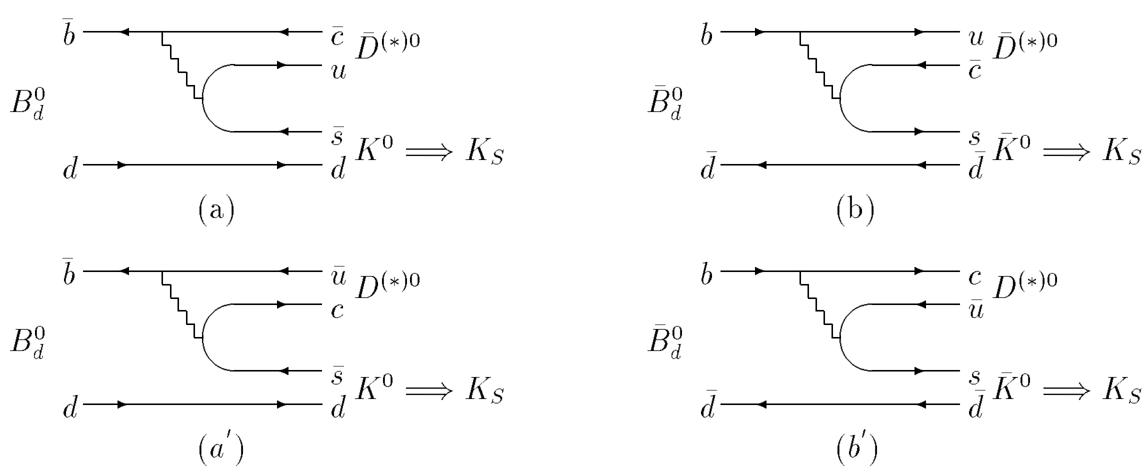

Fig. 2 Quark diagrams for B_d^0 versus $\bar{B}_d^0$ decays to $\bar{D}^{(*)0} K_S$ and $D^{(*)0} K_S$.