Possible Signals of $D^0$-$\bar{D}^0$ Mixing and CP Violation

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Abstract

In view of the discovery potential associated with the future experiments of high-luminosity fixed target facilities, B-meson factories and \(\tau\)-charm factories, we highlight some typical signals of $D^0$-$\bar{D}^0$ mixing and CP violation which are likely to show up in neutral $D$-meson decays to the semileptonic final states, the hadronic CP eigenstates, the hadronic non-CP eigenstates and the CP-forbidden states. Both time-dependent and time-integrated measurements are discussed, and particular interest is paid to $D^0/\bar{D}^0 \to K_{S,L} + \pi^0$ and $D^0/\bar{D}^0 \to K^{\pm}\pi^{\mp}$ transitions.

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1 Introduction

The study of $D^0$-$\bar{D}^0$ mixing and $CP$ violation in neutral $D$-meson decays is not only complementary to our knowledge obtained and to be obtained from $K^0-\bar{K}^0$ and $B^0-\bar{B}^0$ systems, but also important for exploring underlying new physics that is out of reach of the standard model predictions. A large discovery potential associated with this topic is expected to exist in the future delicate experiments of high-luminosity fixed target facilities, $B$-meson factories, and $\tau$-charm factories [1].

Without $CP$ violation, the mass eigenstates of $D^0$ and $\bar{D}^0$ mesons can be written as

\[
|D_L\rangle = p|D^0\rangle + q|\bar{D}^0\rangle, \\
|D_H\rangle = p|D^0\rangle - q|\bar{D}^0\rangle, 
\]

where $p$ and $q$ are complex parameters determined by off-diagonal elements of the $D^0$-$\bar{D}^0$ mixing Hamiltonian. The rate of $D^0$-$\bar{D}^0$ mixing is commonly measured by two well-defined dimensionless quantities,

\[
x_D \equiv \frac{\Delta m}{\Gamma}, \\
y_D \equiv \frac{\Delta \Gamma}{2\Gamma},
\]

which correspond to the mass and width differences of $D_H$ and $D_L$ (i.e., $\Delta m \equiv m_H - m_L$ and $\Delta \Gamma \equiv \Gamma_L - \Gamma_H$). The latest result from the Fermilab experiment E791 has set an upper bound on the rate of $D^0$-$\bar{D}^0$ mixing [2]:

\[
r_D \equiv \frac{x_D^2 + y_D^2}{2} < 5 \times 10^{-3}. 
\]

In the standard model, the short-distance contribution to $D^0$-$\bar{D}^0$ mixing is via box diagrams and its magnitude is expected to be negligibly small. But different approaches to the long-distance effects in $D^0$-$\bar{D}^0$ mixing, which come mainly from the real intermediate states of SU(3) multiplets, have given dramatically different estimates for the magnitudes of $x_D$ and $y_D$ [3]. If calculations based on the standard model can reliably limit $x_D$ and $y_D$ to be well below $10^{-2}$, then observation of $r_D$ at the level of $10^{-4}$ or so will imply the existence of new physics [4]. On the other hand, improved experimental knowledge of $r_D$, in particular the relative magnitude of $x_D$ and $y_D$, can definitely clarify the ambiguities in current theoretical estimates and shed some light on both the dynamics of $D^0$-$\bar{D}^0$ mixing and possible sources of new physics beyond the standard model.

In principle, there may be three different types of $CP$-violating signals in neutral $D$-meson transitions [3, 4]:

(a) $CP$ violation in $D^0$-$\bar{D}^0$ mixing. This implies $|q/p| \neq 1$. In practice, we have the following $CP$-violating observable:

\[
\Delta_D \equiv \frac{|p|^4 - |q|^4}{|p|^4 + |q|^4}. 
\]

It is expected that the magnitude of $\Delta_D$ should be at most of the order $10^{-3}$ in the standard model. However, a reliable estimation of $\Delta_D$ suffers from large long-distance uncertainties.

(b) $CP$ violation in direct decay. For a decay mode $D^0 \to f$ and its $CP$-conjugate process $\bar{D}^0 \to \bar{f}$, this implies

\[
|\langle \bar{f}|H_{eff}|\bar{D}^0\rangle| \equiv \left| \sum_n \left[ A_n e^{i(\delta_n - \phi_n)} \right] \right| \neq |\langle f|H_{eff}|D^0\rangle| \equiv \left| \sum_n \left[ A_n e^{i(\delta_n + \phi_n)} \right] \right|,
\]

(1.5)
where a parametrization of the decay amplitudes with the weak ($\phi_n$) and strong ($\delta_n$) phases is also given. We see that $n \geq 2$, $\phi_m - \phi_n \neq 0$ or $\pi$ and $\delta_m - \delta_n \neq 0$ or $\pi$ are necessary conditions for the above direct $CP$ violation.

(c) $CP$ violation from the interplay of decay and mixing. Let us define two rephasing-invariant quantities

$$\lambda_f \equiv \frac{q}{p} \cdot \frac{\langle f | H_{\text{eff}} | D^0 \rangle}{\langle f | H_{\text{eff}} | D^0 \rangle}, \quad \bar{\lambda}_f \equiv \frac{p}{q} \cdot \frac{\langle \bar{f} | H_{\text{eff}} | D^0 \rangle}{\langle f | H_{\text{eff}} | D^0 \rangle},$$

(1.6)

where the hadronic states $f$ and $\bar{f}$ are common to the decay of $D^0$ (or $\bar{D}^0$). Even in the assumption of $|q/p| = 1$, indirect $CP$ violation can appear if $\text{Im}\lambda_f - \text{Im}\bar{\lambda}_f \neq 0$.

(1.7)

Provided $f$ is a $CP$ eigenstate (i.e., $|\bar{f} = \pm |f$)) and the decay is dominated by a single weak phase, then we have $\bar{\lambda}_f = \lambda_f^*$.

$CP$ violation at the percent level has not been observed in experiments $[7]$. But signals of $O(10^{-3})$ are expected in some neutral $D$ decays within the standard model, and those of $O(10^{-2})$ cannot be ruled out in some channels beyond the standard model.

Subsequently we shall highlight some typical signals of $D^0-\bar{D}^0$ mixing and $CP$ violation which are likely to show up in weak decays of neutral $D$ mesons. A systematic and comprehensive study of this topic can be found in Ref. $[6]$ and references therein.

2 Typical signals of $D^0-\bar{D}^0$ mixing

For simplicity and instruction, we assume $\Delta_D = 0$ in the discussion of $D^0-\bar{D}^0$ mixing effects. This assumption should be safe both within and beyond the standard model, and it can be tested by detecting $CP$ violation in the semileptonic decays of $D^0$ and $\bar{D}^0$ mesons.

A. Time-integrated measurements

For fixed target experiments or $e^+e^-$ collisions at the $\Upsilon(4S)$ resonance, the produced $D^0$ and $\bar{D}^0$ mesons are incoherent. Knowledge of $D^0-\bar{D}^0$ mixing is expected to come from ratios of the wrong-sign to right-sign events of semileptonic $D$ decays:

$$\frac{\mathcal{R}(D^0_{\text{phys}} \to K^+l^-\bar{\nu}_l)}{\mathcal{R}(D^0_{\text{phys}} \to K^-l^+\nu_l)} \approx \frac{\mathcal{R}(\bar{D}^0_{\text{phys}} \to K^-l^+\nu_l)}{\mathcal{R}(\bar{D}^0_{\text{phys}} \to K^+l^-\bar{\nu}_l)} \approx r_D$$

(2.1)

in the assumption made above. The Fermilab experiment E791 gives $r_D < 0.5\%$ at the 90% confidence level $[2]$, the best model-independent limit on $D^0-\bar{D}^0$ mixing today.

For a $\tau$-charm factory running on the $\psi(3.77)$ resonance, coherent $D^0\bar{D}^0$ events with odd $C$-parity can be produced. If $e^+e^-$ collisions take place at the $\psi(4.16)$ resonance, coherent $D^0\bar{D}^0$
Three types of joint decay modes are interesting for measuring $D^0$-$\bar{D}^0$ mixing:

\[(D^0_{\text{phys}} \bar{D}^0_{\text{phys}}) _C \longrightarrow (l^\pm X^\mp )_D (l^\pm X^\mp )_D,\]
\[(K^\pm \pi^\mp )_D (l^\pm X^\mp )_D,\]
\[(K^\pm \tau^\mp )_D (K^\pm \pi^\mp )_D,\]

where we have used the notations $X^+ \equiv K^+ \bar{\nu}_l$ and $X^- \equiv K^- \nu_l$. Note that $D^0 \to K^+\pi^-$ is a doubly Cabibbo-suppressed decay (DCSD). This effect is usually measured by the following ratio of decay rates:

\[R_{\text{DCSD}} \equiv \frac{|\langle K^+\pi^-|\mathcal{H}_{\text{eff}}|D^0\rangle|^2}{|\langle K^-\pi^+|\mathcal{H}_{\text{eff}}|D^0\rangle|^2}.\]  

In the assumption of $r_D = 0$, $R_{\text{DCSD}} \approx 0.77\%$ and $0.68\%$ are respectively obtained by CLEO II and Fermilab E791 experiments [8]. For our present purpose, we list the possible signals of $D^0$-$\bar{D}^0$ mixing associated with the joint decays (2.2) in Table 1, where $|q/p| = 1$ has been used and the interference terms $T_{\text{int}}^\pm$ are given by

\[T_{\text{int}}^+ = \sqrt{R_{\text{DCSD}} \left[ y_D \cos(\delta_{K\pi} - \phi_D) - x_D \sin(\delta_{K\pi} - \phi_D) \right]},\]
\[T_{\text{int}}^- = \sqrt{R_{\text{DCSD}} \left[ y_D \cos(\delta_{K\pi} + \phi_D) - x_D \sin(\delta_{K\pi} + \phi_D) \right]}\]  

with $\phi_D \equiv \text{arg}(q/p)$ and $\delta_{K\pi} \equiv \text{arg}(\langle K^+\pi^-|\mathcal{H}_{\text{eff}}|D^0\rangle/\langle K^-\pi^+|\mathcal{H}_{\text{eff}}|D^0\rangle)$. Here we have assumed $\delta_{K\pi}$ to be a pure strong phase shift by neglecting the tiny weak phase ($\sim 10^{-4}$) from the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements.

Table 1: $D^0$-$\bar{D}^0$ mixing and DCSD effects in three types of coherent $D^0$-$\bar{D}^0$ decays [9].

| Observable | Signal (C-odd) | Signal (C-even) |
|------------|----------------|-----------------|
| $\mathcal{R}(l^\pm X^\mp; l^\pm X^\mp)_C/\mathcal{R}(l^\pm X^\mp; l^\pm X^\mp)_C$ | $r_D$ | $3r_D$ |
| $\mathcal{R}(K^\pm \pi^\mp; l^\pm X^\mp)_C/\mathcal{R}(K^\pm \pi^\mp; l^\pm X^\mp)_C$ | $R_{\text{DCSD}} + r_D$ | $R_{\text{DCSD}} + 3r_D + 2T_{\text{int}}^\pm$ |
| $\mathcal{R}(K^\pm \pi^\mp; K^\pm \pi^\mp)_C/\mathcal{R}(K^\pm \pi^\mp; K^\pm \pi^\mp)_C$ | $r_D$ | $4R_{\text{DCSD}} + 3r_D + 4T_{\text{int}}^\pm$ |

We observe that $r_D$, $R_{\text{DCSD}}$ and $T_{\text{int}}^\pm$ can all be determined from measurements of the above joint decays, only if the size of $r_D$ is comparable with that of $R_{\text{DCSD}}$. In particular, the information about $T_{\text{int}}^\pm$ is useful to give some hints on the relative size of $x_D$ and $y_D$ as well as the $CP$-violating phase $\phi_D$. In the case that $D^0$-$\bar{D}^0$ mixing is negligibly small, we are able to isolate the DCSD rate $R_{\text{DCSD}}$ solely on the $\psi(3.77)$ resonance.
Figure 1: Illustrative plot for changes of two $D^0$-$\bar{D}^0$ mixing observables with proper time $t$, where $x_D = 0.05$, $y_D = 0$, $\delta_{K\pi} = 0$ and $\phi_D = \pi/2$ have been taken.

B. Time-dependent measurements

Let us illustrate two examples about the time-dependent measurement of $D^0$-$\bar{D}^0$ mixing. The first is associated with the well-known DCSDs $D^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^-\pi^+$ [10]. The time-dependent decay rates of these two modes, in comparison with the rates of their Cabibbo-allowed counterparts, read as follows:

\[
\frac{\mathcal{R}[D^0(t) \to K^+\pi^-]}{\mathcal{R}[D^0(t) \to K^-\pi^+]} = R_{DCSD} + T^+_\text{int}(\Gamma t) + \frac{r_D}{2} (\Gamma t)^2 ,
\]
\[
\frac{\mathcal{R}[\bar{D}^0(t) \to K^-\pi^+]}{\mathcal{R}[\bar{D}^0(t) \to K^+\pi^-]} = R_{DCSD} + T^-\text{int}(\Gamma t) + \frac{r_D}{2} (\Gamma t)^2 ,
\]

where $\Delta_D = 0$ has been assumed. Just for the purpose of illustration, we take $x_D = 0.05$, $y_D = 0$, $\delta_{K\pi} = 0$, $\phi_D = \pi/2$ and $R_{DCSD} = 0.7\%$ to plot changes of the above two observables with proper time $t$ in Fig. 1. We see that nonvanishing $D^0$-$\bar{D}^0$ mixing can give rise to detectable time-evolution behaviors in $\mathcal{R}[D^0(t) \to K^+\pi^-]/\mathcal{R}[D^0(t) \to K^-\pi^+]$ and $\mathcal{R}[\bar{D}^0(t) \to K^-\pi^+]/\mathcal{R}[\bar{D}^0(t) \to K^+\pi^-]$, while the difference between these two ratios comes from $CP$ violation hidden in the interference terms $T^{\pm}_{\text{int}}$.

Next we consider the $D^0$-$\bar{D}^0$ mixing signals in neutral $D$ decays to $CP$ eigenstates $K_S\pi^0$ and $K_L\pi^0$, where tiny $CP$-violating effects induced by $D^0$-$\bar{D}^0$ mixing ($\Delta_D$) and $K^0$-$\bar{K}^0$ mixing ($\epsilon_K$) are neglected. Since $D^0 \to K^0\pi^0$ is doubly Cabibbo-suppressed in contrast with the Cabibbo-allowed transition $D^0 \to \bar{K}^0\pi^0$, we define a ratio

\[
R'_{\text{DCSD}} \equiv \frac{\langle K^0\pi^0|\mathcal{H}_{\text{eff}}|D^0\rangle}{\langle K^0\pi^0|\mathcal{H}_{\text{eff}}|D^0\rangle}^2 ,
\]
Figure 2: Illustrative plot for changes of two $D^0$-$\bar{D}^0$ mixing observables with proper time $t$, where (a) $x_D = y_D = 0.05$, $\phi_D = \pi/4$ (corresponding to the solid curves) and (b) $x_D = 0.05$, $y_D = 0$, $\phi_D = \pi/2$ (corresponding to the dark solid curves) have been taken.

3 Typical signals of $CP$ violation

It is expected that $CP$ violation induced by $D^0$-$\bar{D}^0$ mixing (i.e., $\Delta_D$) can manifest itself, apparently or indirectly, in all neutral $D$-meson decay modes. But this effect should be negligibly

$$\frac{\mathcal{R}[\bar{D}^0(t) \to K_L\pi^0]}{\mathcal{R}[D^0(t) \to K_L\pi^0]} = \frac{2 + 2( y_D \cos \phi_D - x_D \sin \phi_D) (\Gamma t) + y_D^2 (\Gamma t)^2}{2 + 2( y_D \cos \phi_D + x_D \sin \phi_D) (\Gamma t) + y_D^2 (\Gamma t)^2}.$$  

Finally it is worth pointing out that a comparison of the interference terms in (2.7) with $T_{int}^\pm$ in (2.4) can provide a model-independent constraint on the strong phase shift $\delta_{K\pi}$. 
small in most cases. A constraint on $\Delta_D$ is possible through measuring the semileptonic decays of either incoherent or coherent $D^0$ and $\bar{D}^0$ mesons. For example,

$$\frac{\mathcal{R}(\bar{D}^0_{\text{phys}} \to K^{-} l^+ \nu_l) - \mathcal{R}(D^0_{\text{phys}} \to K^{+} l^- \bar{\nu}_l)}{\mathcal{R}(\bar{D}^0_{\text{phys}} \to K^{-} l^+ \nu_l) + \mathcal{R}(D^0_{\text{phys}} \to K^{+} l^- \bar{\nu}_l)} = \Delta_D \quad (3.1)$$

and

$$\frac{\mathcal{R}(K^{-} l^+ \nu_l; K^{-} l^+ \nu_l)_C - \mathcal{R}(K^{+} l^- \bar{\nu}_l; K^{+} l^- \bar{\nu}_l)_C}{\mathcal{R}(K^{-} l^+ \nu_l; K^{-} l^+ \nu_l)_C + \mathcal{R}(K^{+} l^- \bar{\nu}_l; K^{+} l^- \bar{\nu}_l)_C} = \Delta_D \quad (3.2)$$

for both $C$-odd and $C$-even cases. In the following we shall pay main attention to the direct and indirect $CP$ asymmetries in some nonleptonic $D$ transitions, where $\Delta_D = 0$ will be assumed.

### A. Time-integrated measurements

For neutral $D$ mesons decaying to a hadronic $CP$ eigenstate $f$, the observables of direct $CP$ violation in the decay amplitude and indirect $CP$ violation from the interplay of decay and $D^0$-$\bar{D}^0$ mixing are expressed as

$$A_{\text{dir}} \equiv \frac{1 - |\rho_f|^2}{1 + |\rho_f|^2}, \quad A_{\text{ind}} \equiv \frac{-2 \text{Im}(\bar{\rho}^\phi \rho_f)}{1 + |\rho_f|^2}, \quad (3.3)$$

where $\rho_f \equiv \langle f | \mathcal{H}_{\text{eff}} | D^0 \rangle / \langle f | \mathcal{H}_{\text{eff}} | D^0 \rangle$. In the time-integrated measurements, the following $CP$ asymmetries can be used to probe $A_{\text{dir}}$ and $A_{\text{ind}}$:

(a) For incoherent decays of $D^0$ and $\bar{D}^0$ mesons, we have

$$\frac{\mathcal{R}(D^0_{\text{phys}} \to f) - \mathcal{R}(\bar{D}^0_{\text{phys}} \to f)}{\mathcal{R}(D^0_{\text{phys}} \to f) + \mathcal{R}(\bar{D}^0_{\text{phys}} \to f)} \approx A_{\text{dir}} + x_D A_{\text{ind}}. \quad (3.4)$$

Note that a cancellation between $A_{\text{dir}}$ and $x_D A_{\text{ind}}$ may take place if they have the opposite signs, leading the above $CP$ asymmetry to a negligibly small value.

(b) For coherent decays of $D^0 \bar{D}^0$ pairs at the $\psi(3.77)$ or $\psi(4.16)$ resonance, one can get

$$\frac{\mathcal{R}(l^{-} X^{+}; f)_C - \mathcal{R}(l^{+} X^{-}; f)_C}{\mathcal{R}(l^{-} X^{+}; f)_C + \mathcal{R}(l^{+} X^{-}; f)_C} \approx \begin{cases} A_{\text{dir}} & (C-\text{odd}) \\ A_{\text{dir}} + 2x_D A_{\text{ind}} & (C-\text{even}) \end{cases}. \quad (3.5)$$

Clearly it is possible to distinguish between direct and indirect $CP$-violating signals, if the magnitude of $A_{\text{dir}}$ is comparable with that of $x_D A_{\text{ind}}$.

(c) At the $\psi(4.16)$ resonance there may be a type of $CP$ violation arising from the $CP$-forbidden decay channels. For example,

$$\frac{\mathcal{R}(f; f)_{C-\text{odd}}}{\mathcal{R}(f; f)_{C-\text{even}}} \approx r_D \left( A_{\text{dir}}^2 + A_{\text{ind}}^2 \right), \quad (3.6)$$

where we have assumed $A_{\text{dir}} < 10\%$ and $A_{\text{ind}} < 10\%$. Such a $CP$-violating signal is in principle interesting, but measuring it might be very difficult due to the smallness of $r_D$.

A more special case is associated with $D^0/\bar{D}^0 \to K_{S,L} + \pi^0$, where $CP$ violation in the decay amplitude or that from $K^0-\bar{K}^0$ mixing can be neglected. We find, on the $\psi(3.77)$ resonance (i.e., $C$-odd), that

$$\frac{\mathcal{R}(K_S \pi^0; K_S \pi^0)}{\mathcal{R}(K_S \pi^0; K_{L} \pi^0)} \approx \frac{\mathcal{R}(K_L \pi^0; K_L \pi^0)}{\mathcal{R}(K_S \pi^0; K_{L} \pi^0)} \approx r_D \sin^2 \phi_D. \quad (3.7)$$
If \( r_D \) were close to its experimental upper bound and \( \phi_D \) were enhanced by new physics, this signal could be measured at a \( \tau \)-charm factory \(^4\).

Now we turn our attention to \( CP \) violation in neutral \( D \) decays to non-\( CP \) eigenstates. Again \( D^0/\bar{D}^0 \to K^{\pm}\pi^{\mp} \) can be taken as a good example for illustration. It is expected that only indirect \( CP \) violation appears in these four decay modes. We denote the signals as follows:

\[
A_{K\pi} \equiv \sqrt{R_{DCSD}} \sin \phi_D \left(y_D \sin \delta_{K\pi} - x_D \cos \delta_{K\pi}\right),
\]

\[
A'_{K\pi} \equiv \sqrt{R_{DCSD}} \sin \phi_D \left(y_D \sin \delta_{K\pi} + x_D \cos \delta_{K\pi}\right),
\]

(3.8)

where \( \phi_D \) and \( \delta_{K\pi} \) have been defined before. If \( |y_D| \ll |x_D| \), as anticipated in some non-standard models \([4, 10]\), we arrive at \( A'_{K\pi} \approx -A_{K\pi} \). For incoherent \( D \)-meson decays, \( A_{K\pi} \) can be measured from the decay-rate asymmetry

\[
\frac{\mathcal{R}(D^0_{phys} \to K^{+}\pi^-) - \mathcal{R}(D^0_{phys} \to K^{-}\pi^+)}{\mathcal{R}(D^0_{phys} \to K^{+}\pi^-) + \mathcal{R}(D^0_{phys} \to K^{-}\pi^+)} \approx A_{K\pi}.
\]

(3.9)

\( CP \)-violating signals in coherent \( D^0/\bar{D}^0 \) decays to the final states \((l^\pm X^{\pm}_D), (K^{\pm}\pi^{\mp})_D\) and \((K^{\pm}\pi^{\mp})_D, (K^{\pm}\pi^{\mp})_D\) are listed in Table 2, where the \( C \)-odd case (associated with vanishing \( CP \) asymmetries) is not included.

Table 2: \( CP \)-violating effects in typical coherent \( D^0/\bar{D}^0 \) decays at the \( \psi(4.16) \) resonance \([6, 9]\):

| Observable | Signal | \( (C\text{-even}) \) |
|------------|--------|-----------------|
| \( \mathcal{R}(l^+X^-;K^{+}\pi^-)_C - \mathcal{R}(l^-X^+;K^{-}\pi^+)_C \) \( \mathcal{R}(l^+X^-;K^{+}\pi^-)_C + \mathcal{R}(l^-X^+;K^{-}\pi^+)_C \) | 2\( A_{K\pi} \) |
| \( \mathcal{R}(l^-X^+;K^{+}\pi^-)_C - \mathcal{R}(l^+X^-;K^{-}\pi^+)_C \) \( \mathcal{R}(l^-X^+;K^{+}\pi^-)_C + \mathcal{R}(l^+X^-;K^{-}\pi^+)_C \) | 4\( A'_{K\pi} \) |
| \( \mathcal{R}(K^{+}\pi^-;K^{+}\pi^-)_C - \mathcal{R}(K^{-}\pi^+;K^{-}\pi^+)_C \) \( \mathcal{R}(K^{+}\pi^-;K^{+}\pi^-)_C + \mathcal{R}(K^{-}\pi^+;K^{-}\pi^+)_C \) | 8\( A_{K\pi} \) |

We see from Table 2 that it is possible to measure (or constrain) \( A_{K\pi} \) and \( A'_{K\pi} \) on the \( \psi(4.16) \) resonance with \( C \)-even \( D^0/\bar{D}^0 \) events at a \( \tau \)-charm factory.

**B. Time-dependent measurements**

\(^4\)In contrast with (3.7), there may be a similar \( CP \)-violating signal for \( B_d \) decays to \( K_SX_c \) and \( K_LX_c \) on the \( \Upsilon(4S) \) resonance, where \( X_c = J/\psi, \psi', \eta_c, \eta_c' \), etc \([4]\). This signal is expected to be of \( O(10\%) \) due to the large \( B_d^0-B_d^0 \) mixing rate \( (x_B \approx 0.7) \) and significant \( CP \)-violating phase \( (\phi_B \sim 19^\circ - 70^\circ) \) in the standard model, thus it should be detectable at the forthcoming \( B \)-meson factories.
For coherent $D^0 \bar{D}^0$ decays at the $\psi(3.77)$ and $\psi(4.16)$ resonances, to measure the time dependence of a joint decay mode requires asymmetric $e^+e^-$ collisions, like the case of an asymmetric $B$-meson factory. A brief discussion about this possibility can be found in Appendix A of Ref. [6]. For incoherent neutral-$D$-meson decays to a $CP$ eigenstate $f$, one can get the time-dependent $CP$ asymmetry

$$R[D^0(t) \to f] - R[\bar{D}^0(t) \to f] \approx A_{\text{dir}} + x_D A_{\text{ind}} (\Gamma t),$$

where $A_{\text{dir}}$ and $A_{\text{ind}}$ have been defined before.

Taking $D^0/\bar{D}^0 \to K_{S,L} + \pi^0$ for example, we obtain

$$\frac{R[D^0(t) \to K_S\pi^0] - R[\bar{D}^0(t) \to K_S\pi^0]}{R[D^0(t) \to K_S\pi^0] + R[\bar{D}^0(t) \to K_S\pi^0]} \approx -2\text{Re}\epsilon_K + x_D \sin \phi_D (\Gamma t),$$

$$\frac{R[D^0(t) \to K_L\pi^0] - R[\bar{D}^0(t) \to K_L\pi^0]}{R[D^0(t) \to K_L\pi^0] + R[\bar{D}^0(t) \to K_L\pi^0]} \approx -2\text{Re}\epsilon_K - x_D \sin \phi_D (\Gamma t)$$

in the assumption of $\Delta_D = 0$. Here $\text{Re}\epsilon_K \approx 1.6 \times 10^{-3}$, signifying the $CP$ asymmetry induced by $K^0-\bar{K}^0$ mixing, cannot be neglected [12]. Even if the $x_D \sin \phi_D$ term is vanishingly small, the effect of $\text{Re}\epsilon_K$ is still detectable from the above decay modes. For the purpose of illustration, we take $x_D = 0.01$ and $\phi_D = 0.1$ to plot changes of the $CP$ asymmetries (3.11) with proper time $t$ in Fig. 3.

Indirect $CP$ violation in neutral-$D$-meson decays to hadronic non-$CP$ eigenstates can be illustrated by taking $D^0/\bar{D}^0 \to K^\pm \pi^\mp$ for example. Assuming $\Delta_D = 0$, we have

$$\frac{R[\bar{D}^0(t) \to K^+\pi^-] - R[D^0(t) \to K^-\pi^+]}{R[\bar{D}^0(t) \to K^+\pi^-] + R[D^0(t) \to K^-\pi^+]} \approx A_{K\pi} (\Gamma t),$$

Figure 3: Illustrative plot for changes of $CP$-violating asymmetries with proper time $t$, where $x_D = 0.01$ and $\phi_D = 0.1$ have been taken.
Figure 4: Illustrative plot for changes of $CP$-violating asymmetries with proper time $t$, where $x_D = 0.05$, $y_D = 0$, $\delta_{K\pi} = 0$ and $\phi_D = \pi/2$ have been taken.

where $A_{K\pi}$ has been given in Eq. (3.8). Another $CP$ asymmetry reads

$$\frac{\mathcal{R}[D^0(t) \to K^+\pi^-] - \mathcal{R}[\bar{D}^0(t) \to K^-\pi^+]}{\mathcal{R}[D^0(t) \to K^+\pi^-] + \mathcal{R}[D^0(t) \to K^-\pi^+]} \approx \frac{A'_{K\pi}}{N_{K\pi}} (\Gamma t)$$

(3.13)

with

$$N_{K\pi} \equiv R_{DCSD} + \frac{T^+_\text{int} + T^-_\text{int}}{2} (\Gamma t) + \frac{r_D}{2} (\Gamma t)^2.$$  

(3.14)

Here $A'_{K\pi}$ and $T^\pm_\text{int}$ have been defined in Eqs. (3.8) and (2.4), respectively. Obviously the asymmetry (3.13) may be large enough or even maximum in magnitude, due to the smallness of $N_{K\pi}$ suppressed by DCSD and mixing effects. To give one a numerical feeling, we plot changes of the $CP$ asymmetries (3.12) and (3.13) with proper time $t$ in Fig. 4 by taking $x_D = 0.05$, $y_D = 0$, $\phi_D = \pi/2$, $\delta_{K\pi} = 0$ and $R_{DCSD} = 0.7\%$.

4 Conclusion

We have higlighted some possible signals of $D^0$-$\bar{D}^0$ mixing and $CP$ violation in neutral $D$-meson decays. Quantitatively, it remains difficult (even impossible) to give reliable predictions for most of such signals. Some progress can certainly be made in this topic if the future experiments are able to probe the $D^0$-$\bar{D}^0$ mixing rate $r_D$ down to the $10^{-4}$ level and to search for $CP$-violating asymmetries down to the $10^{-3}$ level. The emergence of new physics in the charm sector would offer a reward for all sophisticated experimental efforts which are underway today.

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