Direct CP Violation in Charm Decays due to

Left-Right Mixing

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Abstract

Motivated by the 3.8\(\sigma\) deviation from no CP violation hypothesis for the CP asymmetry (CPA) difference between \(D^0 \to K^+K^-\) and \(D^0 \to \pi^+\pi^-\), reported recently by LHCb and CDF, we investigate the CP violating effect due to the left-right (LR) mixing in the general LR symmetric model. In particular, in the non-manifest LR model we show that the large CPA difference could be explained, while the constraints from \((\epsilon'/\epsilon)_K\) and \(D^0\bar{D}^0\) are satisfied.
In the standard model (SM), we expect that the CP asymmetries (CPAs) in $D^0$ decays, defined by

$$A_{CP}(D^0 \to f) \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}, \quad (f = K^+K^-, \pi^+\pi^-)$$

should be vanishingly small, and therefore an observation of a large CPA in the charm sector clearly indicates physics beyond the SM. Recently, both LHCb [1] and CDF [2] collaborations have seen a large difference between the time-integrated CPAs in the decays $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, $\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$, given by

$$\Delta A_{CP} = (-0.82 \pm 0.21{\text{(stat.)}} \pm 0.11{\text{(sys.)}})\% \quad \text{(LHCb)},$$

$$= (-0.62 \pm 0.21{\text{(stat.)}} \pm 0.10{\text{(sys.)}})\% \quad \text{(CDF)},$$

based on 0.62 fb$^{-1}$ and 9.7 fb$^{-1}$ of data, respectively. By combing the above results with fully uncorrelated uncertainties, one obtains the average value [2]

$$\Delta A_{CP}^{\text{avg}} = (-0.67 \pm 0.16)\%,$$

which is about $3.8\sigma$ away from zero.

As the time dependent CPA involves both direct and indirect parts, i.e. $A_{CP}^{\text{dir}}(D^0 \to f)$ and $A_{CP}^{\text{ind}}(D^0 \to f)$, one gets [1]

$$\Delta A_{CP} \simeq \Delta A_{CP}^{\text{dir}} + (9.8 \pm 0.3)\%A_{CP}^{\text{ind}},$$

where $\Delta A_{CP}^{\text{dir}} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$ and $A_{CP}^{\text{ind}} \equiv A_{CP}^{\text{ind}}(D^0 \to f)$ is universal for $f = K^+K^-$ and $\pi^+\pi^-$ and less than 0.3% due to the mixing parameters. It is clear that the average value in Eq. (3) is dominated by the difference of the direct CP asymmetries, $\Delta A_{CP}^{\text{dir}}$.

In order to have a nonzero direct CPA, two amplitudes $A_1$ and $A_2$ with both nontrivial weak and strong phase differences, $\theta_W$ and $\delta_S$, are essential, giving the CPA

$$A_{CP}(D^0 \to f) = \frac{-2|A_1||A_2| \sin \theta_W \sin \delta_S}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2| \cos \theta_W \cos \delta_S}. \quad (5)$$

The SM description of the direct CPA for $D^0 \to f$ arises from the interference between tree and penguin contributions, in which decay amplitudes have the generic expressions

$$A_{SM}^q(D^0 \to f) = V_{eq}^* V_{uq} \left( T_{SM}^q + E_{SM}^q e^{i\delta_q} \right) - V_{cb}^* V_{ub} P_{SM}^q e^{i\delta_q}, \quad (6)$$
where \( q = (d, s) \) represents \( f = (\pi^+\pi^-, K^+K^-) \), respectively, \( V_{q'q} \) is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element, \( T'_SM(P'_{SM}) \) denotes the tree (penguin) contribution in the SM, \( E'_{SM}(P'_{SM}) \) stands for the contributions of W-exchange topology, and \( \delta^q_S(\phi^q_S) \) is the associated CP-even phase. Due to the hierarchy in the CKM matrix elements \( V^{\ast}_{cq}V_{uq} \gg V^{\ast}_{cb}V_{ub} \), the direct CPA could be estimated by

\[
A_{CP}'(D^0 \to f) \sim Im \left( \frac{V^*_{cb}V_{ub}}{V^*_{cq}V_{uq}} \right) \frac{2P^q_{SM}}{T^q_{SM} + E^q_{SM}e^{i\delta^q_S}} \left( T^q_{SM} \sin \phi^q_S + E^q_{SM} \sin(\delta^q_S - \phi^q_S) \right). \tag{7}
\]

With \( Im(V^*_{cb}V_{ub}/V^*_{cq}V_{uq}) \approx \pm A^2 \lambda^4 \eta, E^q_{SM} \sim T^q_{SM} \), and \( \sin \phi^q_S \sim \sin(\delta^q_S - \phi^q_S) \sim O(1) \), we could have

\[
A_{CP}(K^-K^+) \sim -A_{CP}(\pi^+\pi^-) \sim -A^2 \lambda^4 \eta \frac{P^q_{SM}}{T^q_{SM}}. \tag{8}
\]

Unless \( P^q_{SM} \) could be enhanced to several orders larger than \( T^q_{SM} \) by some unknown QCD effects, normally the predicted \( \Delta A_{CP} \) in the SM is far below the central value in Eq. \( \text{(3)} \). The detailed analysis by various approaches in the SM can be referred to Refs. \([3–7]\). Clearly, a solution to the large \( \Delta A_{CP} \) in Eq. \( \text{(3)} \) is to introduce some new CP violating mechanism beyond the CKM.

To understand the LHCb and CDF data, many theoretical studies \([3–30]\) have been done. Since the mixing induced CPA in \( D \)-meson now is limited to be less than around 0.3% and no significant evidence shows a non-vanishing CPA, if a large \( \Delta A_{CP} \) indicates some new physics effects, the same mechanism contributing to \( A_{CP}^{ind} \) should be small or negligible. To satisfy the criterion of a small \( A_{CP}^{ind} \), it is interesting to explore the tree induced new CP violating effects in which the loop contributions are automatically suppressed. In this paper, we examine the new CP source associated with right-handed charged currents and the left-right (LR) mixing angle, \( \xi \), in a general \( SU(2)_L \times SU(2)_R \times U(1) \) model \([31, 32]\). It is known that the unitarity of the CKM matrix gives a strict limit on \( \xi \). \([35]\) However, it was found that the allowed value of the mixing angle indeed could be as large as of order of \( 10^{-2} \) when the right-handed mixing matrix has a different pattern from the CKM and carries large CP phases \([32]\). The constraints from rare \( B \) decays could be referred to Refs. \([33, 34]\). Based on the possible large new CP phases and sizable \( \xi \), we study the impact on the direct CPAs in \( D^0 \to f \) decays.

In terms of the notations in Ref. \([32]\), we first write the mass eigenstates of charged gauge
bosons as
\[
\begin{pmatrix}
W_L^+ \\
W_R^+
\end{pmatrix}
=
\begin{pmatrix}
\cos \xi & -\sin \xi \\
e^{i\omega} \sin \xi & e^{i\omega} \cos \xi
\end{pmatrix}
\begin{pmatrix}
W_1^+ \\
W_2^+
\end{pmatrix}.
\tag{9}
\]
The phase \(\omega\) arises from the complex vacuum expectation values (VEVs) of bidoublet scalars which are introduced to generate the masses of fermions. Since \(m_W \ll m_{W_R}\), it is more useful to take the approximation of \(\cos \xi \approx 1\) and \(\sin \xi \approx \xi\). Accordingly, the charged current interactions in the flavor space can be expressed by
\[
-\mathcal{L}_{CC} = \frac{1}{\sqrt{2}} \bar{U} \gamma_\mu \left( g_L V^L P_L + g_R \xi \bar{V}^R P_R \right) D W_1^+ \\
+ \frac{1}{\sqrt{2}} \bar{U} \gamma_\mu \left( -g_L \xi V^L P_L + g_R \bar{V}^R P_R \right) D W_2^+ + h.c.
\tag{10}
\]
where the flavor indices are suppressed, \(V^L\) is the CKM matrix, \(\bar{V}^R = e^{i\omega} V^R\) and \(V^R\) is the flavor mixing matrix for right-handed currents. Consequently, the four-Fermi interactions for \(c \rightarrow uq\bar{q}\) induced by the LR mixing are given by
\[
\mathcal{H}_{\lambda\lambda'}^q = \frac{4G_F g_R}{\sqrt{2}} g_L \xi \left[ V_{uq}^\dagger V_{cq}^* (C_1(\mu)(\bar{u}q)\chi'\bar{c}c) + C_2(\mu)(\bar{u}_a q_\beta)\chi'\bar{q}_\beta c_a \right]
+ V_{uq}^\dagger V_{cq}^* (C_1(\mu)(\bar{u}q)\chi'\bar{c}c) + C_2(\mu)(\bar{u}_a q_\beta)\chi'\bar{q}_\beta c_a \right],
\tag{11}
\]
where \(\chi = L(R)\) and \(\chi' = R(L)\) while \(q = s(d)\), and \((\bar{q}q')_{LR} = \bar{q}q' P_{LR} q'\). The Wilson coefficients \(C_1' = \eta_+\) and \(C_2' = -(\eta_+ - \eta_-)/3\) with QCD corrections could be estimated by \([36, 37]\)
\[
\eta_+ = \left( \frac{\alpha_s(\mu)}{\alpha_s(m_c)} \right)^{-3/27} \left( \frac{\alpha_s(m_c)}{\alpha_s(m_b)} \right)^{-3/25} \left( \frac{\alpha_s(m_b)}{\alpha_s(m_W)} \right)^{-3/23},
\eta_- = \eta_+^{-8}.
\tag{12}
\]
Due to the suppression of \(g_R^2/m_{W_R}^2\), as usual we neglect the \(W_R\) itself contributions \([32, 37]\).

Based on the decay constants and transition form factors, defined by
\[
\langle 0| \bar{q}' \gamma^\mu \gamma_5 q | p(p) \rangle = i f_P p^\mu,
\langle p(p_2)| \bar{q} q'_\mu c | D(p_1) \rangle = F_{PP}^D(k^2) \left\{ Q_\mu - \frac{Q \cdot k}{k^2} k_\mu \right\}
+ \frac{Q \cdot k}{k^2} F_0^D(k^2) k_\mu,
\tag{13}
\]
respectively, with \(Q = p_1 + p_2\) and \(k = p_1 - p_2\), the decay amplitude for \(D^0 \rightarrow f\) in the QCD factorization approach is found to be
\[
A_{LR}^q(D^0 \rightarrow f) = (\bar{V}_{cq}^R V_{uq}^L - V_{cq}^L \bar{V}_{uq}^R) T_{LR}^q
\tag{14}
\]
with

\[
T^d_{LR} = \frac{G_F g_R}{\sqrt{2} g_L} \xi a'_1 f_{\pi} F_0^{D\pi} (m_D^2 - m_{\pi}^2),
\]

\[
T^s_{LR} = \frac{f_K F_0^{DK}}{f_{\pi} F_0^{D\pi}} \frac{m_D^2 - m_{\pi}^2}{m_D^2 - m_{K}^2} T^d_{RL},
\]

and \(a'_1 = C'_1 + C'_2/N_c\). The associated branching ratio could be obtained by \(B(D^0 \to f) = \tau_D |p_f| A^q(D^0 \to f)|^2/8\pi m_D^2\), where \(\tau_D\) is the lifetime of the \(D^0\) meson, \(|p_f|\) is the magnitude of the \(\pi(K)\) momentum and \(A^q = A^q_{SM} + A^q_{LR}\). With \(V_{us}^L \approx -V_{cd}^L \approx \lambda\), the squared amplitudes differences between \(D^0 \to f\) and its CP conjugate are

\[
|A^d|^2 - |A^d|^2 = -4E^d_{SM} T^d_{LR} \sin \delta^d_S \frac{a'_1}{a_1} \xi \left( \lambda^2 ImV_{ud}^R - \lambda ImV_{cd}^R \right),
\]

\[
|A^s|^2 - |A^s|^2 = -4E^s_{SM} T^s_{LR} \sin \delta^s_S \frac{a'_1}{a_1} \xi \left( \lambda^2 ImV_{us}^R + \lambda^2 ImV_{cs}^R \right). \tag{15}
\]

Clearly, the direct CPA in \(D^0 \to f\) decay will strongly depend on the CP violating phases in \(V_{cq, uq}^R\). Since the (pseudo) manifest LR model, denoted by \(V^L = V^{R(*)}\), has a strict limit on \(\xi\), in this paper, we only focus on the non-manifest LR model, where except the unitarity, the elements in \(V^R\) are arbitrary free parameters.

In the numerical calculations, the input values of the SM are listed in Table I \[4, 38, 39\], where the resulting branching ratios (BRs) for \(D^0 \to (\pi^-\pi^+, K^-K^+)\) are estimated as \((1.38, 3.96) \times 10^{-3}\), while the current data are \(B(D^0 \to \pi^-\pi^+) = (1.400 \pm 0.026) \times 10^{-3}\) and \(B(D^0 \to K^-K^+) = (3.96 \pm 0.08) \times 10^{-3}\) \[39\]. Although the QCD related SM inputs are extracted from the Cabibbo allowed decays, the influence of the new effects on these decays is small. Due to the W-exchange topology dominated by the final state interactions, the short-distance effects could be ignored. It is known that the box diagrams with \(W_L\) and \(W_R\) yield important contributions to the \(K^0-\bar{K}^0\) mixing \[40\]. However, due to the quarks in the diagrams for the D-system being down-type ones, we find the enhancement on the
$D^0$-$D^0$ oscillation is small. Hence, the constraint from $\Delta m_D$ could be ignored. Since the CPAs involve $V_{ud,us}$, we need to consider the constraint from the direct CPA in $K \rightarrow \pi\pi$ decays. Using the result in Ref. [41], we know $(\epsilon'/\epsilon)_K \sim 1.25 \times 10^{-3} g_R/g_L \xi Im(V_{us}^R - \lambda V_{ud}^R)$. Therefore, to avoid the constraint from $(\epsilon'/\epsilon)_K$, we adopt two cases: (I) $Im(V_{us,ud}^R) \rightarrow 0$ and (II) $Im(V_{us}^R) \approx \lambda Im(V_{ud}^R)$ [41]. We investigate the two cases separately as follows:

**Case I:** In this case, Eq. (15) is simplified as

\[
|A^d|^2 - |\bar{A}^d|^2 = 4E_{SM}^d T_{LR}^d \sin \delta_S \frac{q^d}{a_1} \xi \lambda ImV_{cd}^R,
\]

\[
|A^s|^2 - |\bar{A}^s|^2 = -4E_{SM}^s T_{LR}^s \sin \delta_S \frac{q^s}{a_1} \xi \lambda^2 ImV_{cs}^R.
\]

In general, $V_{cd}^R$ and $V_{cs}^R$ are free parameters. In order to illustrate the impact of the LR mixing effects on $\Delta A_{CP}$ and make the CPAs of $\pi^+\pi^-$ and $K^+K^-$ modes to be more correlated, an interesting choice is $V_{cd}^R \approx -\lambda e^{i\theta}$ and $V_{cs}^R \approx e^{i\theta}$. Hence, the involving free parameters for the CPAs are the CP phase $\theta$ and the mixing angle $\xi$. Using Eqs. (14) and $A^0 = A^0_{SM} + A^0_{LR}$, BRs for $D^0 \rightarrow \pi^+\pi^-$ (dashed) and $D^0 \rightarrow K^+K^-$ (dash-dotted) as functions of $\xi$ and $\theta$ are shown in Fig. [1] where $1\sigma$ errors of data in BRs with units of $10^{-3}$ are taken. From this figure, we constrain the free parameters as

\[-5.3 \times 10^{-2} < \xi < -3. \times 10^{-2}, \quad 1.47 < \theta < 1.87.\]

**Case II:** In this case, Eq. (15) becomes

\[
|A^s|^2 - |\bar{A}^s|^2 = -4E_{SM}^s T_{LR}^s \sin \delta_S \frac{q^s}{a_1} \xi \lambda^2 (ImV_{ud}^R + ImV_{cs}^R).
\]

Without further limiting the pattern of $V^R$, apparently the situation in Case II is more complicated. It was pointed out that one can have a weaker constraint on the mass of $W_R$ when the right-handed flavor mixing matrix is centered around the following two forms [32]:

\[
V_A^R(\alpha) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\alpha & \pm s_\alpha \\ 0 & s_\alpha & \mp c_\alpha \end{pmatrix}, \quad V_B^R(\alpha) = \begin{pmatrix} 0 & 1 & 0 \\ c_\alpha & 0 & \pm s_\alpha \\ s_\alpha & \mp c_\alpha & 0 \end{pmatrix},
\]

where $c_\alpha = \cos \alpha$, $s_\alpha = \sin \alpha$ and $\alpha$ is an arbitrary angle. We note that the null elements denote the values that are smaller than $O(\lambda^2)$, thus their effects could be ignored in the analysis. We will focus on the implication of the two special forms. In $V_A^R(\alpha)$, since $V_{cd}^R \rightarrow 0$ and $Im(V_{ud}^R) \rightarrow 0$ due to $(\epsilon'/\epsilon)_K$, only the CPA for $D^0 \rightarrow K^+K^-$ could be compatible with
1. FIG. 1. BRs for $D^0 \rightarrow \pi^+\pi^-$ (dashed) and $D^0 \rightarrow K^+K^-$ (dash-dotted) and $\Delta A_{CP}$ (solid), where the shaded band represents the allowed region.

The current data, while the CPA for $D^0 \rightarrow \pi^+\pi^-$ decay is small, i.e. $\Delta A_{CP} \approx A_{CP}(D^0 \rightarrow K^+K^-)$. With $\alpha \approx 0$ which satisfies the constraint from $b \rightarrow d\gamma$ [34], we present the constraint of $B(D^0 \rightarrow K^+K^-)$ and $\Delta A_{CP}$ as functions of $\bar{\xi} = g_R/g_L\xi$ and $\theta = \text{arg}(\bar{V}_c^R)$ in Fig. 2 where the shaded band shows the allowed region for the parameters, corresponding to

$$0.7 \times 10^{-2} < \xi < 1.4 \times 10^{-2}, \quad 0.56 < \theta < 2.61. \quad (20)$$

For $V_{HB}^R(\alpha)$, due to $V_{ud,cs}^R \rightarrow 0$, the CPA for $D^0 \rightarrow K^+K^-$ is small and only $A_{CP}(D^0 \rightarrow \pi^+\pi^-)$ could be compatible with the data. As a result, we have $\Delta A_{CP} \approx -A_{CP}(D^0 \rightarrow \pi^+\pi^-)$. Similar to $V_{JU}^R(0)$ with $\alpha = 0$, we display $B(D^0 \rightarrow \pi^+\pi^-)$ (dashed) and $\Delta A_{CP}$ (solid) as functions of $\bar{\xi}$ and the phase $\theta$ defined as $\bar{V}_c^R = -\lambda e^{-i\theta}$ in Fig. 3. In this case, the allowed $\xi$ is negative

$$-1.6 \times 10^{-2} < \xi < -0.6 \times 10^{-2}, \quad 1.12 < \theta < 2.76. \quad (21)$$

In summary, we have studied the impact of the LR mixing in the general LR model on the CPA difference between $D^0 \rightarrow K + K^-$ and $D^0 \rightarrow \pi^+\pi^-$. It is found that when
FIG. 2. BR for $D^0 \to K^+K^-$ (dash-dotted) and $\Delta A_{CP}$ (solid), where the shaded band stands for the allowed region.

the constraint from $(\epsilon' / \epsilon)_K$ is considered, the proposed LR mixing mechanism could be compatible with the value of $\Delta A_{CP}$ averaged by the LHCb and CDF new data. To illustrate the influence of the LR mixing effects, we have adopted two cases for the new flavor mixing matrix $\bar{V}^R$ to explain the large $\Delta A_{CP}$. In Case I, we have found that $A_{CP}(D^0 \to K^+K^-) \approx -A_{CP}(D^0 \to \pi^+\pi^-)$ can be achieved. In Case II, we have used two special forms for $V^R$, resulting in $A_{CP}(D^0 \to \pi^+\pi^-) \approx 0$ and $A_{CP}(D^0 \to K^+K^-) \approx 0$, respectively.

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FIG. 3. The Legend is the same as Fig. 2 but for $D^0 \to \pi^+ \pi^-$.  

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