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Study of *CP* violation in $D \to$

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ABSTRACT

In this Letter, we intend to study the problem of *CP* violation in D meson by $D \to VV$ decay mode in which the T violating triple-product correlation is examined. That would undoubtedly be another excellent probe of New Physics beyond Standard Model. For the neutral D, we focus on direct *CP* violation without considering D^0–$\bar{D}^0$ oscillation. Experimentally, by a full angular analysis one may obtain such *CP* violating signals, and particularly it is worth mentioning that the upcoming large D data samples at BES-III in Beijing will provide a great opportunity to perform it.

The topic of *CP* violation in the D-meson sector has been the subject of extensive studies involving both charged and neutral D meson decays these years [1–12]. In a recent reference [13], they exploited the angular and quantum correlation in the $D^0\bar{D}^0$ pairs produced through the decay of the $\psi(3770)$ resonance at BES-III to investigate *CP* violation. They build *CP* violating observables in $e^+e^- \to \psi(3770) \to D^0\bar{D}^0 \to (V_1V_2)(V_3V_4)$ (V denotes vector meson) to isolate specific New Physics effects in the charm sector [13].

In practice, one can also probe the *CP* violation in D meson by one D decay without considering the quantum correlation, which is the motivation of this Letter. Among the various kinds of D decay modes, $D \to V_1V_2$ and subsequently decaying to two pseudoscalars for each vector meson is a particularly interesting one in the perspective of the copious kinematics of final state interaction (FSI). As the same case in B meson [14,15], the new type of T violating signal involving so-called triple-product (TP) will emerge by comparing a pair of *CP* conjugate processes, where TP is composed of the momentum of one vector meson and two polarizations. Assuming *CPT* invariance, T violating TP asymmetry is equivalent to *CP* violating. We shall see in this Letter that such TP asymmetries are related to the helicity components in the angular distribution of the $D \to V_1V_2$ process. Moreover, performing a full angular analysis is feasible and realistic in experiment.

On the other hand, TP asymmetry (in the latter section we sometimes also refer to TP asymmetry as *CP* asymmetry assuming *CPT* invariance) is a sensitive signal of New Physics. It is well known that Standard Model (SM) predictions for *CP* violation in the charm sector are very small, thus any significant such signals would be exciting. Currently, the BES-III experiment is collecting data at $\psi(3770)$ peak. In the short future, lots of events of D decay will be accumulated, which will provide a great opportunity to perform a full angular analysis to further achieve a valuable information for the question discussed here.

Let us first consider the process $D(p) \to V_1(k,\epsilon_1)V_2(q,\epsilon_2)$, where the two vectors V_1, V_2 are characterized as their four-momenta and polarizations (k,ϵ_1) and (q,ϵ_2), respectively. We can write the most general invariant amplitude as a sum of three terms that we will call s, d, p [14–17],

$$\mathcal{M} \equiv as + bd + icp = a\epsilon_1^* \cdot \epsilon_2^* + \frac{b}{m_1m_2}(p\cdot\epsilon_1^*)(p\cdot\epsilon_2^*) + i\frac{c}{m_1m_2}\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta, \tag{1}$$

where m_1 (m_2) is the mass of V_1 (V_2), and the scalar coefficients a, b and c are generally complex and can receive contributions from several amplitudes with different phases. Thus, one can parameterize the coefficients as [14]

$$a = \sum_j a_j e^{i\delta_{sj}} e^{i\phi_{sj}},$$
$$b = \sum_j b_j e^{i\delta_{dj}} e^{i\phi_{dj}},$$
$$c = \sum_j c_j e^{i\delta_{pj}} e^{i\phi_{pj}}, \tag{2}$$

where a_j, b_j and c_j are the moduli of their corresponding complex quantities, and δ_j denotes strong phase (also called unitary phase in Ref. [14]), and ϕ_j is the weak phase which is the necessary

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condition for occurring of *CP* violation on the basis of Cabibbo–Kobayashi–Maskawa (CKM) mechanism [18,19] in the SM. Squaring the matrix element of Eq. (1), one obtains

$$
\begin{aligned}
|\mathcal{M}|^2 = {} & |a|^2\left|\epsilon_1^*\cdot\epsilon_2^*\right|^2 + \frac{|b|^2}{m_1^2m_2^2}\left|\left(k\cdot\epsilon_2^*\right)\left(q\cdot\epsilon_1^*\right)\right|^2 \\
& + \frac{|c|^2}{m_1^2m_2^2}\left|\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta\right|^2 \\
& + 2\frac{\mathrm{Re}(ab^*)}{m_1m_2}\left(\epsilon_1^*\cdot\epsilon_2^*\right)\left(k\cdot\epsilon_2^*\right)\left(q\cdot\epsilon_1^*\right) \\
& + 2\frac{\mathrm{Im}(ac^*)}{m_1m_2}\left(\epsilon_1^*\cdot\epsilon_2^*\right)\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta \\
& + 2\frac{\mathrm{Im}(bc^*)}{m_1^2m_2^2}\left(k\cdot\epsilon_2^*\right)\left(q\cdot\epsilon_1^*\right)\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta.
\end{aligned}
\tag{3}
$$

Next, using *CPT* invariance, the matrix element for the antiparticle decay $\bar{D}(p)\to\bar{V}_1(k,\epsilon_1)\bar{V}_2(q,\epsilon_2)$ can be written as

$$
\begin{aligned}
\overline{\mathcal{M}} = {} & \bar{a}\epsilon_1^*\cdot\epsilon_2^* + \frac{\bar{b}}{m_1m_2}\left(p\cdot\epsilon_1^*\right)\left(p\cdot\epsilon_2^*\right) \\
& - i\frac{\bar{c}}{m_1m_2}\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta,
\end{aligned}
\tag{4}
$$

with

$$
\begin{aligned}
\bar{a} &= \sum_j a_j e^{i\delta_{sj}}e^{-i\phi_{sj}}, \\
\bar{b} &= \sum_j b_j e^{i\delta_{dj}}e^{-i\phi_{dj}}, \\
\bar{c} &= \sum_j c_j e^{i\delta_{pj}}e^{-i\phi_{pj}}.
\end{aligned}
\tag{5}
$$

Note that *CP* operator leaves strong phases invariant and only changes the sign of weak phase. From Eqs. (1) and (4), we will find that the p wave amplitude in $\bar{\mathcal{M}}$ changes the sign comparing with $\mathcal{M}$, which will induce an interesting property between $|\bar{\mathcal{M}}|^2$ and $|\mathcal{M}|^2$. To be clear, we would square the matrix element for the antiparticle decay in Eq. (4):

$$
\begin{aligned}
|\overline{\mathcal{M}}|^2 = {} & |\bar{a}|^2\left|\epsilon_1^*\cdot\epsilon_2^*\right|^2 + \frac{|\bar{b}|^2}{m_1^2m_2^2}\left|\left(k\cdot\epsilon_2^*\right)\left(q\cdot\epsilon_1^*\right)\right|^2 \\
& + \frac{|\bar{c}|^2}{m_1^2m_2^2}\left|\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta\right|^2 \\
& + 2\frac{\mathrm{Re}(\bar{a}\bar{b}^*)}{m_1m_2}\left(\epsilon_1^*\cdot\epsilon_2^*\right)\left(k\cdot\epsilon_2^*\right)\left(q\cdot\epsilon_1^*\right) \\
& - 2\frac{\mathrm{Im}(\bar{a}\bar{c}^*)}{m_1m_2}\left(\epsilon_1^*\cdot\epsilon_2^*\right)\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta \\
& - 2\frac{\mathrm{Im}(\bar{b}\bar{c}^*)}{m_1^2m_2^2}\left(k\cdot\epsilon_2^*\right)\left(q\cdot\epsilon_1^*\right)\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta.
\end{aligned}
\tag{6}
$$

For $D^0\to V_1V_2$ decay, one can define an asymmetry $\mathcal{A_T}$ with the definite sign for the triple product $(\vec{k}\cdot\vec{\epsilon}_1^*\times\vec{\epsilon}_2^*)$ as [14]

$$
\mathcal{A_T} = \frac{N(\vec{k}\cdot\vec{\epsilon}_1^*\times\vec{\epsilon}_2^*>0) - N(\vec{k}\cdot\vec{\epsilon}_1^*\times\vec{\epsilon}_2^*<0)}{N_{total}},
\tag{7}
$$

where the subscript $\mathcal{T}$ implies triple products and N denotes the corresponding number of events. Eq. (7) above is actually

$$
\mathcal{A_T} = \frac{\Gamma(\vec{k}\cdot\vec{\epsilon}_1^*\times\vec{\epsilon}_2^*>0) - \Gamma(\vec{k}\cdot\vec{\epsilon}_1^*\times\vec{\epsilon}_2^*<0)}{\Gamma(\vec{k}\cdot\vec{\epsilon}_1^*\times\vec{\epsilon}_2^*>0) + \Gamma(\vec{k}\cdot\vec{\epsilon}_1^*\times\vec{\epsilon}_2^*>0}.
\tag{8}
$$

Similarly, for $\bar{D}^0\to\bar{V}_1\bar{V}_2$ decay, $\bar{\mathcal{A}}_\mathcal{T}$ can also be constructed as the same way. In $|\mathcal{M}|^2$, a triple-product correlation arises from interference terms involving the p amplitude, and will be present if $\mathrm{Im}(ac^*)$ (or $\mathrm{Im}(bc^*)$) is non-zero. After a simple calculation by inserting Eqs. (2) and (5), we see that

$$
\mathcal{A_T} \propto \mathrm{Im}\left(ac^*\right) = \sum_{i,j} a_i c_j \sin\left[(\phi_{si}-\phi_{pj}) + (\delta_{si}-\delta_{pj})\right].
\tag{9}
$$

Note that a non-zero triple correlation does not necessarily imply *CP* violation, since final state interactions (FSI) can fake it, namely the strong phase can also produce non-zero $\mathcal{A_T}$ (or $\bar{\mathcal{A}}_\mathcal{T}$) even the weak phases are zero. Yet comparing a triple correlation for *CP* conjugate transitions allows to distinguish genuine *CP* violation from FSI effects. Thus we obtain

$$
\begin{aligned}
\frac{1}{2}(\mathcal{A_T}+\bar{\mathcal{A}}_\mathcal{T}) &\propto \frac{1}{2}\left[\mathrm{Im}\left(ac^*\right) - \mathrm{Im}\left(\bar{a}\bar{c}^*\right)\right] \\
&= \sum_{i,j} a_i c_j \sin(\phi_{si}-\phi_{pj})\cos(\delta_{si}-\delta_{pj}),
\end{aligned}
\tag{10}
$$

and

$$
\begin{aligned}
\frac{1}{2}(\mathcal{A_T}-\bar{\mathcal{A}}_\mathcal{T}) &\propto \frac{1}{2}\left[\mathrm{Im}\left(ac^*\right) + \mathrm{Im}\left(\bar{a}\bar{c}^*\right)\right] \\
&= \sum_{i,j} a_i c_j \cos(\phi_{si}-\phi_{pj})\sin(\delta_{si}-\delta_{pj}).
\end{aligned}
\tag{11}
$$

So far, a non-zero value $\mathcal{A_T}+\bar{\mathcal{A}}_\mathcal{T}$ will be undoubtedly a clean signal of *CP* non-conservation, because there must be at least one non-zero weak phase ϕ. Here, we also note that if there is only one amplitude contributing to each partial wave, one can simultaneously determine the strong phase difference and weak phase difference from Eqs. (10) and (11).

Experimentally, one can perform a full angular analysis to obtain the above TP asymmetry information because the complex coefficients a, b, c are related to the helicity amplitudes A_0, $A_\parallel$, $A_\perp$ as discussed in Refs. [16,20],

$$
\begin{aligned}
A_0 &= -ax - b\left(x^2-1\right), \\
A_\parallel &= \sqrt{2}a, \\
A_\perp &= \sqrt{2}c\sqrt{x^2-1},
\end{aligned}
\tag{12}
$$

where

$$
x = \frac{k\cdot q}{m_1m_2} = \frac{m_D^2-m_1^2-m_2^2}{2m_1m_2},
\tag{13}
$$

where m_D is the mass of D meson.

Now we turn to the full angular dependence of process $D\to V_1V_2\to(P_1P_2)(P_3P_4)$ with P pseudoscalar, after some algebra one can get

$$
\begin{aligned}
\frac{d\Gamma}{d\cos\theta_1\,d\cos\theta_2\,d\phi} \propto {} & \frac{1}{2}\sin^2\theta_1\sin^2\theta_2\cos^2\phi|A_\parallel|^2 \\
& + \frac{1}{2}\sin^2\theta_1\sin^2\theta_2\sin^2\phi|A_\perp|^2 \\
& + \cos^2\theta_1\cos^2\theta_2|A_0|^2 \\
& - \frac{1}{2}\sin^2\theta_1\sin^2\theta_2\sin 2\phi\,\mathrm{Im}\left(A_\perp A_\parallel^*\right) \\
& - \frac{\sqrt{2}}{4}\sin 2\theta_1\sin 2\theta_2\cos\phi\,\mathrm{Re}\left(A_\parallel A_0^*\right) \\
& + \frac{\sqrt{2}}{4}\sin 2\theta_1\sin 2\theta_2\sin\phi\,\mathrm{Im}\left(A_\perp A_0^*\right),
\end{aligned}
\tag{14}
$$

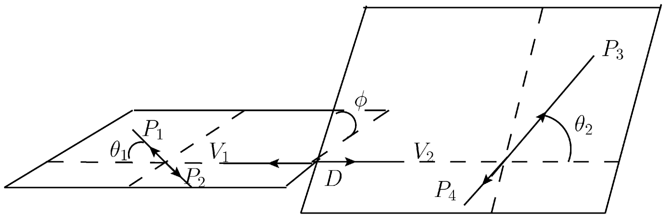

Fig. 1. Illustrative plot for the decay kinematics of process $D \to V_1V_2 \to (P_1P_2)(P_3P_4)$ in the rest frame of $V_{1,2}$.

where we have introduced $A_\perp$ with definite odd CP eigenvalue and the CP even partners A_0, $A_\parallel$ via

$$A_0 = A_0,$$
$$A_\parallel = \frac{1}{\sqrt{2}}(A_{11} + A_{-1-1}),$$
$$A_\perp = \frac{1}{\sqrt{2}}(A_{11} - A_{-1-1}), \tag{15}$$

with $A_{\lambda_1\lambda_2}$ denoting the helicity mode of two vector mesons. θ_i's ($i = 1, 2$) are the angles between the direction of motion of one of the $V_{1,2} \to PP$ pseudoscalar final states and the inverse direction of motion of the D meson as measured in the $V_{1,2}$ rest frame, ϕ is the angle between the two decay plane of vector mesons in the D rest frame. Fig. 1 illustrates the decay kinematics of the process $D \to V_1V_2 \to (P_1P_2)(P_3P_4)$ in the rest frame of $V_{1,2}$. Eq. (14) is consistent with that from Refs. [21,22].

As discussed previously, the TP asymmetry is connected with the angular dependence, combining Eqs. (10)–(12), one can define the following T-odd quantities [14,15],

$$\mathcal{A}_T^0 \equiv \frac{\mathrm{Im}(A_\perp A_0^*)}{|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2}, \tag{16}$$

and

$$\mathcal{A}_T^\parallel \equiv \frac{\mathrm{Im}(A_\perp A_\parallel^*)}{|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2}, \tag{17}$$

thus we will derive the CP violating observables,

$$\mathcal{A} = \frac{1}{2}(\mathcal{A}_T^0 + \bar{\mathcal{A}}_T^0)$$
$$= \frac{1}{2}\left(\frac{\mathrm{Im}(A_\perp A_0^*)}{|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2} + \frac{\mathrm{Im}(\bar{A}_\perp \bar{A}_0^*)}{|\bar{A}_0|^2 + |\bar{A}_\perp|^2 + |\bar{A}_\parallel|^2}\right), \tag{18}$$

and

$$\mathcal{A}' = \frac{1}{2}(\mathcal{A}_T^\parallel + \bar{\mathcal{A}}_T^\parallel)$$
$$= \frac{1}{2}\left(\frac{\mathrm{Im}(A_\perp A_\parallel^*)}{|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2} + \frac{\mathrm{Im}(\bar{A}_\perp \bar{A}_\parallel^*)}{|\bar{A}_0|^2 + |\bar{A}_\perp|^2 + |\bar{A}_\parallel|^2}\right). \tag{19}$$

Before this study, there had been attempts to study CP violation of D meson via T violating TP correlation in theoretical viewpoint that differs from our method [12,23,24]. But the only reported experimental search for T-odd asymmetries is from FOCUS in the $D^0 \to K^+K^-\pi^+\pi^-$ and $D_S^+ \to K_SK^+\pi^+\pi^-$ decay modes [25], as listed in Table 1. No evidence for a T asymmetry is observed. The large BES-III data sample is expected to provide enhanced sensitivity to possible T violating asymmetries.

At last, we consider the potential sensitivity on the CP violating observables $\mathcal{A}$ and $\mathcal{A}'$ at BES-III. From Eq. (7), for a small asymmetry, there is a general result that it's error is approximately estimated as $1/\sqrt{N_{total}}$, where N_{total} is the total number of events observed. At BES-III, with an integrated luminosity of 20 fb^{-1} at $\psi(3770)$ peak, about $72 \times 10^6 D^0\bar{D}^0$ pairs will be collected with four year's running [26,27]. Table 2 lists some promising channels to search for T asymmetry for both neutral and charged D decays and the corresponding expected statistical errors are estimated. The projected efficiencies are extracted from Ref. [26] and branching ratios are obtained from Ref. [28].

Table 1
T violating asymmetries in D meson decays from the FOCUS experiment [25].

Decay mode	$\mathcal{A}$ (%)
$D^0 \to K^+K^-\pi^+\pi^-$	$1.0 \pm 5.7 \pm 3.7$
$D^+ \to K_SK^+\pi^+\pi^-$	$2.3 \pm 6.2 \pm 2.2$
$D_S^+ \to K_SK^+\pi^+\pi^-$	$-3.6 \pm 6.7 \pm 2.3$

Table 2
The promising (VV) modes with large branching fractions, efficiencies and expected errors on the T asymmetry: the corresponding expected errors are estimated by assuming 20 fb^{-1} data at $\psi(3770)$ peak at BES-III; the branching fractions with asterisk are estimated according to Refs. [29–32]. The last row is from D^+ decay.

VV	Br (%)	Eff. (ϵ)	Expected errors
$\rho^0\rho^0 \to (\pi^+\pi^-)(\pi^+\pi^-)$	0.18	0.74	0.004
$\bar{K}^{*0}\rho^0 \to (K^-\pi^+)(\pi^+\pi^-)$	1.08	0.68	0.002
$\rho^0\phi \to (\pi^+\pi^-)(K^+K^-)$	0.14	0.26	0.006
$\rho^+\rho^- \to (\pi^+\pi^0)(\pi^-\pi^0)$	0.6*	0.55	0.002
$K^{*+}K^{*-} \to (K^+\pi^0)(K^-\pi^0)$	0.08*	0.55	0.006
$K^{*0}\bar{K}^{*0} \to (K^+\pi^-)(K^-\pi^+)$	0.048	0.62	0.002
$\bar{K}^{*0}\rho^+ \to (K^-\pi^+)(\pi^+\pi^0)$	1.33	0.59	0.001

In Table 2, the branching fractions with asterisks have not been measured yet, but some estimates combining naive factorization and models for FSI are available from Refs. [29–32]. Note that in Table 2, the estimated efficiencies are average value for the various partial waves by assuming that the magnitude of the longitudinal polarization is half of the decay rate. In the future, a careful measurements at BES-III about the efficiency and fraction for each partial wave are suggested. A more realistic analysis requires a likelihood fit to the full angular dependence of the $D \to V_1V_2 \to (P_1P_2)(P_3P_4)$ mode. Systematics will arise from the mis-reconstruction as V_1V_2 of the events that actually come from other resonances or non-resonance $D \to P_1P_2P_3P_4$ background contributions. In view of the sizable width of the vector resonances, we expect that these systematics will dominate the final result. Their precise estimate in the BES-III experiment is beyond the scope of this Letter. However, as pointed out in Ref. [24] by Bigi, the four-body decay of $D \to P_1P_2P_3P_4$ both with and without intermediate states can all be used to probe T asymmetry in the frame work of TP.

In conclusion, we studied the CP violation in $D \to VV$ decay mode in which the T violating triple-product correlation is examined. That would undoubtedly be another excellent probe of New Physics beyond the SM. The CP violating observables in connection with angular distribution are constructed. For neutral D decays, we neglect the CP violation induced by D^0–$\bar{D}^0$ oscillation. Experimentally, by doing a full angular analysis one may obtain such CP violating signals, and particularly it is worth mentioning that the upcoming large D data sample at BES-III will provide a great opportunity to perform it. The sensitivities for CP violating observables are estimated by assuming 20^{-1} fb data-taking at $\psi(3770)$ peak at BES-III.

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