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Probing new CP violating observables in D meson decays

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Abstract. CP violation in the charm quark sector has not been examined very well as the case for strange and beauty ones. Some novel insights into the issue on the CP violation in D meson decay are discussed. Specifically, i) the T-violating observables in $D \to VV$ decays are constructed. Assuming CPT invariance T violation implies CP violation. This is a new idea and an alternative way for probing CP violation in D decays; ii) the decay of quantum correlated $D\overline{D}$ pair to vector mesons (denoted by V) is explored, which offers the new CP violating observables that have not been noticed before;

1. Introduction

CP violation in D decay is still a primary and hot topic in flavor physics. In the Standard Model (SM), this quantity is shown to be small, and in fact, up to now, has not been well determined in experiment. Any large signal of CP violation would be a smoking gun for new physics, see e.g. Refs. [1, 2]. The general consensus is that in SM the CP asymmetry is highly suppressed and out of the current experimental capability, however, in a New Physics (NP) model, CP violation can reach a relatively large quantity. In Ref. [2] the authors show the CP violation can yield order of 10^{-2}, which is comparable to the current experimental sensitivity. Or contrarily, the non-observation of these CP violating signal will at least put severe constraint on these NP models.

The decays $D \to PP$ (P is a pseudoscalar, typical examples are $D \to K\pi$, $\pi\pi$) have been extensively considered, however, we notice that the mode of D decaying to vector meson can provide rich information in angular distribution due to the polarization of spin-1 meson. In case of $D \to VV$ decay, we show the triple production (TP) term can occur which violates the time-reversal invariance. These signals can be accessed by a angular analysis in experiment. The quantum coherent double D decays, $\psi(3770) \to D\overline{D} \to (VV)(VV)$, is also quite interesting, since it provides new CP violating observables that have not been aware of before. We may denote $\psi(3770)$ resonance by ψ for simplicity. Below we will sketch this method. Replacing one VV pair by $K\pi$, one has $\psi(3770) \to D\overline{D} \to (VV)(K\pi)$, which is exploited to render a new information on the strong phase δ, required for the extraction of the angle γ in Cabibbo-Kobayashi-Maskawa (CKM) matrix [3, 4].

2. Single D decays to VV

The mode of single D decaying to VV is used to explore the CP violation [5]. The vector meson can provide a polarization factor (denoted by ϵ) and thus the triple product like $\vec{k}\cdot(\epsilon_1\times\epsilon_2)$ can be composed. It is interesting to note that such triple product (TP) violates time-reversal (T) symmetry. Then if such structures can be isolated from the angular analysis, these would be measurable in experiment. By comparing a pair of CP-conjugate process, the term of correlation of triple product can be extracted in a way such that the clean T-violation can be probed [6]. For the process $D(p)\to V_1(k,\epsilon_1)V_2(q,\epsilon_2)$, where in the parenthesis the four-momenta and polarization is indicated for each vector meson, the amplitude can be written as [6],

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

The coefficients a, b and c are general complex and can be parameterized as [6]

$$a=\sum_j a_je^{i\delta_{sj}}e^{i\phi_{sj}}\,,\quad b=\sum_j b_je^{i\delta_{dj}}e^{i\phi_{dj}}\,,\quad c=\sum_j c_je^{i\delta_{pj}}e^{i\phi_{pj}} \tag{2}$$

where j is only symbolic to show they can receive several pieces of amplitudes with their phases, δ is the phase coming from the strong interaction, and ϕ is the weak phase violating CP symmetry. Under CP transformation, δ does not change sign while ϕ does. Calculating the modulus squared, one obtains

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

Note that the term $\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta$ in the rest frame of D meson takes just $\vec{p}\cdot(\epsilon_1^*\times\epsilon_2^*)$ which changes sign under the time-reversal transformation. With CPT invariance one can write the amplitude for $\bar{D}(p)\to\bar{V}_1(k,\epsilon_1)\bar{V}_2(q,\epsilon_2)$ as

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

with

$$\bar{a}=\sum_j a_je^{i\delta_{sj}}e^{-i\phi_{sj}}\,,\quad \bar{b}=\sum_j b_je^{i\delta_{dj}}e^{-i\phi_{dj}}\,,\quad \bar{c}=\sum_j c_je^{i\delta_{pj}}e^{-i\phi_{pj}}\,. \tag{5}$$

And then

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

Comparing $|M|^2$ and $|\overline{M}|^2$, one finds

$$\mathcal{A}_{\mathcal{T}} \propto Im(ac^*) = \sum_{i,j} a_i c_j \sin[(\phi_{si} - \phi_{pj}) + (\delta_{si} - \delta_{pj})] \tag{7}$$

and

$$\begin{aligned} \frac{1}{2}(\mathcal{A}_{\mathcal{T}} + \bar{\mathcal{A}}_{\mathcal{T}}) \propto \frac{1}{2}[Im(ac^*) - Im(\bar{a}\bar{c}^*)] &= \sum_{i,j} a_i c_j \sin(\phi_{si} - \phi_{pj}) \cos(\delta_{si} - \delta_{pj}) \,, \\ \frac{1}{2}(\mathcal{A}_{\mathcal{T}} - \bar{\mathcal{A}}_{\mathcal{T}}) \propto \frac{1}{2}[Im(ac^*) + Im(\bar{a}\bar{c}^*)] &= \sum_{i,j} a_i c_j \cos(\phi_{si} - \phi_{pj}) \sin(\delta_{si} - \delta_{pj}) \,. \end{aligned} \tag{8}$$

$\mathcal{A}_{\mathcal{T}}$ itself is not a signal of T violation, since even $\phi = 0$ one can still get a non-zero $A_{\mathcal{T}}$ due to the contamination of the strong phase. However, $\mathcal{A}_{\mathcal{T}} + \bar{\mathcal{A}}_{\mathcal{T}}$ is a clean identification of the T-violation. The next step is to build the bridge between $\mathcal{A}_{\mathcal{T}}$ and an experimentally accessable quantities.

Keeping in mind that a, b, c is related to the helicity amplitude, the angular distribution should contain these T-violating information. To that end, the helicity formalism developed by Jacob and Wick [7] is proved to be very useful. The two-body decay amplitude can be written as (see also Ref. [8])

$$\mathcal{A}(a \to 1 + 2) = \sqrt{\frac{2J+1}{4\pi}} D^{J*}_{M\lambda}(\phi_1, \theta_1, 0) H_{\lambda_1\lambda_2}, \tag{9}$$

where J is the total angular momentum of particle a, M the spin projection along an arbitrarily chosen z-axis, (θ, ϕ) is the polar angle of $\vec{p}_1$ in the rest frame of a; λ's are the corresponding helicities, and H is the helicity amplitude. The Rotation matrix is defined as

$$D^j_{m'm}(\alpha, \beta, \gamma) = e^{-i\alpha m'} d^j_{m'm}(\beta) e^{-i\gamma m} \tag{10}$$

with the Wigner d function. In Eq. (9), we have chosen the choice $\gamma = 0$ [7]. For cascade two-body decay, the amplitude is just given the product of each reaction. Then the differential decay rate can be calculated, containing the helicity amplitudes $H_{1,1}$, $H_{0,0}$, $H_{-1,-1}$ corresponding to the helicity configurations for the two vector mesons. In a practical experimental analysis, the transversity basis can be also introduced,

$$A_{||} = \frac{1}{\sqrt{2}}(H_{1,1} + H_{-1,-1}), \quad A_0 = H_0, \quad A_{\perp} = \frac{1}{\sqrt{2}}(H_{1,1} + H_{-1,-1}) \tag{11}$$

which has a good CP transformation behavior with eigenvalues $+1$, $+1$ and -1 respectively. This point can be understood by [7, 8]

$$CP|JM, \lambda_1\lambda_2; 1, 2\rangle = \eta_1\eta_2(-)^{J-s_1-s_2}|JM, \lambda_1\lambda_2; \bar{1}, \bar{2}\rangle. \tag{12}$$

For the current case, $0^- \to 1^- + 1^-$, we have the total angular momentum $J = 0$, the spin of vector mesons $s_1 = s_2 = 1$, and the intrinsic parity $\eta_1 = \eta_2 = -1$, then $H_{\lambda_1,\lambda_2} = \bar{H}_{-\lambda 1,-\lambda_2}$. Here we write out the angular distribution for the process $D \to VV \to (PP)(PP)$,

$$\begin{aligned} \frac{d\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} \propto\ & \frac{1}{2}\sin^2\theta_1 \sin^2\theta_2 \cos^2\phi |A_{||}|^2 + \frac{1}{2}\sin^2\theta_1 \sin^2\theta_2 \sin^2\phi |A_{\perp}|^2 \\ & + \cos^2\theta_1 \cos^2\theta_2 |A_0|^2 - \frac{1}{2}\sin^2\theta_1 \sin^2\theta_2 \sin 2\phi Im(A_{\perp}A^*_{||}) \\ & - \frac{\sqrt{2}}{4}\sin 2\theta_1 \sin 2\theta_2 \cos\phi Re(A_{||}A^*_0) + \frac{\sqrt{2}}{4}\sin 2\theta_1 \sin 2\theta_2 \sin\phi Im(A_{\perp}A^*_0) \,. \end{aligned} \tag{13}$$

The parts $(A_\perp A_0^*)$ and $(A_{||} A_\perp^*)$ are related to T-violating signal and can be measured in experiment. Such angular distribution formula with helicity amplitudes are also investigated in Refs. [9, 10]. We also plan to extend this framework to the interesting decay mode $B \to \pi\pi l \bar{\nu}_l$ [11].

3. Quantum correlated $D\overline{D}$ decay

3.1. $\psi(3770) \to D^0\overline{D}^0 \to (V_1V_2)(V_3V_4)$

The original idea is motivated by that CP violation occurs in the correlated $D^0\overline{D}^0$ decays to final state $f_a f_b$ with the same CP eigenvalue under the CP transformation [12]. This is simply because $f_a f_b$, that is produced from $\psi \to D^0\overline{D}^0$, is in the state of P-wave. As for e.g., the $(PP)(PP)$ or $(PP)(VP)$ decay product, the only observable is the decay rate or branching ratio, since the helicity is fixed in these cases, however, as mentioned before, for the $(VV)(VV)$ mode very rich angular information can be available due to the polarization of vector meson. We will describe our decay chain as

$$\psi \to D^0\overline{D}^0,\ D^0 \to V_1V_2,\ \overline{D}^0 \to V_3V_4, \tag{14}$$

where the vector meson decays to pseudoscalar pairs,

$$\begin{aligned} V_1 &\to M_1M_1', \quad V_2 \to M_2M_2', \\ V_3 &\to M_3M_3', \quad V_4 \to M_4M_4'. \end{aligned} \tag{15}$$

According to the idea that the final states must have different CP eigenstates, the transiversity combinations $(0,0)$, $(||,||)$, $(\perp,\perp)$, $(0,||)$, $(||,0)$, for the two pairs of vector mesons violate CP symmetry since A_0 and $A_{||}$ are CP-even while $A_\perp$ CP-odd. The next step is to pick out these pieces in the angular distribution and e.g. [13],

$$\int d\Gamma \frac{1}{128}\prod_{i=1}^{4}(5\cos^2\theta_i - 1) \sim |\mathcal{A}(D^0 \to V_1V_2)|^2 |\mathcal{A}(D^0 \to V_3V_4)|^2 |\rho^0_{V_1V_2} - \rho^0_{V_3V_4}|^2. \tag{16}$$

with the defination

$$\rho_f = \frac{\mathcal{A}(\overline{D}^0 \to f)}{\mathcal{A}(D^0 \to f)}. \tag{17}$$

For more details, we refer readers to the original paper [13] and more supplements in Ref. [14, 15]. Here we mainly concentrate at the physics behind. In experiment, the information of $|\rho^0_{V_1V_2} - \rho^0_{V_3V_4}|^2$ can be easily accessed in terms of the expression for branching ratio

$$BR(D^0\overline{D}^0 \to f_a f_b) = 2\, BR(D^0 \to f_a)\, BR(D^0 \to f_b)\, |\rho_a - \rho_b|^2. \tag{18}$$

In above equation, all the small quantities due to the mixing have been neglected. One can parameterize $\rho_f = \eta_f(1+\delta_f)\exp(i\alpha_f)$ where δ_f represents CP- violation in decay, and α_f is the phase difference between D^0 and $\overline{D}^0$ to the same final state f. Then one has, neglecting δ_f,

$$|\rho_a - \rho_b|^2 = 4\sin^2\frac{\alpha_a - \alpha_b}{2}. \tag{19}$$

Up to now, there is no direct measurement for joint $D^0\overline{D}^0$ decay. Assuming non-observation of the CP-violating signals, taking the $(V_1V_2) = (\rho^0\rho^0)_0$ ("0" part), $(V_3V_4) = (\bar{K}^{*0}\rho^0)_{||}$ ("$||$" part) as example, one can put the constraint that the corresponding angle difference is smaller than 5 degrees around. The statistics knowledge on estimating the rare signal has been used, namely, taking the method proposed in Ref. [16], an upper limit 2.4 for the signal event is setted for non-observation of a signal in a true experiment with average background event number $b = 3$. This has been widely used in estimating the upper limit of rare signals, see e.g. for the $\Lambda - \overline{\Lambda}$ oscillation [17, 18]. In the estimate, we have considered the 20 fb^{-1} $\psi(3770)$ data. At last we stress that the two vector meson pairs should not be identical. More clearly, they are either different particles or in different transeversity combination (like $(0, ||)$ or $(||, 0)$, but can not be $(0, 0)$, $(||, ||)$ and $(\perp, \perp)$), otherwise, the branching ratio will be zero, as can be seen easily from Eq. (18).

3.2. $\psi(3770) \to D^0\overline{D}^0 \to (V_1V_2)(K\pi)$

This subsection is devoted to the better extraction of the strong phase δ occuring in the $D \to K\pi$ decay, that is needed to extract the CKM matrix angle γ in the Atwood-Dunietz-Soni (ADS) method [19]. In 1997, the authors ADS proposed a nice method that makes it possible for a clean extraction of angle γ, by combining the measurements of $B^- \to K^- D^0(D^0 \to f)$ and $B^- \to K^-\overline{D}^0(\overline{D}^0 \to f)$, where f is doubly-Cabibbo-suppressed mode of D^0 and thus a Cabibbo-favoured state of $\overline{D}^0$, but f is not necessary a CP-eigenstate. In fact, $K\pi$ is a typical example. In doing so, the knowledge on $D \to K\pi$ decay is an essential input for that procedure. One can introduce the strong phase δ by the ratio of amplitudes

$$r\, e^{i\delta} = \frac{\mathcal{A}(D^0 \to K^-\pi^+)}{\mathcal{A}(\overline{D}^0 \to K^-\pi^+)}. \tag{20}$$

Adapting the formula for the $4V$ modes to current case for $(V_1V_2)(K\pi)$ one will get the differential decay rate. It depends on the amplitudes of $D \to VV$ part, i.e., A_0, $A_{||}$, $A_\perp$ and also r and δ. The new feature is the emergence of the $|\sin\delta|$ term. Note that δ has been measured from the $D^0\overline{D}^0 \to (PP)(PP)$ mode, and the results show that δ is a quite small number since $\cos\delta \approx 1$ [20, 21]. Considering this fact, the sensitivity on $\sin\delta$ is much larger than the one for $\cos\delta$ and we expect to use this measurement to improve the errors on δ.

4. Conclusion

The processes $\psi(3770) \to D^0\overline{D}^0 \to (VV)(VV)$, $\psi(3770) \to D^0\overline{D}^0 \to (VV)(K\pi)$ and $D \to VV \to (PP)(PP)$ are explored, where P and V denote the pseudoscalar and vector mesons, respectively. The motivation is to fully exploit the polarization of vector meson and thus provides rich angular observables. Concerning the $4V$ mode, we show that the new CP violating observables can be constructed, and as for $(VV)(K\pi)$ we point out it can be used to extract the strong phase δ in the decay $D \to K\pi$. The appearance of $\sin\delta$ term makes it more welcome than $\cos\delta$ since δ is very small. Besides these quantum correlated $D^0\overline{D}^0$ decay we notice that $D \to VV$ is also a promising mode. Here the novelty is utilizing the T-violation. Assuming CPT invariance, T-violation is equivalent to a CP-violating signal. These proposals can be tested in BES or the future super tau-charm factory with much higher luminosity.

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References

[1] Delepine D, Faisel G and Ramirez C A 2013 *Phys. Rev.* D **87** 075017
[2] Grossman Y, Kagen A L and Nir Y 2007 *Phys. Rev.* D **75** 036008
[3] Cabibbo N 1963, *Phys. Rev. Lett.* **10**, 531 (1963)
[4] Kobayashi M and Maskawa T 1973, *Prog. Theor. Phys.* **49**, 652
[5] Kang X W and Li H B 2010, *Phys. Lett.* B **684**, 137 (*Preprint* arXiv:0912.3068 [hep-ph])
[6] Valencia G, *Phys. Rev.* D **39**, 3339
[7] Jacob M and Wick G C 1959, *Annals Phys.* **7**, 404; [Annals Phys. **281**, 774 (2000)].
[8] Richman J D 1984, *"An Experimenter's Guide to the Helicity Formalism"*, CALT-68-1148.
[9] Kang X W, Li H B, Lu G R and Zou B S 2010, *Chin. Phys.* C **34**, 1061 (*Preprint* arXiv:0911.2998 [hep-ph])
[10] Kang X W, Li H B, Lu G R and Datta A 2011, *Int. J. Mod. Phys.* A **26**, 2523 (*Preprint* arXiv:1003.5494 [hep-ph])
[11] Kang X W, Kubis B, Hanhart C and Meißner U G 2014, *Phys. Rev.* D **89**, 053015 (*Preprint* arXiv:1312.1193[hep-ph])
[12] Bigi I I Y and Sanda A I 1984, *Phys. Rev.* D **29**, 1393
[13] Charles J, Descotes-Genon S, Kang X W, Li H B and Lu G R 2010, *Phys. Rev.* D **81**, 054032 (*Preprint* arXiv:0912.0899 [hep-ph])
[14] Kang X W, Charles J, Descotes-Genon S and Li H B 2010, PoS ICHEP **2010**, 247 (*Preprint* [arXiv:1010.1687 [hep-ph]])
[15] Charles J, Descotes-Genon S, Kang X W and Li H B 2011, *Int. J. Mod. Phys. Conf. Ser.* **02**, 132
[16] Roe B P and Woodroofe M B 1999, *Phys. Rev.* D **60**, 053009 (*Preprint* physics/9812036)
[17] Kang X W, Li H B and Lu G R 2010, *Phys. Rev.* D **81**, 051901 (*Preprint* arXiv:0906.0230 [hep-ph])
[18] Kang X W, Li H B and Lu G R 2010, *"Probe $\Lambda - \bar{\Lambda}$ oscillation in $J/\psi \to \Lambda\bar{\Lambda}$ decay at BES-III,"* (*Preprint* arXiv:1008.2845 [hep-ph])
[19] Atwood D, Dunietz I and Soni A 1997, *Phys. Rev. Lett.* **78**, 3257 (*Preprint* hep-ph/9612433)
[20] Asner D M *et al* 2012 [CLEO Collaboration], *Phys. Rev.* D **86** 112001 (*Preprint* arXiv:1210.0939[hep-ex])
[21] Ablikim M *et al* 2014 [BESIII Collaboration], *Phys. Lett.* B **734**, 227 (*Preprint* arXiv:1404.4691[hep-ex])