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New CP violation effect in charm decays

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We find a new *CP*-violation effect in charm decays into neutral kaons, which results from the interference between two tree (Cabibbo-favored and doubly Cabibbo-suppressed) amplitudes with the mixing of final-state mesons. This effect, estimated to be of order of 10^{-3}, is much larger than the direct *CP* asymmetries in these decays, but missed in the literature. If confirmed, the new effect has to be taken into account, as the above direct *CP* asymmetries are used to search for new physics.

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CP violation has been well established in the kaon and *B* meson systems, but not yet in the charm sector. It can occur via the interference between the Cabibbo-favored (CF) and doubly Cabibbo-suppressed (DCS) channels of $D \to fK_S^0$, with f being a final-state particle. These decays, with large branching factions from the CF amplitudes, are more experimentally accessible. However, the *CP* asymmetries, such as

$$A_{CP}(D^+ \to \pi^+ K_S^0) = (-3.63 \pm 0.94 \pm 0.67) \times 10^{-3}, \tag{1}$$

with 3.2σ from zero observed by the Belle Collaboration [1], are mainly attributed to the K^0-$\overline{K}^0$ mixing. It has been claimed [1, 2, 3, 4, 5] that deviation from the kaon-mixing effect in a precise measurement of the above mode can be identified as the direct *CP* violation. Due to its smallness in the SM, the direct *CP* violation in these decays has been regarded as a promising observable for searching for new physics [2, 3, 6, 7].

In the work [8] we have pointed out a new *CP*-violation effect in charm decays into neutral kaons, which results from the interference between the CF and DCS amplitudes with the mixing of final-state mesons. This new effect, estimated to be of order of 10^{-3}, turns out to be much larger than the direct *CP* asymmetry, but has been missed in the literature [1, 2, 4, 5]. It has been emphasized that only when this new effect is well determined, can the direct *CP* asymmetries in charm decays into neutral kaons be extracted correctly and used to search for new physics.

A K_S^0 state is reconstructed via its decay into two charged pions at a time close to its lifetime τ_S in measurements of the $D \to fK_S^0$ processes. Hence, not only K_S^0 but also K_L^0 serve as the intermediate states in the $D \to fK(t)(\to \pi^+\pi^-)$ chain decays through the K_S^0-K_L^0 oscillation, and to their *CP* asymmetries [4]. The K_S^0 and K_L^0 states are linear combinations of the flavor eigenstates $|K_{S,L}^0\rangle = p|K^0\rangle \mp q|\overline{K}^0\rangle$, where $q/p = (1-\varepsilon)/(1+\varepsilon)$, and ε is a small complex parameter characterizing the indirect *CP* violation in the kaon mixing with the magnitude $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$ and the phase $\phi_\varepsilon = 43.52 \pm 0.05^\circ$ [9]. Let $m_{S,L}$, $\Gamma_{S,L}$, and $\tau_{S,L}$ denote the masses, widths and lifetimes of $|K_{S,L}^0\rangle$, respectively. The average of widths is then given by $\Gamma = (\Gamma_S + \Gamma_L)/2$, and the differences of widths and masses are $\Delta\Gamma \equiv \Gamma_S - \Gamma_L$ and $\Delta m \equiv m_L - m_S$, respectively. We write the ratio between the DCS and CF amplitudes as

$$\mathscr{A}(D \to fK^0)/\mathscr{A}(D \to f\overline{K}^0) = r_f\, e^{i(\phi+\delta_f)}, \tag{2}$$

with the magnitude $r_f \propto |V_{cd}^* V_{us}/V_{cs}^* V_{ud}| \sim \mathscr{O}(10^{-2})$, the relative strong phase δ_f that depends on final states, and the weak phase $\phi \equiv Arg\left[-V_{cd}^* V_{us}/V_{cs}^* V_{ud}\right] = (-6.2 \pm 0.4) \times 10^{-4}$ in the SM.

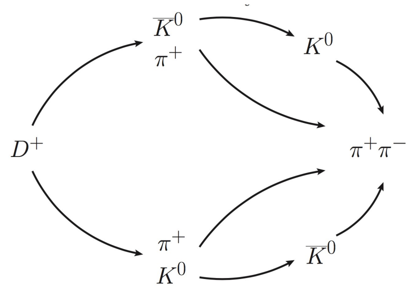

Figure 1: Schematic description of the chain decay $D^+ \to \pi^+ K(t)(\to \pi^+\pi^-)$.

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Consider the time-dependent CP asymmetry

$$A_{CP}(t) \equiv \frac{\Gamma_{\pi\pi}(t) - \overline{\Gamma}_{\pi\pi}(t)}{\Gamma_{\pi\pi}(t) + \overline{\Gamma}_{\pi\pi}(t)}, \tag{3}$$

where $\Gamma_{\pi\pi}(t) \equiv \Gamma(D \to fK(t)(\to \pi^+\pi^-))$ and $\overline{\Gamma}_{\pi\pi}(t) \equiv \Gamma(\overline{D} \to \overline{f}K(t)(\to \pi^+\pi^-))$. Neglecting the tiny direct CP asymmetry in the $K \to \pi\pi$ decays, namely, assuming the equality of the amplitudes $\mathscr{A}(\overline{K}^0 \to \pi^+\pi^-) = -\mathscr{A}(K^0 \to \pi^+\pi^-)$, we derive from Eq. (3),

$$A_{CP}(t) \simeq \left[A_{CP}^{\overline{K}^0}(t) + A_{CP}^{\rm dir}(t) + A_{CP}^{\rm int}(t)\right]/D(t), \tag{4}$$

with the denominator $D(t) = e^{-\Gamma_S t}(1 - 2r_f\cos\delta_f\cos\phi) + e^{-\Gamma_L t}|\varepsilon|^2$. The first term corresponds to the known CP violation in the kaon mixing [4],

$$A_{CP}^{\overline{K}^0}(t) = 2e^{-\Gamma_S t}\mathscr{R}e(\varepsilon) - 2e^{-\Gamma t}\left[\mathscr{R}e(\varepsilon)\cos(\Delta m t) + \mathscr{I}m(\varepsilon)\sin(\Delta m t)\right], \tag{5}$$

which is independent of r_f, i.e., of the DCS amplitude. The second term is the direct CP asymmetry originating from the interference between the CF and DCS amplitudes,

$$A_{CP}^{\rm dir}(t) = e^{-\Gamma_S t}\, 2r_f \sin\delta_f \sin\phi. \tag{6}$$

The third term in Eq. (4) represents the new CP-violation effect [8],

$$A_{CP}^{\rm int}(t) = -4r_f\cos\phi\sin\delta_f\left[e^{-\Gamma_S t}\mathscr{I}m(\varepsilon) - e^{-\Gamma t}\left(\mathscr{I}m(\varepsilon)\cos(\Delta m t) - \mathscr{R}e(\varepsilon)\sin(\Delta m t)\right)\right], \tag{7}$$

which is induced by the interference between the CF and DCS amplitudes of the decays $D \to f\overline{K}^0(t)(\to \pi^+\pi^-)$ and $D \to fK^0(t)(\to \pi^+\pi^-)$ with the kaon mixing. The mechanism responsible for Eq. (7) is more complicated than for the ordinary mixing-induced CP asymmetry in, for example, the $B^0(t) \to \pi^+\pi^-$ mode: both the oscillation and decay take place in the mother particle in the latter, while $A_{CP}^{\rm int}$ arises from the mother decay and the daughter mixing as depicted in Fig. 1. $A_{CP}^{\rm int}$ is not a direct CP asymmetry in charm decays, since it does not vanish as $\phi = 0$.

Unlike the singly Cabibbo-suppressed (SCS) case, both the CF and DCS amplitudes, being of the tree level, can be extracted from measured branching fractions [10, 11, 12, 13]. A global fit to the newest data in the factorization-assisted topological-amplitude (FAT) approach [10] gives the parameters $r_{\pi^+} = -0.073 \pm 0.004$ and $\delta_{\pi^+} = -1.39 \pm 0.05$ for the $D^+ \to \pi^+ K_S^0$ decay [14]. The solution with opposite signs of δ_{π^+} contributes equivalently to branching fractions, which depend only on the cosine of strong phases. The one presented above is preferred by the central value of the CP-asymmetry data in Eq. (1) in the global fit, to which the sign of strong phases is relevant.

The time-dependent CP asymmetries in the $D^+ \to \pi^+K(t)(\to \pi^+\pi^-)$ decay as a function of t/τ_S are displayed in Fig. 2. It is found that the total CP asymmetry is dominated by $A_{CP}^{\overline{K}^0}$, and the new effect $A_{CP}^{\rm int}$, reaching order of 10^{-3} or even 10^{-2} in the range $2\tau_S \lesssim t \lesssim 5\tau_S$, are experimentally accessible. The direct CP asymmetry is too small (being of order of 10^{-4}) to be seen in the plots. Hence, deviation of the total CP asymmetry in $D \to fK_S^0$ decays from $A_{CP}^{\overline{K}^0}$ should be attributed to $A_{CP}^{\rm int}$, instead of to the direct CP asymmetry.

In this work we have studied the time-dependent CP asymmetries in the $D \to fK_S^0(\to \pi^+\pi^-)$ chain decays. A new CP-violation effect was identified in these processes, which is induced by

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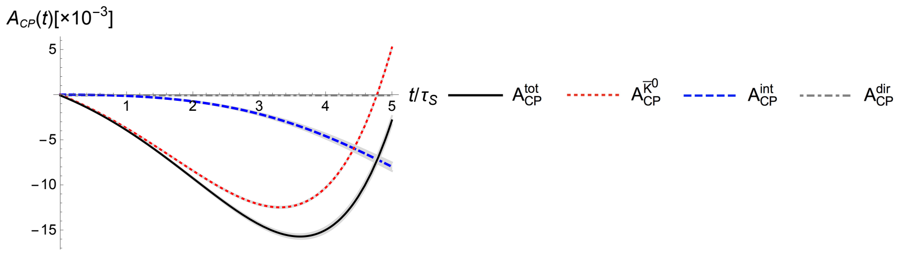

Figure 2: Time-dependent *CP* asymmetries in the $D^+ \to \pi^+ K(t)(\to \pi^+\pi^-)$ decay as a function of t/τ_S. The gray bands represent the theoretical uncertainties.

the interference between the CF and the DCS amplitudes with the K^0-$\overline{K}^0$ mixing. Unlike the SCS processes, both the CF and DCS amplitudes, occurring at the tree level, can be extracted from measured branching fractions. Therefore, their *CP* asymmetries can be estimated more accurately, and have been shown to be as large as 10^{-3} in the $D^+ \to \pi^+ K_S^0$ mode. Nevertheless, its effect has been missed in the literature. We emphasize that the direct *CP* asymmetries used to search for new physics must be determined by subtracting the kaon-mixing and DCS interference effects from total *CP* asymmetries.

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