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# $CP$ violation in charmed hadron decays into neutral kaons

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We find a new $CP$ violating effect in charmed hadron decays into neutral kaons, which is induced by the interference between the Cabibbo-favored and doubly Cabibbo-suppressed amplitudes with the $K^0-\overline{K}^0$ mixing [1]. It is estimated to be of order of $\mathcal{O}(10^{-3})$, much larger than the direct $CP$ asymmetry, but missed in the literature. To reveal this new $CP$ violation effect, we propose a new observable, the difference of the $CP$ asymmetries in the $D^+\to\pi^+K_S^0$ and $D_s^+\to K^+K_S^0$ modes. Once the new effect is determined by experiments, the direct $CP$ asymmetry then can be extracted and used to search for new physics.

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*CP* asymmetry plays an unique role in understanding the matter-antimatter asymmetry and searching for new physics. It has been well established in the kaon and $B$ meson systems [2, 3, 4, 5], but not yet in the charm sector. In the past decade, many efforts have been devoted to study the *CP* violation in the singly Cabibbo-suppressed (SCS) $D$ meson decays. The most precise experimental result of *CP* violation in SCS decays is [6]

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = (-0.10 \pm 0.08 \pm 0.03)\%. \tag{1}$$

With the precision lower than $10^{-3}$, the *CP* violation in charm decays has not been observed.

*CP* asymmetry can also occur in $D \to fK_S^0$ decays, where $f$ is a final-state particle. For example, the *CP* violation in $D^+ \to \pi^+K_S^0$ has been measured by Belle collaboration with $3.2\sigma$ from zero [7]. In this work, We point out a new *CP*-violation effect, which is induced by the interference between the Cabibbo-favored (CF) and doubly Cabibbo-suppressed (DCS) amplitudes with the mixing of final-state mesons [1]. It is estimated to be of order of $10^{-3}$, much larger than the direct *CP* asymmetry, however, missed in the literature [7, 8, 9, 10]. We propose a new observable, the difference between the *CP* asymmetries in the $D^+ \to \pi^+K_S^0$ and $D_s^+ \to K^+K_S^0$ decays, to measure the new *CP* violation effect. Once the new effect is obtained, the direct *CP* asymmetry in charm decays can be extracted correctly and used to search for new physics.

In experiments, the $K_S^0$ state is reconstructed by $\pi^+\pi^-$ final state. The time-dependent *CP* violation in $D$ meson decays into neutral kaons is defined by

$$A_{CP}(t) \equiv \frac{\Gamma(D \to K(t)(\to \pi^+\pi^-)f) - \Gamma(\overline{D} \to K(t)(\to \pi^+\pi^-)\overline{f})}{\Gamma(D \to K(t)(\to \pi^+\pi^-)f) + \Gamma(\overline{D} \to K(t)(\to \pi^+\pi^-)\overline{f})}, \tag{2}$$

where $K(t)$ donates the immediate state of neutral kaons. The mass eigenstates of neutral kaons, $|K_S^0\rangle$ of mass $m_S$ and width $\Gamma_S$ and $|K_L^0\rangle$ of mass $m_L$ and width $\Gamma_L$, are linear combinations of the flavor eigensates $|K^0\rangle$ and $|\overline{K}^0\rangle$, $|K_{S,L}^0\rangle = p_K|K^0\rangle \mp q_K|\overline{K}^0\rangle$, with $p_K = (1+\varepsilon)/\sqrt{2(1+|\varepsilon|^2)}$ and $q_K = (1-\varepsilon)/\sqrt{2(1+|\varepsilon|^2)}$, and $\varepsilon$ is a small parameter characterizing the indirect *CP* violation in neutral kaon mixing [5]. For convenience, the ratio between DCS and CF amplitudes is set as

$$\mathscr{A}(D \to K^0 f)/\mathscr{A}(D \to \overline{K}^0 f) = r_f\, e^{i(\phi+\delta_f)}, \tag{3}$$

where $r_f$ is the size of the ratio, $\phi$ and $\delta_f$ are relative weak and strong phases respectively. In the SM, $r_f \sim |V_{cd}^* V_{us}/V_{cs}^* V_{ud}| \sim \mathscr{O}(10^{-2})$ and $\phi \equiv Arg\left[-V_{cd}^* V_{us}/V_{cs}^* V_{ud}\right] = (-6.17 \pm 0.43) \times 10^{-4}$ [5]. With the small parameters $\varepsilon$, $r_f$ and $\phi$, we obtain the time-dependent *CP* violation as

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

in which $D(t) = e^{-\Gamma_S t}(1 - 2r_f \cos\delta_f \cos\phi) + e^{-\Gamma_L t}|\varepsilon|^2$. The $A_{CP}^{\overline{K}^0}(t)$ term is the indirect *CP* violation in $K^0 - \overline{K}^0$ mixing,

$$A_{CP}^{\overline{K}^0}(t) = -2e^{-\Gamma t}\big(Re(\varepsilon)\cos(\Delta m t) + Im(\varepsilon)\sin(\Delta m t)\big) + 2Re(\varepsilon)e^{-\Gamma_S t}. \tag{5}$$

The $A_{CP}^{\rm dir}(t)$ term is the direct *CP* violation in charm decay induced by the interference between the CF and DCS amplitudes,

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

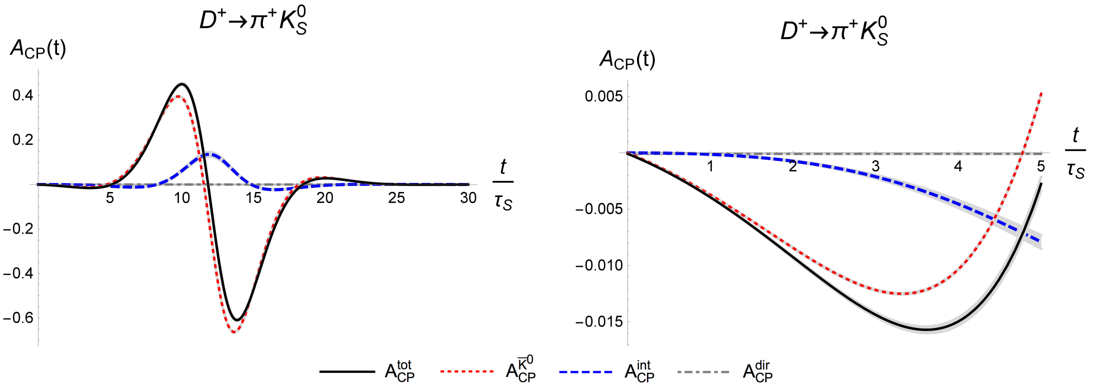


**Figure 1:** The plot of time-dependent $CP$ asymmetries in the $D^+ \to \pi^+ K(t)(\to \pi^+\pi^-)$ given by [1], where the right figure is the zoomed plot for the small $t$ region of the left one, and the gray bands are the theoretical uncertainties.

The $A_{CP}^{\rm int}(t)$ term is the interference effect between the CF and DCS amplitudes with $K^0 - \overline{K}^0$ mixing,

$$A_{CP}^{\rm int}(t) = -4r_f \cos\phi \sin\delta_f \left(Im(\varepsilon)e^{-\Gamma_S t} - e^{-\Gamma t}(Im(\varepsilon)\cos(\Delta m t) - Re(\varepsilon)\sin(\Delta m t))\right). \tag{7}$$

The parameters $r_f$ and $\delta_f$ for the $D^+ \to \pi^+ K_S^0$ and $D_s^+ \to K^+ K_S^0$ decays have been estimated in the factorization-assisted topological-amplitude (FAT) approach [11, 12]. The dependences of the $CP$ asymmetry in the $D^+ \to \pi^+ K(t)(\to \pi^+\pi^-)$ decay on $t/\tau_S$ are displayed in Fig. 1. It is found that the total $CP$ violation dominated by $A_{CP}^{\overline{K}^0}(t)$, and the deviation from $A_{CP}^{\overline{K}^0}(t)$ mainly comes from $A_{CP}^{\rm int}(t)$. The direct $CP$ asymmetries are too small to be seen in Fig. 1, being of order of $\mathcal{O}(10^{-5})$. According to Eqs. (5) and (7), $A_{CP}^{\overline{K}^0}(t=0) = A_{CP}^{\rm int}(t=0) = 0$, resulting in $A_{CP}(t=0) = A_{CP}^{\rm dir}(t=0)$. Both the forthcoming experiments cannot neausre the direct $CP$ asymmetries, unless the large weak phase differences are provided by new physics. Thereby, an observation with nonvanishing $A_{CP}(t=0)$ indicates new physics. Compared to the SCS processes, in which the $CP$ asymmetry cannot discriminate new physics due to the ambiguities in estimating the penguin amplitudes, the direct $CP$ asymmetry in neutral kaon modes would give a more unambiguous new physics signal.

The time-integrated $CP$ asymmetry is

$$A_{CP} = \frac{\int_0^\infty F(t)[A_{CP}^{\overline{K}^0}(t) + A_{CP}^{\rm dir}(t) + A_{CP}^{\rm int}(t)]dt}{\int_0^\infty F(t)D(t)dt}, \tag{8}$$

where $F(t)$ is a function to take into account relevant experimental effects. With the approximation of $F(t) = 1$ in the interval $[t_1, t_2]$ and $F(t) = 0$ elsewhere [9], quation (8) yields

$$\begin{aligned} A_{CP}(t_1,t_2) = \frac{2Re(\varepsilon) - 4Im(\varepsilon) r_f \cos\phi \sin\delta_f}{1 - 2r_f\cos\delta_f\cos\phi}\left[1 - \frac{\left[c(t_1)-c(t_2)\right] + \frac{Im(\varepsilon)+2Re(\varepsilon)r_f\cos\phi\sin\delta_f}{Re(\varepsilon)-2Im(\varepsilon)r_f\cos\phi\sin\delta_f}\left[s(t_1)-s(t_2)\right]}{\tau_S\Gamma(1+x^2)(e^{-\Gamma_S t_1} - e^{-\Gamma_S t_2})}\right] \\ +2r_f\sin\delta_f\sin\phi, \end{aligned} \tag{9}$$

where $x = \Delta m/\Gamma$, $c(t) = e^{-t\Gamma}[\cos(\Delta m t) - x\sin(\Delta m t)]$, and $s(t) = e^{-t\Gamma}[x\cos(\Delta m t) + \sin(\Delta m t)]$. In the first line, those terms proportional to $r_f$ represent the new effect $A_{CP}^{\rm int}(t_1,t_2)$, and those without

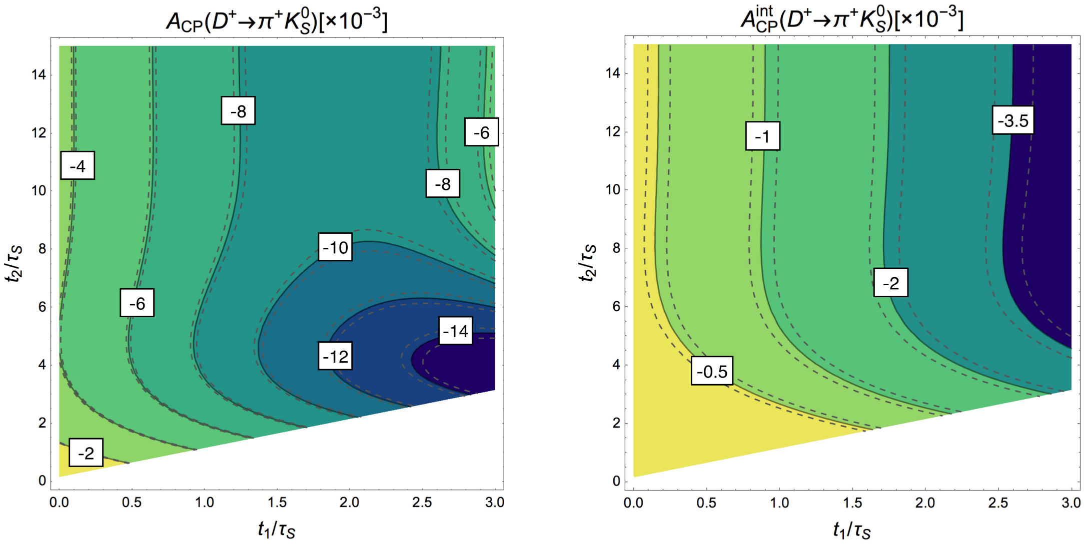


**Figure 2:** The plot of time-integrated $CP$ asymmetries in the $D^+ \to \pi^+ K_S^0$ given in [1], where the left plot is the total $CP$ asymmetry and the right one is the new $CP$-violation effect. The dashed lines is the theoretical uncertainties of our predictions.

$r_f$ are the $CP$ violation in the neutral kaon mixing. The second line, which is independent of $t_{1,2}$, corresponds to the direct $CP$ asymmetry in charm decays. The time-integrated $CP$ asymmetries in the $D^+ \to \pi^+ K_S^0$ and the new $CP$ violating effect are exhibited in Fig. 2. In some ranges of $t_1$ and $t_2$, these two quantities are relatively larger than other ranges. The experimental investigations could choose the favorable time intervals. In some experiments, including Belle and LHCb, the new $CP$ violation effect is in absence [7, 13, 14, 15, 16]. However, since this new effect is of the same order as the direct $CP$ asymmetries in the SCS processes, it cannot be neglected in these measurements.

In order to measure the new $CP$-violation effect in experiments, we propose an observable

$$\Delta A_{CP}^{\pi^+,K^+} \equiv A_{CP}^{D^+\to\pi^+K_S^0}(t_1,t_2) - A_{CP}^{D_s^+\to K^+K_S^0}(t_1,t_2). \tag{10}$$

The $CP$ violation in the kaon mixing cancels in the above difference, and the direct $CP$ violation is negligible. Our global-fit analysis indicates that the $2r_f \cos\phi \cos\delta_f$ term in denominator of Eq. (9) matters little due to the large strong phases $\delta_f$ [12], which is consistent with those derived in the literature [17, 18, 19, 20] and supported by experiment [21]. Then we have

$$\Delta A_{CP}^{\pi^+,K^+} \simeq A_{CP}^{\text{int},D^+\to\pi^+K_S^0}(t_1,t_2) - A_{CP}^{\text{int},D_s^+\to K^+K_S^0}(t_1,t_2). \tag{11}$$

The model-independent $SU(3)$ symmetry analysis shows the new effects in two modes are constructive in $\Delta A_{CP}^{\pi^+,K^+}$. The dependencies of $\Delta A_{CP}^{\pi^+,K^+}$ on $t_1$ and $t_2$ are plotted in Fig. 3. $\Delta A_{CP}^{\pi^+,K^+}$ is of order of $10^{-3}$ in most of time intervals, which is accessible at Belle II and LHCb upgrade experiments [6, 15, 22, 23].

In summary, we investigated the time-dependent and time-integrated $CP$ violation in charm decays into neutral kaons. We first pointed out a new measurable $CP$-violating effect, the interference between charm decays and kaon mixing, exists in these modes. It could be revealed by measuring the difference of $CP$ asymmetries in the $D^+ \to \pi^+ K_S^0$ and $D_s^+ \to K^+ K_S^0$ modes on Belle

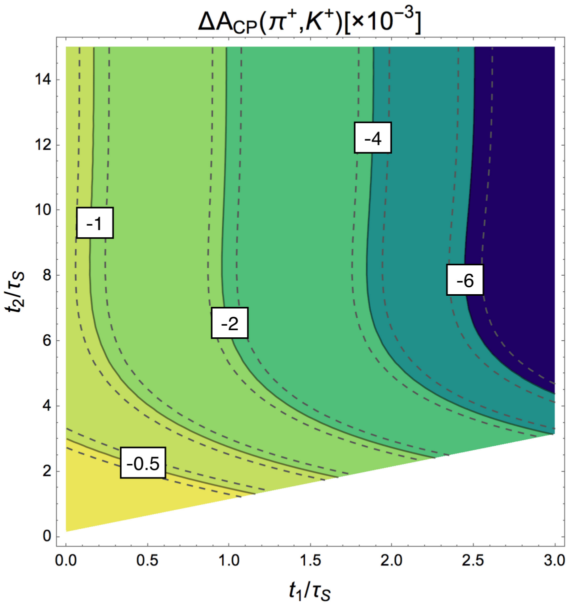


**Figure 3:** The dependences of $\Delta A_{CP}^{\pi^+,K^+}$ on $t_1$ and $t_2$ given in [1].

II and LHCb upgrade. In addition, an observation with non-zero *CP* violation at $t = 0$ would signal new physics.


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