Direct $CP$ violation in charm at Belle

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Using the full data sample collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider, we have searched for $CP$ violation of charmed mesons in $D^+ \rightarrow K^0_S\pi^+$ and $D^0 \rightarrow h^+h^-$ decays, where $h$ denotes $K$ and $\pi$. We observe evidence for $CP$ violation in $D^+ \rightarrow K^0_S\pi^+$ decay with 3.2 standard deviations away from zero, $(-0.363 \pm 0.094 \pm 0.067)\%$, while the asymmetry is consistent with the expected $CP$ violation due to the neutral kaon in the final state. No evidence for $CP$ violation in $D^0 \rightarrow h^+h^-$ is observed with $A_{CP}^{KK} = (-0.32 \pm 0.21 \pm 0.09)\%$ and $A_{CP}^{\pi\pi} = (+0.55 \pm 0.36 \pm 0.09)\%$. The $CP$ asymmetry difference between $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays is also measured with $\Delta A_{CP}^{hh} = (-0.87 \pm 0.41 \pm 0.06)\%$, which is 2.1 standard deviations away from zero and supports recent LHCb and CDF measurements.

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Violation of the combined Charge-conjugation and Parity symmetries (CP) in the standard model (SM) is produced by a non-vanishing phase in the Cabibbo-Kobayashi-Maskawa flavor-mixing matrix [1], where the violation may be observed as a non-zero CP asymmetry defined as

\[ A_{CP}^{D\rightarrow f} = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})} \tag{1} \]

where \( \Gamma \) is the partial decay width, \( D \) denotes a charmed meson, and \( f \) is a final state.

In this presentation, we report CP asymmetries of charmed mesons in the decays \( D^+ \rightarrow K^0_S \pi^+ \), \( D^0 \rightarrow K^+ K^- \), \( D^0 \rightarrow \pi^+ \pi^- \) [3], and the CP asymmetry difference between \( D^0 \rightarrow K^+ K^- \) and \( D^0 \rightarrow \pi^+ \pi^- \), which is an update of our previous publications [3, 4] using the full data sample collected with the Belle detector [5] at the KEKB [6] asymmetric-energy \( e^+ e^- \) collider. The \( D^+ \rightarrow K^0_S \pi^+ \) final state is a coherent sum of Cabibbo-favored and doubly Cabibbo-suppressed decays where no SM CP violation in charm decay is expected, while \((-0.332 \pm 0.006)\%\) CP violation due to \( K^0 - \bar{K}^0 \) mixing (denoted by \( A_{CP}^{K^0} \)) is expected with a neutral kaon in the final state. The \( D^0 \rightarrow h^+ h^- \) final states where \( h \) denotes \( K \) and \( \pi \) are singly Cabibbo-suppressed decays in which both direct (\( A_{CP}^{D\rightarrow f} \)) and indirect CP violations (\( A_{ind}^{D\rightarrow f} \)) are expected in the SM, while the CP asymmetry difference between the two decays, \( \Delta A_{CP}^{hh} = A_{CP}^{KK} - A_{CP}^{\pi\pi} \), reveals approximately direct CP violation with the universality of indirect CP violation in charm decays [8]. The data were recorded at the \( \Upsilon(nS) \) resonances \((n = 1, 2, 3, 4, 5)\) or near the \( \Upsilon(4S) \) resonance and the integrated luminosity is \( \sim 1 \) ab\(^{-1}\).

We determine the quantity \( A_{CP}^{D\rightarrow f} \) defined in Eq. (1) by measuring the asymmetry in the signal yield

\[ A_{rec}^{D\rightarrow f} = \frac{N_{rec}^{D\rightarrow f} - N_{rec}^{\bar{D}\rightarrow \bar{f}}}{N_{rec}^{D\rightarrow f} + N_{rec}^{\bar{D}\rightarrow \bar{f}}} = A_{CP}^{D\rightarrow f} + A_{FB} + A_{\varepsilon}^{f}, \tag{2} \]

where \( N_{rec} \) is the number of reconstructed decays. The \( A_{FB} \) is forward-backward asymmetry in \( e^+ e^- \rightarrow c\bar{c} \) process and the \( A_{\varepsilon}^{f} \) is final state particle detection asymmetry where the latter depends on the final state particles while the former does not. For a slow pion detection asymmetry which is involved in \( D^0 \rightarrow h^+ h^- \) reconstruction via \( D^+ \), we correct for the asymmetry using the method described in our previous publication [3]. A fast pion detection asymmetry which is involved in \( D^+ \rightarrow K^0_S \pi^+ \) reconstruction is corrected for using the method described in Ref. [3]. With assumption the \( A_{FB} \) is the same for all charmed mesons, Refs. [3, 4] use CP violation free large statistics of resonance data samples to correct for the \( A_{\varepsilon}^{f} \). For the final state with a neutral kaon, we have to take into account additional corrections which are asymmetry due to different interactions between \( K^0 \) and \( \bar{K}^0 \) with detector [10] and experiment dependent \( A_{CP}^{K^0} \) with \( K_S^0 \) decay time dependency on it [11]. Once we correct for \( A_{\varepsilon}^{f} \), then \( A_{CP}^{D\rightarrow f} \) is obtained in bins of the polar angle of charmed meson momentum at the center-of-mass system (c.m.s.) using antisymmetry of \( A_{FB} \) in the polar angle of charmed meson momentum at the c.m.s.

Figure [1] shows invariant masses of \( D^\pm \rightarrow K^0_S \pi^\pm \) together with the fits that result in \( \sim 1.74 \)M reconstructed decays and the measured \( A_{CP} \) in bins of the polar angle of \( D^\pm \) momentum at the c.m.s. From the right plot in Fig. [1], we obtain \( A_{CP}^{D^+\rightarrow K^0_S \pi^+} = (-0.363 \pm 0.094 \pm 0.067)\% \) which shows 3.2\( \sigma \) deviations from zero. This is the first evidence for CP violation in charm decays from a single decay mode while the measured asymmetry is consistent with the \( A_{CP}^{K^0} \). After subtracting experiment dependent \( A_{CP}^{K^0} \) [11], the CP violation due to change in charm, \( A_{CP}^{M_{CP}} \), is measured to be \((-0.024 \pm 0.094 \pm 0.067)\% \) [9].
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Figure 1: $M(K_{S}^{0} \pi^{+})$ (left top) and $M(K_{S}^{0} \pi^{-})$ (left bottom) distributions where the shaded and hatched are $D_{s}^{+} \rightarrow K_{S}^{0} K^{+}$ due to particle misidentification and combinatorial backgrounds. Right plot is $A_{CP}$ as a function of $\cos \theta_{D_{s}^{+}}^{c.m.s.}$ where the thick line is the mean value of $A_{CP}$ while the hatched band is the $\pm 1 \sigma_{\text{total}}$ interval, where $\sigma_{\text{total}}$ is the total uncertainty.

Figure 2: Left four plots show reconstructed signal distributions described in the text and right two plots show preliminary results of $A_{CP}$ as a function of the polar angle of $D^{*+}$ momentum at the c.m.s.

Figure 2 shows reconstructed signal distributions showing 14.7M $D^{0} \rightarrow K^{-} \pi^{+}$, 3.1M $D^{*+}$ tagged $D^{0} \rightarrow K^{-} \pi^{+}$, 282k $D^{*+}$ tagged $D^{0} \rightarrow K^{+} K^{-}$, and 123k $D^{*+}$ tagged $D^{0} \rightarrow \pi^{+} \pi^{-}$ on top of the high signal purities, respectively, and the measured $A_{CP}$ in bins of the polar angle of $D^{*+}$ momentum at the c.m.s. From the right plot in Fig. 2, we obtain $A_{CP}^{KK} = (-0.32 \pm 0.21 \pm 0.09)\%$ and $A_{CP}^{\pi\pi} = (+0.55 \pm 0.36 \pm 0.09)\%$ where the former shows the best sensitivity to date. From the two measurements, we obtain $\Delta A_{CP}^{hh} = (-0.87 \pm 0.41 \pm 0.06)\%$ which shows 2.1σ deviations from zero and supports recent LHCb and CDF measurements [12, 13]. By combining LHCb, CDF, and Belle results, the average of $\Delta A_{CP}^{hh}$ becomes $(-0.74 \pm 0.15)\%$.

With a help from Marco Gersabeck from Heavy Flavor Averaging Group (HFAG), Fig. 3 shows $\Delta A_{CP}$ and $A_{F}$ fit reflecting the new Belle results reported in this presentation and results in $\Delta a_{CP}^{\text{dir}} = (-0.678 \pm 0.147)\%$ and $a_{CP}^{\text{ind}} = (+0.027 \pm 0.163)\%$ [4].

In summary, we observe evidence for $CP$ violation in the decay $D^{+} \rightarrow K_{S}^{0} \pi^{+}$ where the ev-
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Figure 3: $\Delta A_{CP}$ and $A_{\Gamma}$ fit from HFAG.

Evidence is consistent with the expected CP violation due to $K^0 - \bar{K}^0$ mixing. No evidence for CP violation in $D^0 \rightarrow h^+h^-$ is observed and the $\Delta A_{CP}^{hh}$ is measured to be $(-0.87 \pm 0.41 \pm 0.06)\%$.

References

[2] Throughout this Letter the charge conjugate decay mode is also implied unless stated otherwise.