CP violation in charm decays 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 present CP violation in charm decays. The $D^0 - \bar{D}^0$ mixing parameter $\gamma_{CP}$ and indirect CP violation parameter $A_\Gamma$ in $D^0 \rightarrow h^+h^-$ decays are reported, where $h$ denotes $K$ and $\pi$. The preliminary results are $\gamma_{CP} = (1.11 \pm 0.22 \pm 0.11)\%$ and $A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%$. We also report searches for CP violation in $D^0 \rightarrow h^+h^-$ and $D^+ \rightarrow K_S^0 K^+$ decays. 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 measured with $\Delta A_{CP}^{hh} = (-0.87 \pm 0.41 \pm 0.06)\%$. The CP asymmetry in $D^+ \rightarrow K_S^0 K^+$ decay is measured to be $(-0.25 \pm 0.28 \pm 0.14)\%$. After subtracting CP violation due to $K^0-\bar{K}^0$ mixing, the CP asymmetry in $D^+ \rightarrow \bar{K}^0 K^+$ decay is found to be $(+0.08 \pm 0.28 \pm 0.14)\%$. 

The European Physical Society Conference on High Energy Physics - EPS-HEP2013
18-24 July 2013
Stockholm, Sweden

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1. Introduction

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 $\left[1\right]$ and that in charm decays is expected to be very small in the SM $\left[2, 3\right]$, thus it provides a unique probe to search for beyond the SM.

2. $y_{CP}$ and $A_{\Gamma}$ measurements with $D^0 \to h^+h^-$ and $D^0 \to K^-\pi^+$ decays

The neutral charmed meson mixing and indirect CP violation (CPV) parameters, $y_{CP}$ and $A_{\Gamma}$ are defined as

$$y_{CP} = \frac{\hat{\Gamma}(D^0 \to h^+h^-) - \hat{\Gamma}(\bar{D}^0 \to h^+h^-)}{2\Gamma} - 1, \quad (2.1)$$

$$A_{\Gamma} = \frac{\hat{\Gamma}(D^0 \to h^+h^-) + \hat{\Gamma}(\bar{D}^0 \to h^+h^-)}{2\Gamma}, \quad (2.2)$$

where $\Gamma$ is the average decay width of the two mass eigenstates of the neutral charmed mesons and $\hat{\Gamma}$ is the effective decay width of $D^0 \to h^+h^-$ that can be described with a single exponential form $\left[4\right]$. Under CP conservation, $y_{CP}$ is $y$ that is $\Delta\Gamma/2\Gamma$ and characterizes the charm mixing where $\Delta\Gamma$ is the decay width difference between the two mass eigenstates of the neutral charm mesons. Therefore, any large deviation between $y_{CP}$ and $y$ strongly indicates CPV in charm decays.

The experimental observable for $y_{CP}$ is the lifetime difference between $D^0 \to h^+h^-$ and $D^0 \to K^-\pi^+$ states, where the former is CP-even and the latter is an equal mixture of CP-even and CP-odd under CP conservation. The CPV parameter $A_{\Gamma}$ can be measured from lifetime difference between the two CP conjugate decays. From Eq. (2.1), the lifetime of $D^0 \to h^+h^-$ can be expressed as $\tau(D^0 \to h^+h^-) = \tau/(1 + y_{CP})$ and from (2.2) that of $D^0 \to h^+h^-$ and $\bar{D}^0 \to h^+h^-$ can be described with $\tau(D^0 \to h^+h^-) = \tau(1 - A_{\Gamma})$ and $\tau(D^0 \to h^+h^-) = \tau(1 + A_{\Gamma})$, respectively, where $\tau$ is the lifetime of $D^0 \to K^-\pi^+$. Therefore, the lifetimes of $D^0 \to h^+h^-$ and $\bar{D}^0 \to h^+h^-$ can be parameterized in terms of $y_{CP}$, $A_{\Gamma}$, and $\tau$ as shown in Eq. (2.3).

$$\tau(D^0 \to h^+h^-) = \tau(1 - A_{\Gamma})/(1 + y_{CP}),$$

$$\tau(\bar{D}^0 \to h^+h^-) = \tau(1 + A_{\Gamma})/(1 + y_{CP}). \quad (2.3)$$

In order to extract $y_{CP}$, $A_{\Gamma}$, and $\tau$, we perform simultaneous fit to the five proper decay time distributions from $D^0 \to K^+K^-$, $\bar{D}^0 \to K^+K^-$, $D^0 \to K^-\pi^+$ + c.c., $D^0 \to \pi^+\pi^-$, and $\bar{D}^0 \to \pi^+\pi^-$. Since the experimental data were taken with two different silicon vertex detector configurations $\left[5\right]$, we treat them separately with the two different proper decay time resolution functions. Figure 1 shows the simultaneous fits to the five proper decay time distributions. To reduce systematic effects due to the resolution function dependence on cos $\theta^*$, where $\theta^*$ is the polar angle of the $D^0$ momentum at the center-of-mass system (c.m.s.), the simultaneous fits are actually performed in bins of cos $\theta^*$ to extract $y_{CP}$, $A_{\Gamma}$ and $\tau$. Figure 2 shows the results of the simultaneous fits, $y_{CP}$, $A_{\Gamma}$, and $\tau$ as a function of the cos $\theta^*$. The averages of the fit results shown in Fig. 3 are $y_{CP} = (1.11 \pm 0.22 \pm 0.11)\%$, $A_{\Gamma} = (-0.03 \pm 0.20 \pm 0.08)\%$, and $\tau = (408.56 \pm 0.54)$ fs, where the last is consistent with world average $\left[6\right]$.

To conclude, we observe $y_{CP}$ with 4.5$\sigma$ significance and find no indirect CPV in $D^0 \to h^+h^-$ decays.
Figure 1: Simultaneous fits to the proper decay time distributions that are integrated over the cos θ∗. Top (bottom) plots are obtained with 3-layer (4-layer) silicon vertex detector. The distributions of signal and sideband regions are shown as error bars and the hatched, respectively. The “(+)” and “(-)” denote the charge of the tagging soft pion.

3. Direct CPV measurements in $D^0 \rightarrow h^+ h^-$ and $D^+ \rightarrow K_s^0 K^+$ decays

The direct CP asymmetry of $D \rightarrow f$ decays is defined as

$$A_{CP}^{D \rightarrow f} = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})},$$

(3.1)

where $\Gamma$ is the partial decay width. Experimental determination of $A_{CP}^{D \rightarrow f}$ can be done with the asymmetry in the signal yield

$$A_{rec}^{D \rightarrow f} = \frac{N_{rec}^{D \rightarrow f} - N_{rec}^{D \rightarrow \bar{f}}}{N_{rec}^{D \rightarrow f} + N_{rec}^{D \rightarrow \bar{f}}} = A_{CP}^{D \rightarrow f} + A_{others},$$

(3.2)

where $N_{rec}$ is the number of reconstructed decays and $A_{others}$ are asymmetries other than $A_{CP}^{D \rightarrow f}$, production and particle detection asymmetries. The methods developed in Refs. [7] and [8] are used to correct for charged kaon and soft pion detection asymmetries, respectively. To correct for asymmetry caused by neutral kaons, we rely on the method in Ref. [9]. Once we correct for asymmetries due to particle detection, then we extract $A_{CP}^{D \rightarrow f}$ using the antisymmetry of the production asymmetry which is the forward-backward asymmetry at Belle.

The $D^0 \rightarrow h^+ h^-$ final states are singly Cabibbo-suppressed (SCS) decays in which both direct and indirect CPV are expected in the SM [2, 3], while the CP asymmetry difference between the
two decays, \( \Delta A_{hh}^{CP} = A_{KK}^{CP} - A_{\pi\pi}^{CP} \) reveals approximately direct \( CPV \) with the universality of indirect \( CPV \) in charm decays [3]. Figure 3 shows reconstructed signal distributions showing 14.7M \( D_0^0 \to K^-\pi^+ \), 3.1M \( D^*_+ \) tagged \( D_0^0 \to K^-\pi^+ \), 282k \( D^*_+ \) tagged \( D_0^0 \to K^+K^- \), and 123k \( D^*_+ \) tagged \( D_0^0 \to \pi^+\pi^- \), respectively, and the measured \( A_{CP} \) in bins of \(|\cos \theta^*_{D^+}| \). From the bottom plots in Fig. 3, we obtain \( A_{KK}^{CP} = (-0.32 \pm 0.21 \pm 0.09)\% \) and \( A_{\pi\pi}^{CP} = (+0.55 \pm 0.36 \pm 0.09)\% \) where the former shows the best sensitivity to date. From the two measurements, we obtain \( \Delta A_{hh}^{CP} = (-0.87 \pm 0.41 \pm 0.06)\% \).

The \( D^+ \) decaying to the final state \( K^0_S K^+ \) proceeds from \( D^+ \to \bar{K}^0 K^+ \) decay which is SCS, where direct \( CPV \) is predicted to occur [2, 3]. With a \( K^0_S \) in the final state, \( D^+ \to K^0_S K^+ \) decay is also expected to generate \( CPV \) due to \( K^0 - \bar{K}^0 \) mixing, referred to as \( A_{CP}^{K^0 - \bar{K}^0} \). The decay \( D^+ \to \bar{K}^0 K^+ \) shares the same decay diagrams with \( D^0 \to K^+K^- \) by exchanging the spectator quarks, \( d \leftrightarrow u \). Therefore, neglecting the helicity and color suppressed contributions in \( D^+ \to \bar{K}^0 K^+ \) and \( D^0 \to K^+K^- \) decays, the direct \( CPV \) in the two decays is expected to be effectively the same. Thus, as a complementary test of the \( \Delta A_{hh}^{CP} \) measurement\(^1\), the precise measurement of \( A_{CP} \) in \( D^+ \to \bar{K}^0 K^+ \) helps to pin down the origin of \( \Delta A_{hh}^{CP} \) [2]. Figure 4 shows invariant masses of \( D^\pm \to K^0_S K^\pm \) together with the fits that result in \( \sim 277k \) reconstructed decays and the measured \( A_{CP} \) in bins of \(|\cos \theta^*_{D^+}| \). From the right plot in Fig. 4, we obtain \( A_{CP}^{D^+ \to K^0_S K^+} = (-0.25 \pm 0.28 \pm 0.14)\% \). After

\(^1\) Now the tension is rather released [10], but was strong [11].
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![Graphs showing reconstructed signal distributions and preliminary results of A_{CP} as a function of the polar angle of D^*+ momentum at the c.m.s.]

Figure 3: Top four plots show reconstructed signal distributions described in the text and bottom two plots show preliminary results of $A_{CP}$ as a function of the polar angle of $D^*^+$ momentum at the c.m.s.

subtracting experiment dependent $A_{CP}^{K^0}$ [13], the CPV in charm decay, $A_{CP}^{D^+\rightarrow\bar{K}^0 K^+}$, is measured to be $(+0.08 \pm 0.28 \pm 0.14)\%$ [14].

4. Summary

In summary, using the full data sample collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider, we report the charm mixing parameter $y_{CP}$ and indirect CPV parameter $A_{\Gamma}$ using $D^0 \rightarrow h^+h^-$ and $D^0 \rightarrow K^-\pi^+$ decays. The preliminary results are:

$$y_{CP} = (1.11 \pm 0.22 \pm 0.11)\%,$$

$$A_{\Gamma} = (-0.03 \pm 0.20 \pm 0.08)\%.$$
We also report searches for CP violation in D^0 \to h^+ h^- and D^+ \to K_S^0 K^+ decays. The preliminary results of $A_{CP}$ in $D^0 \to h^+ h^-$ decays and the difference between the two $A_{CP}$ results are:

$$A_{CP}^{K K} = (-0.32 \pm 0.21 \pm 0.09\%)$$,
$$A_{CP}^{\pi \pi} = (+0.55 \pm 0.36 \pm 0.09\%)$$,
$$\Delta A_{CP}^{hh} = (-0.87 \pm 0.41 \pm 0.06\%)$$,

and the results of $A_{CP}$ in $D^+ \to K_S^0 K^+$ decays are:

$$A_{CP}^{D^+ \to K_S^0 K^+} = (-0.25 \pm 0.28 \pm 0.14\%)$$,
$$A_{CP}^{D^+ \to K^0 K^+} = (+0.08 \pm 0.28 \pm 0.14\%)$$.

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