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 \( y_{CP} \) and indirect CP violation parameter \( A_{\Gamma} \) in \( D^0 \to h^+ h^- \) decays are reported, where \( h \) denotes \( K \) and \( \pi \). The preliminary results are \( y_{CP} = (1.11 \pm 0.22 \pm 0.11)\% \) and \( A_{\Gamma} = (-0.03 \pm 0.20 \pm 0.08)\% \).

We also report searches for CP violation in \( D^0 \to h^+ h^- \) and \( D^+ \to K^0_S K^+ \) decays. No evidence for CP violation in \( D^0 \to h^+ h^- \) 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 \( D^0 \to K^+ K^- \) and \( D^0 \to \pi^+ \pi^- \) decays is measured with \( \Delta A_{CP}^{hh} = (-0.87 \pm 0.41 \pm 0.06)\% \). The CP asymmetry in \( D^+ \to K^0_S K^+ \) 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 \( D^+ \to \bar{K}^0 K^+ \) 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 [1] and that in charm decays is expected to be very small in the SM [2, 3], thus it provides a unique probe to search for beyond the SM.

2. \( \gamma_{CP} \) and \( A_{\Gamma} \) measurements with \( D^0 \rightarrow h^{+}h^{-} \) and \( D^0 \rightarrow K^{-}\pi^{+} \) decays

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

\[
\gamma_{CP} = \frac{\hat{\Gamma}(D^0 \rightarrow h^{+}h^{-}) + \hat{\Gamma}(\bar{D}^0 \rightarrow h^{+}h^{-})}{2\Gamma} - 1, \tag{2.1}
\]

\[
A_{\Gamma} = \frac{\hat{\Gamma}(D^0 \rightarrow h^{+}h^{-}) - \hat{\Gamma}(\bar{D}^0 \rightarrow h^{+}h^{-})}{2\Gamma}, \tag{2.2}
\]

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 \( D^0 \rightarrow h^{+}h^{-} \) that can be described with a single exponential form [4]. Under CP conservation, \( \gamma_{CP} \) 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 charmed mesons. Therefore, any large deviation between \( \gamma_{CP} \) and \( y \) strongly indicates CPV in charm decays.

The experimental observable for \( \gamma_{CP} \) is the lifetime difference between \( D^0 \rightarrow h^{+}h^{-} \) and \( D^0 \rightarrow K^{-}\pi^{+} \) 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 \( D^0 \rightarrow h^{+}h^{-} \) can be expressed as \( \tau(D^0 \rightarrow h^{+}h^{-}) = \tau/(1+\gamma_{CP}) \) and from (2.2) that of \( D^0 \rightarrow h^{+}h^{-} \) and \( \bar{D}^0 \rightarrow h^{+}h^{-} \) can be described with \( \tau(D^0 \rightarrow h^{+}h^{-}) = \tau(1-A_{\Gamma}) \) and \( \tau(\bar{D}^0 \rightarrow h^{+}h^{-}) = \tau(1+A_{\Gamma}) \), respectively, where \( \tau \) is the lifetime of \( D^0 \rightarrow K^{-}\pi^{+} \). Therefore, the lifetimes of \( D^0 \rightarrow h^{+}h^{-} \) and \( \bar{D}^0 \rightarrow h^{+}h^{-} \) can be parameterized in terms of \( \gamma_{CP} \), \( A_{\Gamma} \), and \( \tau \) as shown in Eq. (2.3).

\[
\tau(D^0 \rightarrow h^{+}h^{-}) = \tau(1-A_{\Gamma})/(1+\gamma_{CP}),
\]

\[
\tau(\bar{D}^0 \rightarrow h^{+}h^{-}) = \tau(1+A_{\Gamma})/(1+\gamma_{CP}). \tag{2.3}
\]

In order to extract \( \gamma_{CP} \), \( A_{\Gamma} \), and \( \tau \), we perform simultaneous fit to the five proper decay time distributions from \( D^0 \rightarrow K^{+}K^{-} \), \( \bar{D}^0 \rightarrow K^{+}K^{-} \), \( D^0 \rightarrow K^{-}\pi^{+} \), \( \bar{D}^0 \rightarrow \pi^{+}\pi^{-} \), and \( D^0 \rightarrow \pi^{+}\pi^{-} \).

Since the experimental data were taken with two different silicon vertex detector configurations [5], 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 \( \gamma_{CP} \), \( A_{\Gamma} \), and \( \tau \). Figure 2 shows the results of the simultaneous fits, \( \gamma_{CP} \), \( A_{\Gamma} \), and \( \tau \) as a function of the cos \( \theta^{*} \). The averages of the fit results shown in Fig. 2 are \( \gamma_{CP} = (1.11 \pm 0.22 \pm 0.11)\% \), \( A_{\Gamma} = (-0.03 \pm 0.20 \pm 0.08)\% \), and \( \tau = (408.56 \pm 0.54) \) fs, where the last is consistent with world average [6].

To conclude, we observe \( \gamma_{CP} \) with 4.5\( \sigma \) significance and find no indirect CPV in \( D^0 \rightarrow h^{+}h^{-} \) decays.
Figure 1: Simultaneous fits to the proper decay time distributions that are integrated over the \( \cos \theta^* \). 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 \( D^0 \to h^+ h^- \) and \( D^+ \to K_S^0 K^+ \) decays

The direct CP asymmetry of \( D \to f \) decays is defined as

\[
A^{D \to f}_{CP} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})},
\]

where \( \Gamma \) is the partial decay width. Experimental determination of \( A^{D \to f}_{CP} \) can be done with the asymmetry in the signal yield

\[
A^{D \to f}_{rec} = \frac{N^{D \to f}_{rec} - N^{\bar{D} \to f}_{rec}}{N^{D \to f}_{rec} + N^{\bar{D} \to f}_{rec}} = A^{D \to f}_{CP} + A_{others},
\]

where \( N_{rec} \) is the number of reconstructed decays and \( A_{others} \) are asymmetries other than \( A^{D \to f}_{CP} \), 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 \( A^{D \to f}_{CP} \) using the antisymmetry of the production asymmetry which is the forward-backward asymmetry at Belle.

The \( D^0 \to h^+ h^- \) 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
Figure 2: $y_{CP}$, $A_{T}$, and $\tau$ as a function of the $\cos \theta^*$. Top (bottom) three plots are obtained with 3-layer (4-layer) silicon vertex detector.

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 $D^0 \rightarrow K^-\pi^+$, 3.1M $D^{*+}$ tagged $D^0 \rightarrow K^-\pi^+$, 282k $D^{*+}$ tagged $D^0 \rightarrow K^+K^-$, and 123k $D^{*+}$ tagged $D^0 \rightarrow \pi^+\pi^-\pi^+$, 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 $K_s^0K^+$ proceeds from $D^+ \rightarrow \bar{K}^0K^+$ decay which is SCS, where direct CPV is predicted to occur [2, 3]. With a $K_s^0$ in the final state, $D^+ \rightarrow K_s^0K^+$ decay is also expected to generate CPV due to $K^0 - \bar{K}^0$ mixing, referred to as $A^{K^0}_{CP}$. The decay $D^+ \rightarrow \bar{K}^0K^+$ shares the same decay diagrams with $D^0 \rightarrow K^+K^-$ by exchanging the spectator quarks, $d \leftrightarrow u$. Therefore, neglecting the helicity and color suppressed contributions in $D^+ \rightarrow \bar{K}^0K^+$ and $D^0 \rightarrow K^+K^-$ 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, the precise measurement of $A^{K_0^*}_{CP}$ helps to pin down the origin of $\Delta A^{hh}_{CP}$ [12]. Figure 4 shows invariant masses of $D^\pm \rightarrow K_0^*K^\pm$ 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 $A^{D^+ \rightarrow K_0^*K^+}_{CP} = (-0.25 \pm 0.28 \pm 0.14)\%$. After

\footnote{Now the tension is rather released [10], but was strong [11].}
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Belle preliminary using 976/fb

![Graphs showing reconstructed signal distributions for various charm decay modes.](image)

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, $A_{CP}^{D^{*+}K^0}$, 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 $\gamma_{CP}$ and indirect CPV parameter $A_{\Gamma}$ using $D^0 \rightarrow h^+h^-$ and $D^0 \rightarrow K^-\pi^+$ decays. The preliminary results are:

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

$$A_{\Gamma} = (-0.03 \pm 0.20 \pm 0.08)\%.$$
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Figure 4: Left two plots show $M(K_S^0 K^+)$ and $M(K_S^0 K^-)$ distributions, respectively, and right plot shows $A_{CP}$ in the decay as a function of the polar angle of $D^+$ momentum at the c.m.s.

We also report searches for $CP$ violation in $D^0 \rightarrow h^+ h^-$ and $D^+ \rightarrow K_S^0 K^+$ decays. The preliminary results of $A_{CP}$ in $D^0 \rightarrow h^+ h^-$ 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 $D^+ \rightarrow K_S^0 K^+$ decays are:

$$A_{CP}^{D^+\rightarrow K_S^0 K^+} = (-0.25 \pm 0.28 \pm 0.14)\%,$$
$$A_{CP}^{D^+\rightarrow K_0^0 K^+} = (+0.08 \pm 0.28 \pm 0.14)\%.$$

References