Measurement of CP asymmetry in Cabibbo suppressed $D^0$ decays

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Abstract

We measure the CP-violating asymmetries in decays to the $D^0 \to K^+ K^-$ and $D^0 \to \pi^+ \pi^-$ CP eigenstates using 540 fb$^{-1}$ of data collected with the Belle detector at or near the $\Upsilon(4S)$ resonance. Cabibbo-favored $D^0 \to K^- \pi^+$ decays are used to correct for systematic detector effects. The results, $A_{\text{KK}}^{CP} = (-0.43 \pm 0.30 \pm 0.11)\%$ and $A_{\text{\pi\pi}}^{CP} = (0.43 \pm 0.52 \pm 0.12)\%$, are consistent with no CP violation.

Key words: Charm mesons, CP violation, Cabibbo suppressed decays
PACS: 11.30.Er, 13.25.Ft, 14.40.Lb

1. Introduction

Decays of neutral $D$ mesons are a promising area in which to search for physics beyond the Standard Model (SM). Recently, evidence for mixing in this system has been obtained [1,2,3]. However, whether the effect observed is due to the Cabibbo-Kobayashi-Maskawa (CKM) theory or due to new physics (NP) has yet to be determined and will require further measurements to resolve. One possible measurement sensitive to NP is that of a CP asymmetry in $D^0$ decays to Cabibbo-suppressed (CS) final states [4]. Within the SM such an asymmetry is predicted to be very small ($\lesssim 0.1\%$), but within NP scenarios it can be substantial ($\gtrsim 1\%$) [5].

In this Letter we present a high statistics search for a CP asymmetry in the CS modes $D^0 \to K^+ K^-$ and $D^0 \to \pi^+ \pi^-$. These final states are accessible
to both $D^0$ and $\bar{D}^0$ mesons. The time-integrated $CP$ asymmetry for decays into a $CP$ eigenstate $f$ is defined as
\[ A_{CP}^f = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} = a_d^f + a_{ind} . \] (1)
This quantity receives contributions from both direct ($a_d^f$) and indirect ($a_{ind}$) $CP$ violation (CPV) [4]. While the direct contribution is in general distinct for different final states, the indirect contribution is the same. The indirect CPV contribution is constrained by our recent measurement of the lifetime difference using $D^0(\bar{D}^0) \to K^+K^-,\pi^+\pi^-$ decays [1]: $A_T \equiv a_{ind} = (0.01 \pm 0.30 \pm 0.15)\%$.

$CP$ asymmetries in CS decays have been searched for previously using $D^0 \to K^+K^-,\pi^+\pi^-$ [6] and $D^0 \to \pi^+\pi^-\pi^0, K^+K^-\pi^0$ [7].

2. Method

The flavour of neutral $D$ mesons at production is tagged by reconstructing $D^{*+} \to D^0\pi^+_s$ decay, in which the charge of the low momentum pion, $\pi_s$, determines the flavour of the $D^0$ meson. The measured asymmetry, $A_{rec}^f = |N(D^0 \to f) - N(\bar{D}^0 \to f)|/[N(D^0 \to f) + N(\bar{D}^0 \to f)]$, with $f = K^+K^-,\pi^+\pi^-$ and $N$ denoting the number of reconstructed decays, can be written as a sum of several (assumed small) contributions:
\[ A_{rec}^f = A_{FB} + A_{CP}^f + A_\pi . \] (2)
In addition to the intrinsic asymmetry $A_{CP}^f$, there is a contribution due to an asymmetry in the reconstruction efficiencies of oppositely charged $\pi_s$ ($A_\pi^f$). Since the final state $f$ is self-conjugate, its reconstruction efficiency does not affect $A_{rec}^f$. Furthermore, there is a forward-backward asymmetry ($A_{FB}$) in the production of $D^{*+}$ mesons in $\gamma - Z^0$ interference and higher order QED effects [8]. This term is an odd function of the cosine of the $D^{*+}$ production polar angle in the center-of-mass (CM) system ($\cos \theta^*$). Since our detector acceptance is not symmetric with respect to $\cos \theta^*$, the measurement is performed in bins of $\cos \theta^*$. This allows us to correct for acceptance and extract both $A_{FB}$ and $A_{CP}^f$ as described below.

1 Charge conjugated processes are implied throughout the paper, unless explicitly noted otherwise.
2 Symbols with an asterix in the paper denote quantities in the CM frame, while those without asterix denote quantities in the laboratory frame.

To reliably determine $A_\pi^f$ we adopt the method of Ref. [6] with some appropriate modifications. In addition to the $D^0 \to h^+h^-$ modes mentioned above, we also reconstruct two $D^0 \to K^-\pi^+$ samples: one consisting of $D$ mesons with tagged initial flavour, and one consisting of untagged candidates. The measured asymmetries for these modes can be written as
\[ A_{rec}^{tag} = A_{FB} + A_{CP}^{K\pi} + A_{\epsilon}^{K\pi} + A_\pi , \]
\[ A_{rec}^{untag} = A_{FB} + A_{CP}^{K\pi} + A_{\epsilon}^{K\pi} . \] (3)

A notable difference with [2] is that this final state is not self-conjugate and thus an additional term $A_{\epsilon}^{K\pi}$ appears as a consequence of a possible asymmetry in the reconstruction efficiency. We first use the two measurements in (3) to determine $A_\pi^f$; we then insert the result into (2) and use the fact that $A_{FB}$ is antisymmetric with respect to $\cos \theta^*$ and $A_{CP}^f$ is independent of this variable.

Reconstruction efficiencies and their asymmetries $A_\epsilon$, however, are functions of momenta of particles $i = \pi_s, K^\pm$ in the laboratory frame. For a $D^0$ meson with a given momentum $\vec{p}_{D^0}$, the efficiency of reconstructing the final state $K^-\pi^+$ is $\epsilon_{K\pi}(\vec{p}_{D^0}) = \int \epsilon_K(\vec{p}_K)\epsilon_\pi(\vec{p}_\pi)w_{\vec{p}_{D^0}}(\vec{p}_K,\vec{p}_\pi)d\vec{p}_Kd\vec{p}_\pi$, where $w_{\vec{p}_{D^0}}(\vec{p}_K,\vec{p}_\pi)$ denotes the 6-dimensional distribution of final state particles. For a given $\vec{p}_{D^0}$, this distribution is independent of whether the $D$ meson candidate is flavour-tagged or not. Using the same selection criteria for the $K$ and $\pi$ candidates in the tagged and untagged sample imposes equality of the selection efficiencies $\epsilon_{K(\pi)}(\vec{p}_{K(\pi)})$. Hence the asymmetry $A_{CP}^{K\pi}(\vec{p}_{D^0})$ is identical for tagged and untagged $D$ mesons of a given momentum $\vec{p}_{D^0}$, as implied by [3]. Since the distribution of $D^0$ mesons is uniform in the azimuthal angle the dimension of the problem can be reduced. It is sufficient to obtain $A_{CP}^{K\pi}$ as a function of the magnitude and polar angle of the laboratory momentum, $p_{D^0}$ and $\cos \theta_{D^0}$.

The slow pion asymmetry $A_\pi^f$ depends on its momentum $\vec{p}_s$, and is independent of the $D^0$ final state. Since the $\pi_s$ azimuthal angle distribution is also found to be uniform, $A_\pi^f$ is examined as a function of $(p_{\pi_s}, \cos \theta_{\pi_s})$.

3. Measurement

The measurement is based on 540 fb$^{-1}$ of data recorded by the Belle detector [9] at the KEKB asymmetric-energy $e^+e^-$ collider [10], running at the CM energy of the $Y(4S)$ resonance and 60 MeV
particle identification criteria \[12\]. Each of the two measuring coordinates is required to have at least two associated SVD hits in each of the two measuring coordinates. To select pion and kaon candidates, we impose standard particle identification criteria \[12\]. D⁰ daughter particles are refitted to a common vertex. The D⁰ production vertex is found by constraining the D⁰ (and π⁺ for the tagged decays) to originate from the e⁺e⁻ interaction region. Confidence levels exceeding 10−3 are required for both fits. The D∗⁺ (D⁰ for untagged decays) momentum must satisfy \( p^{*}_D > 2.5 \text{ GeV}/c^2 \) in order to reject D-mesons produced in B-meson decays and to suppress combinatorial background.

We accept candidates with a D⁰ invariant mass \( M \) in the range 1.81 GeV/c² < \( M < 1.91 \) GeV/c². For final states with a π⁺, we require that the energy released in the D∗⁺ decay, \( q = (M_{D^{*+}} - M - m_π) c^2 \), be less than 20 MeV. In this expression, \( M_{D^{*+}} \) is the invariant mass of the \( D^0 \pi^+_s \) combination and \( m_π \) is the charged pion mass. For the small fraction of events with multiple candidates (0.1% for the tagged samples, 2.9% for the untagged sample), we select only one candidate: that in which the sum of the production and decay vertex \( \chi^2 \)'s is smallest. We also require \[3\] \(| \cos \theta_{D^0} | < 0.9 \) to remove events in which large slow pion asymmetry corrections and consequently large systematic uncertainties are expected. The resulting invariant mass spectra are shown in Fig. 1.

We measure the signal yield by performing a mass-sideband subtraction, as this method is robust and reduces sensitivity to the signal shape. The possibility of a non-linear background shape is considered as a systematic uncertainty. The sizes of signal windows in \( M \) and \( q \) are chosen to minimize the expected statistical error on the \( A_{CP} \) measurement. Using the Monte Carlo (MC) simulation, which has been tuned to reproduce the signal shapes and the signal-to-background ratios of the real data, the optimal signal windows are found to be \(| \Delta M | < 17.5 (18.6, 16.8) \text{ MeV}/c^2 \) and \(| \Delta q | < 1.00 (1.85, 0.90) \text{ MeV} \) for the \( K\bar{K} \) (\( K\pi \pi \)) final states. The quantities \( \Delta M \) and \( \Delta q \) measure the difference of the corresponding observable and the nominal D⁰ mass and the nominal released energy of the D∗⁺ decay, respectively. Sidebands of the same size as signal window are chosen starting at \( \pm 20 \text{ MeV}/c^2 \) from the D⁰ nominal mass. Within the optimal signal window we find \( 6.3 \times 10^6 \) untagged \( K^- \pi^+ \) signal events with a purity of 80%; the number of tagged signal events is \( 120 \times 10^3 \) \( K^0 \bar{K}^- \), \( 1.3 \times 10^6 \) \( K^- \pi^+ \) and \( 51 \times 10^3 \) \( \pi^+ \pi^- \), with purities of 97%, 99% and 91%, respectively.

We determine first the asymmetry \( A_{\text{rec,tag}} \) of the untagged \( K\pi \) sample in 20 × 20 bins of the two-dimensional phase space \( (p_{D^0}, \cos \theta_{D^0}) \) by

\[
A_{\text{rec,tag}}^{\text{untag}} = \frac{N_{ij} - \overline{N}_{ij}}{N_{ij} + \overline{N}_{ij}},
\]

where \( N_{ij} \) and \( \overline{N}_{ij} \) are the numbers of reconstructed \( D^0 \) and \( D^0 \) decays, respectively, in bin \( i,j \). In order to avoid large statistical fluctuations near the phase space boundaries, we calculate the asymmetry only for those bins having \( N_{ij} + \overline{N}_{ij} > 1000 \). This asymmetry is used to correct the tagged \( K\pi \) events by weighting each \( D^0(\bar{D}^0) \) candidate falling into a valid bin with a weight.

![Fig. 1. Invariant mass spectra of selected events. For the tagged data samples (b,c,d) events with |Δq| < 1 MeV are selected. The cross-hatched area represents the signal region; the sideband positions are indicated by vertical lines.](image-url)
in a corrected asymmetry \( A_{\text{rec}}^f \) of (2), \( A_{\text{rec}}^{f,\text{corr}} \), which is free of the contribution due to the slow pion efficiency asymmetry. It is calculated as
\[
A_{\text{rec}}^{f,\text{corr}}(\cos \theta^*) = \frac{m_f(\cos \theta^*) - \overline{m}_f(\cos \theta^*)}{m_f(\cos \theta^*) + \overline{m}_f(\cos \theta^*)}, \tag{8}
\]
where \( m_f(\overline{m}_f) \) represent the sum of weights of the \( D^0(D^0) \) candidates in each bin of \( \cos \theta^* \).

Finally, taking into account their specific dependence on \( \cos \theta^* \), the asymmetries \( A_{CP}^f \) and \( A_{FB}^f \) are extracted by adding or subtracting bins at \( \pm \cos \theta^* \):
\[
A_{CP}^f = \frac{A_{\text{rec}}^{f,\text{corr}}(\cos \theta^*) + A_{\text{rec}}^{f,\text{corr}}(-\cos \theta^*)}{2},
\]
\[
A_{FB}^f = \frac{A_{\text{rec}}^{f,\text{corr}}(\cos \theta^*) - A_{\text{rec}}^{f,\text{corr}}(-\cos \theta^*)}{2}. \tag{9}
\]

The results are presented in Fig. 3. By fitting a constant to the \( A_{CP}^f \) data points we obtain results consistent with no \( CP \) violation:
\[
A_{CP}^{KK} = (0.43 \pm 0.30)\%,
A_{CP}^{\pi\pi} = (+0.43 \pm 0.52)\%. \tag{10}
\]

The errors are statistical only; however, the statistical uncertainties of the slow pion corrections are not included. The forward-backward asymmetry \( A_{FB}^f \) decreases with \( \cos \theta^* \) and has a value \( \approx -3\% \) at \( \cos \theta^* = 0.8 \); results from the two samples are consistent. At leading order, the asymmetry at this energy is expected to be \( A_{FB}^{0/0}(\cos \theta^*) = a_{CC} \cos \theta^* / (1 + \cos^2 \theta^*) \), with \( a_{CC} = -2.9\% \) [13]. A simultaneous fit to the two samples yields an acceptable goodness-of-fit (\( \chi^2/\text{dof} = 4.5/7 \)) and \( a_{CC} = (-4.9 \pm 0.8)\% \), where the error is statistical (see Fig. 3).

4. Systematics

The experimental procedure was checked using the generic continuum MC simulation; the resulting \( A_{CP}^f \) and \( A_{FB}^f \) were found to be in good agreement with the generated values. We also tested for possible bias in the result by re-weighting MC samples with several non-zero \( A_{CP}^f \) values; no significant bias was found.

We consider three sources of systematic uncertainty to be significant (Table 1). The first source is the mass-sideband subtraction procedure used for signal counting. Possible systematic uncertainties arise due to the difference in signal shapes of \( D^0 \) and \( D^0 \) candidates and due to the possible difference in the background between the signal window.
and sideband. The former source can introduce an additional asymmetry if the signal window is not sufficiently wide. We observe small but significant differences in the $q$ signal shape of the tagged samples. By studying the normalized (in order to assess only the effect of the shape difference) $q$ distributions of the tagged $D^0(\bar{D}^0) \to K\pi$ samples we estimate the systematic uncertainty of this source to be 0.02% (0.04%) for the $KK$ ($\pi\pi$) sample. To account for a possible difference in backgrounds we vary the position of the sideband. We find 0.01% ($KK$) and 0.03% ($\pi\pi$) variations in the result. Background due to a correctly reconstructed $D^0$ candidate combined with a random slow pion is not removed by the $M$ sideband subtraction. Its fraction (0.6%) is estimated from the tuned MC simulation. The possible asymmetry induced by this type of background is estimated from the $q$ sideband to be at most 0.03%.

The second source of systematic error is the slow pion efficiency correction. The statistical errors on $A^\pi_\ell(p_\pi, \cos \theta_\pi)$ contribute an uncertainty of 0.09%. The impact of binning of the slow pion asymmetry is studied by producing maps with three different choices of bin sizes ($10 \times 10$, $20 \times 20$, $50 \times 50$ for $A^\text{un}{}_{\text{tag}}\pi$, and $5 \times 5$, $10 \times 10$, $20 \times 20$ for $A^\text{rec}\pi$) and repeating the procedure for extracting $A_{CP}$. We find 0.03% ($KK$) and 0.02% ($\pi\pi$) variations in the result.

The minimum required number of events per bin is varied from 100 to 10000, and the resulting variation in $A_{CP}$ is 0.04% (0.03%) for the $KK$ ($\pi\pi$) sample.

The third source of systematic uncertainty is the $A_{CP}$ extraction procedure. By varying the binning in $|\cos \theta^a|$ we obtain a 0.03% variation in the result. We change the treatment of the running periods with 3- and 4-layer SVD configuration; we find an 0.01% (0.02%) change in the result for the $KK$ ($\pi\pi$) sample.

Finally, we add the individual contributions in quadrature to obtain the total systematic uncertainty. The result is 0.11% (0.12%) for the $KK$ ($\pi\pi$) sample. The dominant source is the statistical uncertainty on $A^\pi_\ell$, and thus the majority of the systematic error will decrease when a larger $K\pi$ data sample is available.

5. Conclusions

We measure time-integrated $CP$-violating asymmetries $A_{CP}$ in decays to $CP$ eigenstates $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ using 540 fb$^{-1}$ of data. The detector-induced asymmetries are corrected with a precision of 0.1% by using tagged and untagged $D^0 \to K^-\pi^+$ decays. We obtain:

\begin{align*}
A_{CP}^{KK} &= (-0.43 \pm 0.30 \pm 0.11)\%, \\
A_{CP}^{\pi\pi} &= (+0.43 \pm 0.52 \pm 0.12)\%, \\
A_{CP}^{KK} - A_{CP}^{\pi\pi} &= (-0.86 \pm 0.60 \pm 0.07)\%. \quad (11)
\end{align*}

The results show no evidence for $CP$ violation and agree with SM predictions. In [11], we also list the difference $A_{CP}^{KK} - A_{CP}^{\pi\pi}$, which is calculated by treating the systematic errors arising from the slow pion corrections and $A_{CP}$ extraction as fully correlated between the two modes. A significant difference between the measured asymmetries in the $KK$ and $\pi\pi$ modes would be a sign of direct CPV (Eq. [1]).

To determine the direct $CPV$ asymmetries $a^\ell_q$ of [11], the results in [11] can be compared to the result for the indirect $CPV$ asymmetry in Ref. [1]. While the selected data samples of $D^0 \to K^+K^-, \pi^+\pi^-$...
in the two measurements are almost identical, the methods of extracting the $CP$ violating asymmetries depend on different observables and hence the statistical uncertainties are uncorrelated. The same holds also for the systematic errors. The direct $CPV$ asymmetries following from the sum of $A_{CP}^f$ and $A_{Γ}$ are

$$a^KK_d = (-0.42 \pm 0.42 \pm 0.19)\%,$$

$$a^ππ_d = (+0.44 \pm 0.60 \pm 0.19)\%.$$  (12)

The measurement uncertainties are above the level of the expected asymmetry in the SM.

We also measure the forward-backward asymmetry in the production of $D_s^+$ that arises from the underlying asymmetry in the $e^+e^- \rightarrow c\bar{c}$ process. The asymmetry agrees with the form $A_{FB}(\cos \theta^*) = a^{c\bar{c}} \cos \theta^*/(1 + \cos^2 \theta^*)$ expected at leading order, but we find $a^{c\bar{c}} = (-4.9 \pm 0.8)\%$, larger than the leading-order value of $-2.9\%$. Radiative and other (hadronic) corrections are expected to cause the effective $a^{c\bar{c}}$ to deviate from its leading-order value.

Acknowledgments

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group and the NII for valuable computing and SINET3 network support. We acknowledge support from MEXT and JSPS (Japan); ARC and DEST (Australia); NSFC (China); DST (India); MOEHRD, KOSEF and KRF (Korea); KBN (Poland); MES and RFFAEE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE (USA).

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