Measurement of the $D^0$-$\overline{D^0}$ lifetime difference using $D^0 \rightarrow K\pi/\bar{K}K$ decays

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Abstract

We report a preliminary measurement of the $D^0$-$\bar{D}^0$ mixing parameter $y_{CP}$ and the CP-violating parameter $A_\Gamma$ using the decay $D^{*+} \rightarrow D^0 \pi^+$ followed by $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^+ K^-$. The results are obtained from a 158 fb$^{-1}$ data sample collected near the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric energy $e^+e^-$ collider.

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INTRODUCTION

The rate of $D^0$-$\bar{D}^0$ mixing, which has not yet been observed, would provide an important window on new physics. The contribution of box diagrams is very small due to GIM suppression, and the mixing rate is believed to be dominated by long-distance processes. These processes are themselves suppressed by $SU(3)$-flavor symmetry. The mixing rate is usually expressed in terms of the parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta \Gamma/(2\Gamma)$, where $\Delta m$ and $\Delta \Gamma$ are the mass- and width-differences of the physical states, and $\Gamma$ is the average decay width. Numerous predictions for $x$ and $y$ exist \cite{1}; a recent calculation gives $x \sim y \sim 10^{-3}$ \cite{2}.

Non-Standard-Model (SM) processes are expected to enhance $x$ relative to $y$, and measuring $x \gg y$ would be a strong indication of new physics \cite{2, 3}.

In this paper we report a measurement of the parameter $y_{CP}$, which is equal to $y$ in the limit where CP is conserved. If CP is violated, the widths of $D^0$ and $\bar{D}^0$ decays into the CP eigenstate $K^+K^−$ differ. These widths can be expressed as \cite{4}

\[
\hat{\Gamma}(D^0 \to K^+K^-) = \Gamma \left[ 1 + R_m(y \cos \phi - x \sin \phi) \right]
\]

\[
\hat{\Gamma}(\bar{D}^0 \to K^+K^-) = \Gamma \left[ 1 + R_m^{-1}(y \cos \phi + x \sin \phi) \right],
\]

where $R_m$ and $\phi$ are CP-violating parameters defined in \cite{4}. CP violation in mixing results in $R_m \neq 1$, and CP violation due to interference between mixed and unmixed decay amplitudes results in $\phi \neq 0$. We investigate whether CP violation is present by measuring the quantity

\[
A_{\Gamma} = \frac{\hat{\Gamma}(D^0 \to KK) - \hat{\Gamma}(\bar{D}^0 \to KK)}{\hat{\Gamma}(D^0 \to KK) + \hat{\Gamma}(\bar{D}^0 \to KK)} \approx \left( \frac{R_m - R_m^{-1}}{R_m + R_m^{-1}} \right) y \cos \phi - x \sin \phi.
\]

The SM predicts $A_{\Gamma} \lesssim 10^{-4}$ \cite{3}; a large value would indicate physics beyond the SM.

Our measurement of $y_{CP}$ is obtained by measuring the lifetime difference between $D^0 \to K^−\pi^+$ and $D^0 \to K^+K^−$ decays. (Throughout this paper, charge-conjugate modes are included unless noted otherwise.) Our measurement of $A_{\Gamma}$ is obtained by measuring the lifetime difference between $D^0 \to K^+K^−$ and $\bar{D}^0 \to K^+K^−$ decays. The analysis is based on 158 fb$^{-1}$ of data, and all results are preliminary. To identify the flavor of the $D^0$ and also reduce background, we require that all $D^0$’s originate from $D^{∗+} \to D^0 \pi^+$ decays.

EVENT SELECTION

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K^0_L$ mesons and to identify muons (KLM). The detector is described in detail elsewhere \cite{6}.

We select well-measured charged tracks that have impact parameters less than 1.0 cm in the radial direction and less than 2.0 cm along the beam direction (z) with respect to the
interaction point (IP). The $D^0$ daughter tracks are required to have at least two hits in each of the $\tau-\phi$ and $z$-measuring SVD layers. This requirement is not applied to the slow pion from $D^{*+} \rightarrow D^0\pi^+$ decays.

For charged particle identification, information from the CDC, TOF, and ACC subsystems is combined to form an overall hadron likelihood:

$$\mathcal{L}(h) = \mathcal{L}^{\text{ACC}}(h) \times \mathcal{L}^{\text{CDC}}(h) \times \mathcal{L}^{\text{TOF}}(h),$$

where $h$ stands for $\pi$ or $K$. Charged particles are identified as pions or kaons using the likelihood ratios:

$$\mathcal{P}(K) = \frac{\mathcal{L}(K)}{\mathcal{L}(K) + \mathcal{L}(\pi)}, \quad \mathcal{P}(\pi) = \frac{\mathcal{L}(\pi)}{\mathcal{L}(K) + \mathcal{L}(\pi)} = 1 - \mathcal{P}(K).$$

Kaon candidates are required to have $\mathcal{P}(K) > 0.6$. This requirement is 88% efficient and has a pion misidentification probability of 8%. Pion candidates are required to satisfy $\mathcal{P}(K) < 0.9$.

Both continuum and $\Upsilon(4S)$ data are used in this analysis. Each event is required to contain at least one $D^{*+}$ meson decaying to $D^0\pi^+$. To remove $D^{*+}$'s resulting from $B$ meson decays, the $D^{*+}$ is required to have a momentum in the $e^+e^-$ center-of-mass frame (CMS) greater than 2.5 GeV/$c$. $D^0$ meson candidates are reconstructed from $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow K^+K^-$ decays. All $D^0$ candidates must satisfy $|M(D^0)_{\text{fit}} - M(K^-\pi^+/K^+K^-)| < 2\sigma_{\text{fit}}$, where $M(D^0)_{\text{fit}}$ and $\sigma_{\text{fit}}$ are the mean and standard deviation of a Gaussian fit to the $D^0$ mass peak in data. These parameters are calculated independently for each $D^0$ decay mode in order to help keep the $K^-\pi^+$ and $K^+K^-$ vertex resolution functions unbiased by the $D^0$ mass requirement. From the fits, $\sigma_{\text{fit}}$ is found to be 5.1 MeV/$c^2$ for $D^0 \rightarrow K^-\pi^+$ and 4.5 MeV/$c^2$ for $D^0 \rightarrow K^+K^-$ (see Table II). The momentum of the slow $\pi^+$ from $D^{*+} \rightarrow D^0\pi^+$ decays is obtained by refitting using the beam position constraint, i.e., the track must project back to the IP region. The invariant mass of the $D^{*+}$ candidates after slow $\pi^+$ refitting is required to satisfy $|M(D^0\pi^+) - M(K^-\pi^+/K^+K^-) + M_{D^0}^{\text{PDG}} - M_{D^*}^{\text{PDG}}| < 1.0$ MeV/$c^2$.

**$D^0$ VERTEX FIT AND DECAY TIME RECONSTRUCTION**

The proper time between the production and decay of the $D^0$ candidates is determined by projecting the momentum $\vec{P}$ and the flight length $\ell$ onto the $xy$ plane transverse to the beam axis:

$$t_{D^0} = \frac{\ell_{xy} \cdot \vec{P}_{xy}}{P_{xy}^2} \times \left(\frac{m_{D^0}}{c}\right).$$

The momentum $\vec{P}$ is the vector sum of the $K$ and $\pi$ momenta, and $\ell$ is the displacement vector between the production and decay vertices. Information from the $z$ projections is not included due to the large uncertainty in the $z$ component of the IP.

To improve the spatial resolution, the vertex fit of $D^0 \rightarrow K^-\pi^+(K^+K^-)$ decays is done in three steps. First, the decay point is fit using only information from the $D^0$ daughter tracks. Then, the $D^0$ production vertex is found by fitting the reconstructed $D^0$ momentum vector with the IP region, whose profile is obtained from a separate study of the full data set. Finally, the $D^0$ decay vertex is corrected using information from the $D^0$ production vertex fit. No mass constraint is applied to the $D^0$ candidates during the vertex fit to avoid
mode-dependent bias that could result from a correlation between the invariant mass and a global momentum correction procedure. The error in the position of the $D^0$ decay vertex obtained from the fit is required to be less than 150 $\mu$m in each of the $x$ and $y$ directions. Fig. 1 illustrates the high efficiency of this cut. This procedure produces typical $D^0$ decay vertex resolutions of 45 $\mu$m in both $x$ and $y$.

![Graph 1](image1.png)

**FIG. 1:** Distributions of decay vertex errors $\sigma_x$ (left plot) and $\sigma_y$ (right plot) returned by the $D^0$ vertex fit after the IP position correction. The horizontal scale is in cm. Vertical lines indicate the position of the fit quality cut: $\sigma_{x,y} < 150$ $\mu$m.

![Graph 2](image2.png)

**FIG. 2:** Invariant mass spectra for $D^0 \rightarrow K^-\pi^+$ candidates (left plot) and $D^0 \rightarrow K^+K^-$ candidates (right plot). The horizontal scale is in GeV/$c^2$. The bin size is 0.5 MeV/$c^2$ and the solid curves show the fit results.

The invariant mass spectra of the selected $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow K^+K^-$ candidates are shown in Fig. 2. The distributions are fit with a sum of two Gaussians representing the signal and a first-order polynomial representing the background. The results of the fit are summarized in Table I.

**RESOLUTION FUNCTION STUDY**

The proper time distribution is represented by an exponential function with time constant $\tau_D$ convolved with the detector vertex resolution. The properties of the detector resolution
TABLE I: Invariant mass spectra fit results.

| Mode     | # events | main Gaussian $\sigma$ (MeV/$c^2$) | main Gaussian fraction (%) | Signal purity (%) |
|----------|----------|-------------------------------------|-----------------------------|-------------------|
| $K^-\pi^+$ | 448000   | 5.1                                 | 78.4                        | 99.1              |
| $K^+K^-$  | 36480    | 4.5                                 | 74.0                        | 97.6              |

FIG. 3: Proper time resolution functions for $D^0 \rightarrow K^-\pi^+$ (left plot) and $D^0 \rightarrow K^+K^-$ (right plot) obtained from MC simulation. The horizontal scale is in fs. The bin size of the data points is 40 fs and the solid curves show the results of the fit. (The fit is performed using a bin size of 10 fs.)

function are studied using Monte Carlo (MC) simulation of the signal decay modes. Approximately $7 \cdot 10^5$ $D^0 \rightarrow K^-\pi^+$ decays and $1 \cdot 10^5$ $D^0 \rightarrow K^+K^-$ decays were simulated, corresponding to two times the data sample and three times the data sample, respectively.

Fig. 3 shows the difference between the generated and reconstructed decay times of the $D^0$ mesons. The distributions are fit with a sum of five Gaussians constrained to a common central value. The results of the fit are summarized in Table II; the confidence level (CL) is 22.2%. Due to similar kinematics, the $K^+K^-$ decay mode is fit with the same resolution function as that used for $K^-\pi^+$. However, to account for small differences between $K^+K^-$ and $K^-\pi^+$, the width of each Gaussian component in the $K^+K^-$ fit is multiplied by a common scale factor $\alpha$. Fitting first the $K^-\pi^+$ distribution and then the $K^+K^-$ distribution, we obtain $\alpha = 1.043 \pm 0.004$. The CL for the $K^+K^-$ fit is 71.3%. The common central values of the Gaussians are found to be $X_0 = -1.51 \pm 0.22$ fs for $K^-\pi^+$ and $X_0 = -1.57 \pm 0.63$ fs for $K^+K^-$. In the lifetime difference fits for both MC and data, the relative fractions of the Gaussian components of the resolution function are fixed to the values determined in the above study. The central value of the $K^+K^-$ resolution function is fixed to that of the $K^-\pi^+$ resolution function, which is consistent with the results above. The possible bias due to this assumption is included in the systematic error.

MC STUDY OF LIFETIME DIFFERENCE FIT

The $D^0$ lifetime difference is obtained from a simultaneous, binned, maximum likelihood fit to the measured proper lifetime distributions of $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow K^-\pi^+$ decays.
TABLE II: $D^0 \to K^-\pi^+$ proper time resolution function fit results.

| Fit parameter | Fraction (%) | Value (fs) |
|---------------|-------------|------------|
| $\sigma_1$    | 26.1        | 95.1 ± 1.3 |
| $\sigma_2$    | 50.4        | 177.0 ± 2.2|
| $\sigma_3$    | 19.8        | 328.7 ± 7.4|
| $\sigma_4$    | 3.1         | 675.7 ± 24.9|
| $\sigma_5$    | 0.6         | 2199 ± 95  |

The consistency and quality of the fitting procedure is tested with MC events. The lifetime distributions of $D^0 \to K\pi/KK$ decays were fit with an exponential function convolved with a resolution function of the form described above. The CL of the fit is 61%. Fig. 4 and Table III show the results of the fit and a comparison to the parameters obtained from the resolution function study. The parameters are seen to agree to within the quoted errors. The resolution function scale factor $\alpha$ determined from the fit is 1.042 ± 0.007, also in agreement with the result from the resolution function study. The $D^0$ lifetime obtained is 411.9 ± 0.8 fs, which is consistent with the generated value of 412.6 fs. The lifetime difference obtained is 0.0 ± 1.7 fs, which is consistent with the generated value of exactly 0 fs.

FIG. 4: Simultaneous lifetime difference fit for $D^0 \to K^-\pi^+$ (left plot) and $D^0 \to K^+K^-$ (right plot) performed on MC-generated events. The horizontal scale is in fs. The bin size of the data points is 40 fs and the solid curves show the results of the fit. (The fit was done using a bin size of 10 fs.)

LIFETIME DIFFERENCE FIT IN DATA

To fit the lifetime difference in data, one must include small contributions from background processes. To include these, the proper time distribution of background is obtained from events in the $D^0$ mass sidebands. The sidebands chosen begin ±25 MeV/$c^2$ from $m_{D^0}$ and cover the same total range as the signal region ($4\sigma_{fit}$).

The background proper time distributions are parameterized as the sum of an exponential convolved with a Gaussian and a Breit-Wigner function. The resulting spectra are shown in Fig. 5. The systematic uncertainties due to the background fitting procedure are evaluated
TABLE III: Results of the simultaneous lifetime fit (MC) vs. standalone resolution function fit.

| Fit parameter | Resolution Function (fs) | Lifetime Fit (fs) |
|---------------|--------------------------|-------------------|
| $\sigma_1$    | 95.1 ± 1.3               | 94.4 ± 1.7        |
| $\sigma_2$    | 177.0 ± 2.2              | 179.0 ± 1.2       |
| $\sigma_3$    | 328.7 ± 7.4              | 328.2 ± 2.2       |
| $\sigma_4$    | 675.7 ± 24.9             | 664.4 ± 8.5       |
| $\sigma_5$    | 2199 ± 95                | 2225 ± 70         |
| $X_0$         | -1.51 ± 0.22             | -0.95 ± 0.54      |
| $\alpha$      | 1.043 ± 0.004            | 1.042 ± 0.007     |

FIG. 5: Background proper time distributions for $D^0 \rightarrow K^-\pi^+$ (left plot) and $D^0 \rightarrow K^+K^-$ (right plot). The horizontal scale is in fs. The bin size is 40 fs and the solid curves show the results of the fit.

by varying the fitting parameters. Since the background contribution is small compared to the signal, the effect of the background magnitude and shape uncertainty is small (approximately 0.1% in $y_{CP}$). It was checked with MC simulation that the small fraction of signal events remaining in the mass sidebands does not affect the $y_{CP}$ measurement above the quoted systematic error on background. The decay time function obtained for background is included (with normalization fixed) in the lifetime fit to the signal region.

TABLE IV: Results of the simultaneous lifetime fit (data) vs. standalone resolution function fit.

| Fit parameter | Resolution Function (fs) | Lifetime Fit (fs) |
|---------------|--------------------------|-------------------|
| $\sigma_1$    | 95.1 ± 1.3               | 112.3 ± 2.6       |
| $\sigma_2$    | 177.0 ± 2.2              | 198.2 ± 1.8       |
| $\sigma_3$    | 328.7 ± 7.4              | 378.0 ± 3.2       |
| $\sigma_4$    | 675.7 ± 24.9             | 864.2 ± 16.4      |
| $\sigma_5$    | 2199 ± 95                | 3197 ± 309        |
| $X_0$         | -1.51 ± 0.22             | 8.6 ± 0.8         |
| $\alpha$      | 1.043 ± 0.004            | 1.056 ± 0.012     |
Fig. 6 and Table IV show the results of the lifetime difference fit to the data. The CL of the fit is 94%. The fitted $D^0 \to K^-\pi^+$ lifetime is $412.6 \pm 1.1$ fs, and the fitted lifetime difference between $D^0 \to K^-\pi^+$ and $D^0 \to K^+K^-$ is $4.76 \pm 2.85$ fs. Together these values give $y_{CP} = 1.15 \pm 0.69\%$.

The parameters obtained by the fit for the resolution function (see Table IV) differ from those obtained from the MC study by more than the quoted errors. This is nominally due to vertex detector misalignment, IP mismeasurement, material unaccounted for in the MC simulation, and momentum dependence. These effects are included when evaluating the overall systematic error on $y_{CP}$ (Table V).

### TABLE V: Systematic errors of the $y_{CP}$ measurement.

| Source                              | Value (%) |
|-------------------------------------|-----------|
| $X_0(K\pi) = X_0(KK)$ assumption   | 0.15      |
| $\alpha$ difference on data and MC | 0.20      |
| Bin size                            | 0.10      |
| $D^0$ mass window                   | 0.20      |
| Background                          | 0.10      |
| Selection requirements              | 0.15      |
| **Total**                           | **0.38**  |

**CPV ASYMMETRY FIT**

The CP-violating parameter $A_\Gamma$ in $D^0 \to K^+K^-$ decays is obtained from fits to the data using the charge of the slow pion from $D^{*\pm} \to D^0\pi^+$ or $\overline{D^0}\pi^-$ to distinguish $D^0$ decays from $\overline{D^0}$ decays. The $D^0$ and $\overline{D^0}$ subsamples are fit separately using the resolution function parameters obtained from the full statistics fit. Background is treated as described in the previous section. The same procedure is performed for $D^0 \to K^-\pi^+$ decays and also for
MC events in order to estimate the systematic uncertainty of the fit. All results are listed in Table VI. The systematic uncertainty of the measurement is taken to be ±0.30%.

| $D^0$ decay mode | data/MC  | $\tau_{(q=+1)} - \tau_{(q=-1)}$ (fs) | $A_\Gamma$ (%) |
|------------------|---------|---------------------------------|---------------|
| $K\pi$           | MC      | 1.2 ± 1.1                       | 0.15 ± 0.13   |
| $KK$             | MC      | 2.6 ± 3.1                       | 0.31 ± 0.38   |
| $K\pi$           | data    | −0.76 ± 1.55                    | −0.09 ± 0.19  |
| $KK$             | data    | −1.67 ± 5.18                    | −0.20 ± 0.63  |

SUMMARY

In conclusion, we report a preliminary measurement of the $D^0\bar{D}^0$ mixing parameter $y_{CP}$ and the CP-violating parameter $A_\Gamma$ obtained by measuring lifetime differences in $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow K^+K^-$ decays. The flavor of the $D^0$ or $\bar{D}^0$ is identified via $D^{*+} \rightarrow D^0\pi^+$ decays. The results obtained are $y_{CP} = (1.15 \pm 0.69 \pm 0.38)\%$ and $A_\Gamma = (-0.20 \pm 0.63 \pm 0.30)\%$.

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