Evidence for D^0-$\bar{D}^0$ Mixing

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We observe evidence for D^0-$\bar{D}^0$ mixing by measuring the difference in the apparent lifetime when a D^0 meson decays to the CP eigenstates K^+K^- and $\pi^+\pi^-$ and when it decays to the final state $K^-\pi^+$. We find the relative difference of the lifetimes y_{CP} to be $[1.31 \pm 0.32(\mathrm{stat}) \pm 0.25(\mathrm{syst})]\%$, 3.2 standard deviations from zero. We also search for a CP asymmetry between D^0 and $\bar{D}^0$ decays; no evidence for CP violation is found. These results are based on 540 fb^{-1} of data recorded by the Belle detector at the KEKB e^+e^- collider.

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The phenomenon of mixing between a particle and its antiparticle has been observed in several systems of neutral mesons [1,2]: neutral kaons, B_d^0, and most recently B_s^0 mesons. In this Letter, we present evidence for D^0-$\bar{D}^0$ mixing [3].

The time evolution of a D^0 or $\bar{D}^0$ is governed by the lifetime $\tau = 1/\Gamma$ and the mixing parameters $x = (M_1 - M_2)/\Gamma$ and $y = (\Gamma_1 - \Gamma_2)/2\Gamma$. $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths of the mass eigenstates, respectively, and $\Gamma = (\Gamma_1 + \Gamma_2)/2$. For no mixing, $x = y = 0$. Within the standard model (SM), the rate of D mixing is expected to be small due to the near degeneracy of the s and d quark masses relative to the W mass and the small value of the b quark couplings. Predictions for x and y are dominated by nonperturbative processes that are difficult to calculate [4,5]. The largest predictions are $|x|, |y| \sim \mathcal{O}(10^{-2})$ [5]. Loop diagrams including new, as-yet-unobserved particles could significantly affect the experimental values [6]. CP-violating effects in D mixing would be a clear signal of new physics, as CP violation (CPV) is expected to be very small in the SM [7].

Both semileptonic and hadronic D decays have been used to constrain x and y [1]. Here we study the decays to CP eigenstates $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$; treating the decay-time distributions as exponential, we measure the quantity

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1, \qquad (1)$$

where $\tau(K^+K^-)$ and $\tau(K^-\pi^+)$ are the lifetimes of $D^0 \to K^+K^-$ (or $\pi^+\pi^-$) and $D^0 \to K^-\pi^+$ decays [8]. It can be shown that $y_{CP} = y\cos\phi - \frac{1}{2}A_M x \sin\phi$ [9], where A_M parametrizes CPV in mixing and ϕ is a weak phase. If CP is conserved, $A_M = \phi = 0$ and $y_{CP} = y$. To date, several measurements of y_{CP} have been reported [10]; the average value is $\sim$2 standard deviations (σ) above zero. Our measurement yields a nonzero value of y_{CP} with $>3\sigma$ significance. We also search for CPV by measuring the quantity

$$A_\Gamma = \frac{\tau(\bar{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\bar{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)}; \qquad (2)$$

this observable equals $A_\Gamma = \frac{1}{2}A_M y \cos\phi - x \sin\phi$ [9].

Our results are based on 540 fb^{-1} of data recorded by the Belle experiment [11] at the KEKB asymmetric-energy e^+e^- collider [12], running at the center-of-mass (c.m.) energy of the $\Upsilon(4S)$ resonance and 60 MeV below. To avoid bias, details of the analysis procedure were finalized without consulting quantities sensitive to y_{CP} and A_Γ.

The Belle detector is described in detail elsewhere [11]: It includes, in particular, a silicon vertex detector [13], a central drift chamber, an array of aerogel Cherenkov counters, and time-of-flight scintillation counters. We reconstruct $D^{*+} \to D^0\pi_s^+$ decays with a characteristic slow pion π_s, and $D^0 \to K^+K^-$, $K^-\pi^+$, and $\pi^+\pi^-$. The charge of the $\pi_s^\pm$ determines the flavor of the produced neutral D meson. Each track is required to have at least two associated vertex detector hits in each of the two measuring coordinates. To select pion and kaon candidates, we impose standard particle identification criteria [14]. D^0 daughter tracks are refitted to a common vertex, and the D^0 production vertex is found by constraining its momentum vector and the π_s track to originate from the e^+e^- interaction region; confidence levels exceeding 10^{-3} are required for both fits. A D^* momentum greater than 2.5 GeV/c (in the c.m.) is required to reject D mesons produced in B-meson decays and to suppress combinatorial background. The proper decay time of the D^0 candidate is then calculated from the projection of the vector joining the two vertices $\vec{L}$ onto the D^0 momentum vector $t = m_{D^0}\vec{L}\cdot\vec{p}/p^2$, where m_{D^0} is the nominal D^0 mass. The decay-time uncertainty σ_t is evaluated event by event from the covariance matrices of the production and decay vertices.

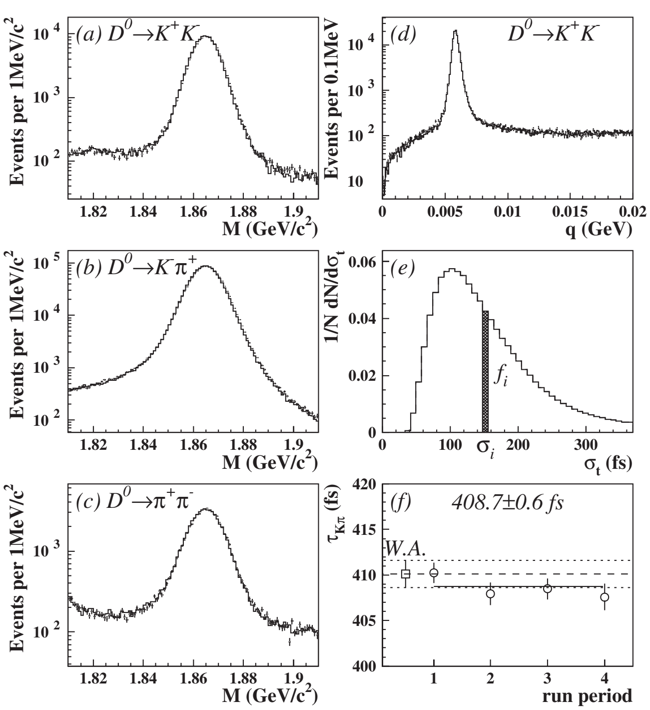

FIG. 1. M distribution of selected events (with $|\Delta q| < 0.80$ MeV and $\sigma_t < 370$ fs) for (a) K^+K^-, (b) $K^-\pi^+$, and (c) $\pi^+\pi^-$ final states. The histogram shows the tuned MC distribution. (d) q distribution (with $|\Delta M|/\sigma_M < 2.3$ and $\sigma_t < 370$ fs) for the K^+K^- final state. (e) Normalized distribution of errors σ_t on the decay time t for $D^0 \to K^-\pi^+$, showing the construction of the resolution function using the fraction f_i in the bin with $\sigma_t = \sigma_i$. (f) Fitted lifetime of D^0 mesons in the $K^-\pi^+$ final state in four running periods with slightly different conditions and the result of a fit to a constant. The world average value (W.A.) is also shown.

Candidate D^0 mesons are selected using two kinematic observables: the invariant mass of the D^0 decay products M and the energy released in the D^{*+} decay $q = (M_{D^*} - M - m_\pi)c^2$. M_{D^*} is the invariant mass of the $D^0\pi_s$ combination, and m_π is the π^+ mass.

According to Monte Carlo (MC) simulated distributions of t, M, and q, background events fall into four categories: (i) combinatorial, with zero apparent lifetime; (ii) true D^0 mesons combined with random slow pions (this has the same apparent lifetime as the signal); (iii) D^0 decays to three or more particles; and (iv) other charm hadron decays. The apparent lifetime of the latter two categories is 10%–30% larger than τ_{D^0}. Since we find differences in M and q distributions between MC simulation and data events, we perform fits to data distributions to obtain scaling factors for the individual background categories and signal widths and then tune the background fractions and signal shapes in the MC simulation event by event.

The sample of events for the lifetime measurements is selected using $|\Delta M|/\sigma_M$, where $\Delta M \equiv M - m_{D^0}$, $|\Delta q| \equiv q - (m_{D^{*+}} - m_{D^0} - m_\pi)c^2$, and σ_t. The invariant mass resolution σ_M varies from 5.5–6.8 MeV/c^2, depending on the decay channel. Selection criteria are chosen to minimize the expected statistical error on y_{CP}, using the tuned MC simulation: We require $|\Delta M|/\sigma_M < 2.3$, $|\Delta q| < 0.80$ MeV, and $\sigma_t < 370$ fs. The data distributions and agreement with the tuned MC distributions are shown in Figs. 1(a)–1(d). We find $111 \times 10^3 K^+K^-$, $1.22 \times 10^6 K^-\pi^+$, and $49 \times 10^3 \pi^+\pi^-$ signal events, with purities of 98%, 99%, and 92%, respectively.

The relative lifetime difference y_{CP} is determined from $D^0 \to K^+K^-$, $K^-\pi^+$, and $\pi^+\pi^-$ decay-time distributions by performing a simultaneous binned maximum likelihood fit to the three samples. Each distribution is assumed to be a sum of signal and background contributions, with the signal contribution being a convolution of an exponential and a detector resolution function:

$$dN/dt = \frac{N_{\rm sig}}{\tau}\int e^{-t'/\tau}R(t-t')dt' + B(t). \qquad (3)$$

The resolution function $R(t - t')$ is constructed from the normalized distribution of the decay-time uncertainties σ_t [see Fig. 1(e)]. The σ_t of a reconstructed event ideally represents an uncertainty with a Gaussian probability density: In this case, we take bin i in the σ_t distribution to correspond to a Gaussian resolution term of width σ_i, with a weight given by the fraction f_i of events in that bin. However, the distribution of "pulls," i.e., the normalized residuals $(t_{\rm rec} - t_{\rm gen})/\sigma_t$ (where $t_{\rm rec}$ and $t_{\rm gen}$ are reconstructured and generated MC decay times), is not well described by a Gaussian. We find that this distribution can be fitted with a sum of three Gaussians of different widths σ_k^{pull} and fractions w_k, constrained to the same mean. We therefore choose a parametrization

$$R(t-t') = \sum_{i=1}^{n} f_i \sum_{k=1}^{3} w_k G(t-t'; \sigma_{ik}, t_0), \tag{4}$$

with $\sigma_{ik} = s_k \sigma_k^{\text{pull}} \sigma_i$, where the s_k are three scale factors introduced to account for differences between the simulated and real σ_k^{pull}, and t_0 allows for a (common) offset of the Gaussian terms from zero.

The background $B(t)$ is parametrized assuming two lifetime components: an exponential and a δ function, each convolved with corresponding resolution functions as parametrized by Eq. (4). Separate $B(t)$ parameters for each final state are determined by fits to the t distributions of events in M sidebands. The tuned MC simulation is used to select the sideband region that best reproduces the timing distribution of background events in the signal region. We find good agreement between the tuned MC simulation and data sidebands, with a normalized χ^2 of 0.85, 0.83, and 0.83 for KK, $K\pi$, and $\pi\pi$, respectively.

The $R(t-t')$ and background parametrizations are validated using MC simulation and the large $D^0 \to K^-\pi^+$ sample selected from data. In the simulation, the ratio of scale factors s_k ($k = 1, 2, 3$) is consistent between decay modes, within small statistical uncertainties. The offset t_0 is also independent of the final state, but it changes slightly for simulated samples describing different running periods. Four such periods, coinciding with changes to the detector, have been identified based on small variations of the mean t value for $D^0 \to K^-\pi^+$ in the data. We perform a separate fit to each period and average the results to obtain the final value of y_{CP}. The free parameters of each simultaneous fit are τ_{D^0}, y_{CP}, the three s_k factors for the $K^-\pi^+$ mode, two terms that rescale the s_k values in the K^+K^- and $\pi^+\pi^-$ channels, the offset t_0, and normalization terms for the three decay modes. Fits to the $D^0 \to K^-\pi^+$ sample show good agreement with the parameters of $R(t-t')$ obtained from simulation.

For the second running period, we modify Eq. (4) to add mode-dependent offsets Δt between the first two Gaussian terms, making the resolution function asymmetric; these three parameters are also left free in the fit. We find that such a function is required to yield the $D^0 \to K^-\pi^+$ lifetime consistent with that in the other running periods. (This behavior has been reproduced with a MC model including a small relative misalignment of the vertex detector and the drift chamber. While small changes in the shape of the resolution function, as described below, influence the individual measured lifetimes, they have a very small effect on the value of y_{CP}.) The lifetime fit results are shown in Fig. 1(f): The mean $\tau_{D^0} = [408.7 \pm 0.6(\text{stat})]$ fs is in good agreement with the current world average (410.1 ± 1.5) fs [1].

Fits to the $D^0 \to K^+K^-$, $K^-\pi^+$, and $\pi^+\pi^-$ data for the four running periods are shown in Figs. 2(a)–2(c), by summing both the data points and the fit functions. Averaging the fit results, we find $y_{CP} = [1.31 \pm 0.32(\text{stat})]\%$, 4.1 standard deviations from zero. The agreement between the data and the fit functions is good: $\chi^2/n_{\text{dof}} = 1.08$ for $n_{\text{dof}} = 289$ degrees of freedom. Fitting $K^+K^-/K^-\pi^+$ and $\pi^+\pi^-/K^-\pi^+$ events separately, we obtain $y_{CP} = [1.25 \pm 0.39(\text{stat})]\%$ and $y_{CP} = [1.44 \pm 0.57(\text{stat})]\%$, respectively, in agreement with each other. The y_{CP} values for the four running periods are also consistent, with $\chi^2/n_{\text{dof}} = 1.53/3$.

To measure the CPV parameter A_Γ, we separately determine the apparent lifetimes of D^0 and $\bar{D}^0$ in decays to the CP eigenstates; the data are fit in four running periods as for y_{CP}. As the scale factors s_i are now determined from the K^+K^- and $\pi^+\pi^-$ samples rather than (mainly) from the large $K^-\pi^+$ sample, to ensure convergence of the fits we fix the scale factor s_3 for the widest Gaussian to the value obtained from the y_{CP} fit. We obtain $A_\Gamma = [0.01 \pm 0.30(\text{stat})]\%$, consistent with zero; the quality of the fit is good, with $\chi^2/n_{\text{dof}} = 1.00$ for $n_{\text{dof}} = 390$. Separate fits to the two CP eigenstates find compatible values: $A_\Gamma = [0.15 \pm 0.35(\text{stat})]\%$ for K^+K^- and $-[0.28 \pm 0.52(\text{stat})]\%$ for $\pi^+\pi^-$.

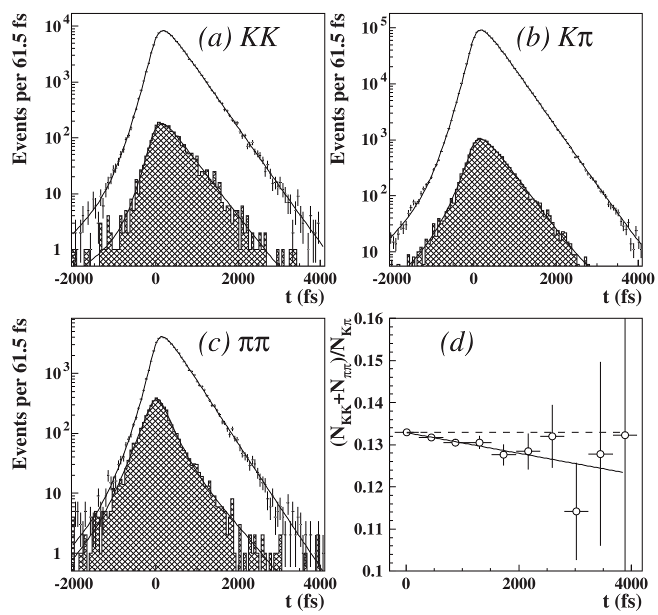

FIG. 2. Results of the simultaneous fit to decay-time distributions of (a) $D^0 \to K^+K^-$, (b) $D^0 \to K^-\pi^+$, and (c) $D^0 \to \pi^+\pi^-$ decays. The cross-hatched area represents background contributions, the shape of which was fitted using M sideband events. (d) Ratio of decay-time distributions between $D^0 \to K^+K^-$, $\pi^+\pi^-$ and $D^0 \to K^-\pi^+$ decays. The solid line is a fit to the data points.

The behavior of the fits has been tested in various ways using MC simulation. Fits to signal events simulated with $y_{CP} = 0$ reproduce this value (and the generated τ_{D^0}) even for a sample much larger than the data, with $(\chi^2/n_{\rm dof}, n_{\rm dof}) = (1.112\,85)$. Using samples of the same size as the data, with background included, we find a satisfactory fit, $(\chi^2/n_{\rm dof}, n_{\rm dof}) = (1.182\,89)$, with a statistical uncertainty in agreement with the error from the fit to the data. Results obtained on reweighted MC samples that cover a wide range of y_{CP} values agree with the input within $\pm 0.04\%$.

The effect of the resolution function on the measured y_{CP} has been tested by replacing the parametrization in Eq. (4) with a single Gaussian. This describes the data poorly and leads to a 3.9% shift in the fitted τ_{D^0} for a simulated $D^0 \to K^-\pi^+$ sample; however, the corresponding shift in y_{CP} is only 0.01%. This shows that the y_{CP} value returned by the fit is robust against imperfections in the parametrization of $R(t - t')$.

The estimated systematic uncertainties are summarized in Table I. We test for acceptance variations with decay time by fitting the generated decay times of reconstructed MC events. We find no deviation but conservatively assign the MC statistical error on y_{CP} ($\pm 0.12\%$) to this source. Another contribution is due to the choice of equal t_0 offsets in different decay modes: Relaxing this assumption leads to y_{CP} changes of $\pm 0.14\%$. Variation of the D^0 mass windows changes y_{CP} by less than $\pm 0.04\%$. The effect of differences between backgrounds in the signal and sideband regions is studied by repeating the fits using MC backgrounds from signal regions; small shifts in the data sidebands used to determine $B(t)$ are also made. The largest resulting change in y_{CP}, $\pm 0.09\%$, is quoted as the systematic error due to the background description. Potential correlations between apparent lifetimes and opening angle distributions (which differ between modes) have a small effect on y_{CP}: $\pm 0.02\%$.

The uncertainty due to the finite number of sideband events, $\pm 0.07\%$, is estimated by varying bin contents according to Poisson statistics and repeating the fits. Comparing alternative fits where all running periods use the symmetric resolution function (4), and the asymmetric function presently used for the second period, we assign an additional uncertainty of $\pm 0.01\%$. Varying selection criteria produces observable effects only in high statistics MC samples, in the σ_t and $|\Delta M|/\sigma_M$ cases. The resulting $\pm 0.11\%$ changes in y_{CP} are conservatively assigned as systematic errors. Finally, varying the binning of the decay-time distribution produces a small effect, $\pm 0.01\%$. Adding all terms in quadrature, we obtain a systematic uncertainty on y_{CP} of $\pm 0.25\%$. The same sources dominate for A_Γ but yield a smaller total systematic uncertainty, $\pm 0.15\%$.

TABLE I. Sources of the systematic uncertainty for y_{CP} and A_Γ.

Source	$\Delta y_{CP}[\%]$	$\Delta A_\Gamma[\%]$
Acceptance	0.12	0.07
Equal t_0	0.14	0.08
M window position	0.04	<0.01
Signal/sideband background differences	0.09	0.06
Opening angle distributions	0.02	...
Background distribution $B(t)$	0.07	0.07
(A)symmetric resolution function	0.01	0.01
Selection variation	0.11	0.05
Binning of t distribution	0.01	0.01
Total	0.25	0.15

In summary, we measure the relative difference of the apparent lifetime of D^0 mesons between decays to CP-even eigenstates and the $K^-\pi^+$ final state to be

$$y_{CP} = [1.31 \pm 0.32(\text{stat}) \pm 0.25(\text{syst})]\%. \quad (5)$$

Combining the errors in quadrature, we find a confidence level of only 6×10^{-4} for the $y_{CP} = 0$ hypothesis. We interpret this result as evidence for mixing in the D^0-$\bar{D}^0$ system, regardless of possible CPV. The effect is presented visually in Fig. 2(d), which shows the ratio of decay-time distributions for $D^0 \to K^+K^-$, $\pi^+\pi^-$ and $D^0 \to K^-\pi^+$ decays. We also search for CP violation by separately measuring decay times of D^0 and $\bar{D}^0$ mesons in CP-even final states. We find an asymmetry consistent with zero:

$$A_\Gamma = [0.01 \pm 0.30(\text{stat}) \pm 0.15(\text{syst})]\%. \quad (6)$$

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