Limits on D^0-$\overline{D}^0$ Mixing and CP Violation from the Ratio of Lifetimes for Decay to $K^-\pi^+$, K^-K^+, and $\pi^-\pi^+$

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We present a measurement of D^0-$\overline{D}^0$ mixing parameters using the ratios of lifetimes extracted from samples of D^0 mesons decaying to $K^-\pi^+$, K^-K^+, and $\pi^-\pi^+$. Using 91 fb^{-1} of data collected by the *BABAR* detector at the PEP-II asymmetric-energy B Factory, we obtain a value $Y = [0.8 \pm 0.4(\text{stat.})\,^{+0.5}_{-0.4}(\text{syst.})]\%$, which, in the limit of CP conservation, corresponds to the mixing parameter $y = \Delta\Gamma/2\Gamma$. Using the difference in lifetimes of D^0 and $\overline{D}^0$ mesons, we obtain the CP-violation parameter $\Delta Y = [-0.8 \pm 0.6(\text{stat.}) \pm 0.2(\text{syst.})]\%$.

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To date there is no experimental evidence for mixing in the D^0-$\overline{D}^0$ system [1,2]. This is consistent with standard model expectations [3,4], which correspond to a level of mixing beyond the reach of current experimental precision. Among the more striking consequences of D^0-$\overline{D}^0$ mixing are different decay-time distributions for D^0 mesons that decay into final states of specific CP [5]. Measurable CP violation in D^0-$\overline{D}^0$ mixing would be evidence of physics beyond the standard model [6].

The two D^0 mass eigenstates can be represented as

$$|D_1\rangle = p|D^0\rangle + q|\overline{D}^0\rangle, \qquad |D_2\rangle = p|D^0\rangle - q|\overline{D}^0\rangle, \quad (1)$$

where $|p|^2 + |q|^2 = 1$. It is traditional to quantify the size of D^0-$\overline{D}^0$ mixing in terms of the parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/2\Gamma$, where $\Delta m = m_1 - m_2$ ($\Delta\Gamma = \Gamma_1 - \Gamma_2$) is the difference in mass (width) of the states of Eq. (1) and $\Gamma = (\Gamma_1 + \Gamma_2)/2$ is the average width. If either x or y is nonzero, mixing will occur. The standard model expectation for the size of both is $\lesssim 10^{-3}$ [3,4].

The effects of CP violation in D^0-$\overline{D}^0$ mixing can be parametrized in terms of the quantities

$$r_m \equiv \left|\frac{q}{p}\right| \quad \text{and} \quad \varphi_f \equiv \arg\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right), \quad (2)$$

where $A_f \equiv \langle f|\mathcal{H}_D|D^0\rangle$ ($\overline{A}_f \equiv \langle f|\mathcal{H}_D|\overline{D}^0\rangle$) is the amplitude for D^0 ($\overline{D}^0$) decaying into a final-state f. A value of $r_m \neq 1$ would indicate CP violation in mixing. A nonzero value of φ_f would indicate CP violation in the interference of mixing and decay. Direct CP violation is expected to be small in the D^0-$\overline{D}^0$ system [7] and is not considered here.

D^0-$\overline{D}^0$ mixing will alter the decay-time distribution of D^0 and $\overline{D}^0$ mesons that decay into final states of specific CP. To a good approximation, these decay-time distributions can be treated as exponential with effective lifetimes [7]

$$\begin{aligned}\tau^+ &= \tau^0[1 + r_m(y\cos\varphi_f - x\sin\varphi_f)]^{-1},\\ \tau^- &= \tau^0[1 + r_m^{-1}(y\cos\varphi_f + x\sin\varphi_f)]^{-1},\end{aligned} \quad (3)$$

where τ^0 is the lifetime for the Cabibbo-favored decays $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^+\pi^-$ and τ^+ (τ^-) is the lifetime for the Cabibbo-suppressed decays of the D^0 ($\overline{D}^0$) into CP-even final states (such as K^-K^+ and $\pi^-\pi^+$). These effective lifetimes can be combined into the following quantities Y and ΔY:

$$Y = \frac{\tau^0}{\langle\tau\rangle} - 1, \qquad \Delta Y = \frac{\tau^0}{\langle\tau\rangle}A_\tau, \quad (4)$$

where $\langle\tau\rangle = (\tau^+ + \tau^-)/2$ and $A_\tau = (\tau^+ - \tau^-)/(\tau^+ + \tau^-)$. Both Y and ΔY are zero if there is no D^0-$\overline{D}^0$ mixing. Otherwise, in the limit of CP conservation in mixing, $Y = y\cos\varphi_f$ and $\Delta Y = x\sin\varphi_f$.

We present a measurement of Y and ΔY obtained from a 91 fb^{-1} data sample collected on or near the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage ring.

The *BABAR* detector, a general-purpose, solenoidal, magnetic spectrometer, is described in more detail elsewhere [8]. Charged particles were detected and their momenta measured by a combination of a drift chamber (DCH) and silicon vertex tracker (SVT), both operating within a 1.5-T solenoidal magnetic field. A ring-imaging Cherenkov detector (DIRC) was used for charged-particle identification.

Four independent samples of D^0 and $\overline{D}^0$ mesons were used in this analysis. The first three samples (referred to as *tagged*) correspond to D^0 mesons that decayed into $K^-\pi^+$, K^-K^+, and $\pi^-\pi^+$ [9] and include the decay $D^{*+} \to D^0\pi^+$ to suppress backgrounds and distinguish D^0 from $\overline{D}^0$. These three samples were used to measure Y and ΔY. The fourth sample (referred to as *untagged*) consisted of K^-K^+ decays that were not matched to a D^{*+} decay and was used to measure Y.

D^0 candidates were selected by searching for pairs of oppositely charged tracks of invariant mass near the expected value for a D^0 meson. Each track was required to contain a minimum number of measurement points in the SVT and DCH. The two D^0-candidate daughter tracks were fitted to a common vertex. The fit probability of this vertex fit was required to be larger than 1%. The interaction point (IP) was determined by calculating the point in space most consistent with the D^0 trajectory and the beam envelope (approximately 6 μm high and 120 μm wide).

Each D^0 daughter track was subjected to a likelihood-based particle identification algorithm. This algorithm relied on the measurement of the Cherenkov angle from the DIRC and on the energy loss (dE/dx) measured with the SVT and DCH. The $K^\pm$ identification efficiency was approximately 80% for tracks within the DIRC acceptance with a $\pi^\pm$ misidentification probability of about 2%. The average $\pi^\pm$ identification efficiency was approximately 90%.

To reduce combinatorial background that tended to accumulate at lower momenta, each D^0 candidate was required to have a momentum in the e^+e^- center-of-mass frame greater than 2.4 GeV$/c$. This requirement was also effective at removing D^0 mesons originating from the decays of B mesons.

The proper decay time and its measurement error σ_t for each D^0 candidate were calculated using the D^0 and IP vertex fits. The world average D^0 mass [1] m_D and the momentum of the D^0 were used to calculate the boost of the D^0 and to obtain the proper decay time. The distribution of σ_t, uncorrelated with true decay time, peaks at a value of 160 fs, and has a long upper tail. Poorly measured D^0 candidates with $\sigma_t > 500$ fs (16% of each sample) were discarded.

The decay $D^{*+} \to D^0\pi^+$ is characterized by a π^+ of low momentum (π_s). To increase acceptance, π_s

candidate tracks were not required to include DCH measurements. To improve momentum resolution, a vertex fit was used to constrain each π_s candidate track to pass through the IP. If the fit probability of this vertex fit was less than 1%, the D^{*+} candidate was discarded.

The distribution of the difference in the reconstructed D^{*+} and D^0 masses (δm) peaked near $145.4\,\mathrm{MeV}/c^2$. Backgrounds were suppressed by discarding D^{*+} candidates with a value of δm that deviated more than 1 (2.5) MeV/c^2 from the peak for those π_s tracks measured with (without) the DCH.

The D^0 mass distributions for the selected D^0 candidates are shown in Fig. 1. Ample sidebands were included to measure the characteristics of the background. The peaks appearing above or below the D^0 mass were due to candidates with misidentified kaons or pions. For presentation purposes only, we define those D^0 candidates with reconstructed masses within 15 MeV/c of m_D as belonging to a mass signal window. The sizes and estimated purities of the four D^0 samples within this window are listed in Table I.

An unbinned maximum-likelihood fit was used to extract the lifetime from each D^0 sample. The likelihood function consisted of two decay-time distribution functions, one for signal and one for background. The signal function was a convolution of an exponential and a resolution function that was the sum of three Gaussian distributions with zero mean. The widths of the first two Gaussians were proportional to σ_t whereas the width of the third, designed to describe mismeasurements, was not. The parameters in the fit associated with the signal for the $K^-\pi^+$ and untagged K^-K^+ samples were the lifetime and the widths and relative proportions of the three Gaussians. The parameters for the tagged K^-K^+ and $\pi^-\pi^+$ samples were the same except for the addition of A_τ.

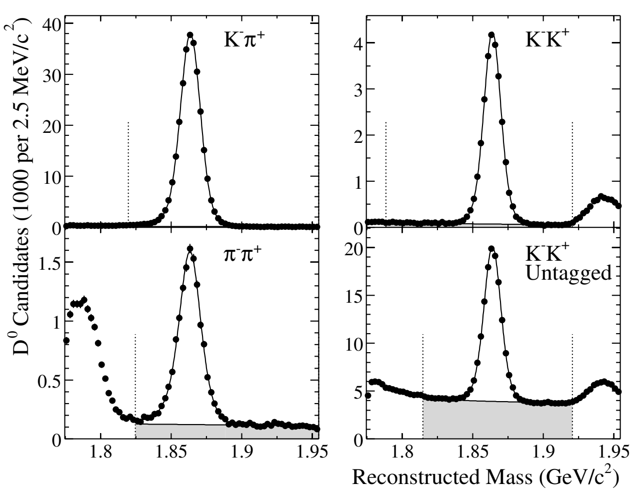

FIG. 1. The reconstructed D^0 mass distribution (points) superimposed on a projection of the mass fit (curve) for the four D^0 samples. The fit was performed within the restricted ranges of mass indicated by the vertical dotted lines. The portion of the sample assigned by the fit to the background is indicated by the shaded region.

As in the signal likelihood function, the background function was a convolution of a resolution function and a lifetime distribution. The background lifetime distribution was the sum of an exponential distribution and a delta function at zero, the latter corresponding to prompt sources of background that originated at the IP. The resolution function consisted of the sum of four Gaussian distributions, the first three of which were similar to those of the signal. The fourth was given a fixed width of 12 ps and accounted for a small number ($< 10^{-3}$) of outliers produced by long-lived particles or reconstruction errors. The additional fit parameters associated with the background included the fraction assigned to zero lifetime sources, the background lifetime, and the relative size of the fourth Gaussian.

To combine the signal and background likelihood functions, the reconstructed mass of each D^0 candidate was used to determine the probability that it was a signal D^0. This calculation was based on a separate fit of the reconstructed D^0 mass distribution (Fig. 1). This fit included a resolution function composed of a Gaussian with an asymmetric tail designed to account for final-state photon radiation. The mass fit for the tagged D^0 samples included a linear portion to describe the background. The slope of the background was constrained with D^0 candidates in the δm sideband ($151 < \delta m < 159\,\mathrm{MeV}/c^2$). For the untagged K^-K^+ sample, the size of the radiative tail was taken from the tagged K^-K^+ sample and the background was described by a quadratic function.

The results of the lifetime fits are shown in Fig. 2. Typical values for the fit parameters were a background lifetime similar to the D^0 lifetime and a third Gaussian width that was several times larger than the typical decay-time error.

To ensure that the analysis was performed in an objective manner, the values of the τ^0, $\langle\tau\rangle$, and A_τ fit parameters were hidden until the analysis method and systematic uncertainties were finalized.

Potential biases in Y and ΔY were investigated using Monte Carlo (MC) samples produced by a GEANT4-based [14] detector simulation and processed by the same reconstruction and analysis programs as the

TABLE I. The four D^0 samples, their use, and, as calculated inside a $\pm 15\,\mathrm{MeV}/c^2$ mass window, their size, and purity.

Sample	Measures	Size	Purity (%)
$K^-\pi^+$	τ^0	265 152	99.4
K^-K^+	$\langle\tau\rangle$, A_τ	26 084	97.0
$\pi^-\pi^+$	$\langle\tau\rangle$, A_τ	12 849	87.9
Untagged K^-K^+	$\langle\tau\rangle$	145 826	68.1

data. To estimate the behavior of both signal and background, the equivalent of 70 fb^{-1} of continuum and $\Upsilon(4S)$ MC data were studied. To augment these samples, separate MC samples were generated for specific decay modes of the D^0 meson. The values of Y and ΔY calculated from the MC samples (generated with $Y = 0$ and $\Delta Y = 0$) were consistent with zero within statistical errors. As can be seen in Fig. 2, the fraction of prompt background is larger in the $\pi^-\pi^+$ and untagged K^-K^+ samples than in the other two, a tendency that is accurately reproduced by the MC simulation.

Potential inaccuracies in the simulation of tracking were explored by varying within current understanding the assumptions used in the MC simulation, including the center-of-mass boost and energy, the strength of the magnetic field, and tracking resolution and efficiency. Small charge asymmetries (at the level of 2% to 4%) in the reconstruction efficiency of π_s tracks produced slightly different momentum and angular distributions for D^0 and $\overline{D}^0$ mesons. The influence of these effects on Y and ΔY was checked by applying the lifetime fits on the data after weighting events to remove these asymmetries.

The size and decay-time characteristics of backgrounds in the data were determined in the likelihood fits without using any MC input. The MC samples were used, however, to determine how well the fits account for the presence of background. As part of these tests, the size of specific types of backgrounds was varied within uncertainties in the MC sample by reweighting. In addition, MC parameters associated with the charm fragmentation function and final-state radiation in D^0 decay were varied. The resulting effect on the fitted lifetime is reported as one source of systematic uncertainty.

Detector misalignment was another potential source of bias. Residual distortions of the SVT, even as small as a few μm, can produce significant variations in the apparent D^0 lifetime. Several studies were used to measure and characterize such distortions and strategies were developed to correct them. One example was the study of proton tracks that were created by the interaction of off-energy beam particles and the beampipe. These tracks were used to measure the radius of the beampipe to a precision of a few microns, which limited the uncertainty in the radial scale of the SVT to 0.3%.

Another example was a study of $e^+e^- \to e^+e^- + 2(\pi^+\pi^-)$ events in which the four pions were known to originate from the IP. By selecting oppositely charged pairs of these pions with opening angles similar to two-body D^0 decays, it was possible to measure the apparent beam position as a function of D^0-candidate trajectory and calculate a correction to the D^0 lifetime. This type of correction nearly cancels in the lifetime ratio and introduces little systematic uncertainty in Y or ΔY.

Because Y and ΔY were measured from the ratio and asymmetry of lifetimes, systematic uncertainties from

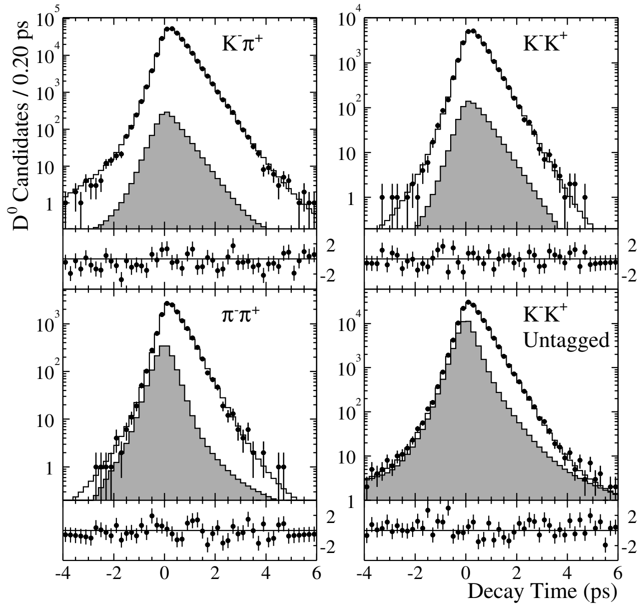

FIG. 2. The decay-time distribution for the four D^0 samples (points) within a $\pm 15\,\mathrm{MeV}/c^2$ mass signal window superimposed on a projection of the lifetime fit (histogram). The shaded histogram is the portion of the sample assigned by the fit to the background. The points presented below the histograms are the difference between data and fit divided by the statistical error with error bars of unit length.

alignment that have a strong influence on τ^0 did not make a large contribution to Y and ΔY. Efforts to reduce these systematic uncertainties are still under way; therefore, a value of τ^0 is not reported in this Letter. A subsample of the data was used to verify that τ^0 is consistent within uncertainties with the world average [1].

The systematic uncertainties in Y and ΔY are summarized in Table II. The separate results for each sample are listed in Table III with combined values that assume the same value of φ_f for the K^-K^+ and $\pi^-\pi^+$ decay modes. All values are consistent with no mixing. Because it is derived from an asymmetry, the systematic uncertainty in ΔY is considerably smaller than in Y.

In summary, we have obtained a value of $Y = [0.8 \pm 0.4(\mathrm{stat.})\,^{+0.5}_{-0.4}\,(\mathrm{syst.})]\%$ that is consistent with no mixing and is at least twice as precise as previous

TABLE II. Summary of systematic uncertainties.

	Change in Y (%)			ΔY (%)	
	Tagged		Untag	Tagged	
Category	K^-K^+	$\pi^-\pi^+$	K^-K^+	K^-K^+	$\pi^-\pi^+$
Tracking	± 0.1	± 0.3	± 0.2	± 0.1	± 0.1
Background	$^{+0.3}_{-0.5}$	± 0.5	± 0.3	± 0.2	± 0.2
Alignment	± 0.1	± 0.1	± 0.1	± 0.1	$^{+0.0}_{-0.1}$
MC Statistics	$^{+0.4}_{-0.1}$	$^{+1.0}_{-0.1}$	$^{+0.4}_{-0.1}$	<0.1	<0.1
Quadrature sum	± 0.5	$^{+1.2}_{-0.6}$	$^{+0.5}_{-0.4}$	± 0.2	± 0.2

TABLE III. Summary of Y and ΔY results. The first error is statistical; the second, systematic.

Sample	Y (%)	ΔY (%)
K^-K^+	$1.5 \pm 0.8 \pm 0.5$	$-1.3 \pm 0.8 \pm 0.2$
$\pi^-\pi^+$	$1.7 \pm 1.2^{+1.2}_{-0.6}$	$0.3 \pm 1.1 \pm 0.2$
Untagged K^-K^+	$0.2 \pm 0.5^{+0.5}_{-0.4}$	$\cdots$
Combined	$0.8 \pm 0.4^{+0.5}_{-0.4}$	$-0.8 \pm 0.6 \pm 0.2$

measurements of this type [10–13], all of which assumed CP conservation. We also obtain for the first time a measurement of $\Delta Y = [-0.8 \pm 0.6(\text{stat.}) \pm 0.2(\text{syst.})]\%$.

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