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

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

The two $D^0$ mass eigenstates can be represented as

$$
\begin{align*}
|D_1\rangle &= \rho |D^0\rangle + q |\bar{D}^0\rangle \\
|D_2\rangle &= \rho |D^0\rangle - q |\bar{D}^0\rangle ,
\end{align*}
$$

(1)

where $|p|^2 + |q|^2 = 1$. It is traditional to quantify the size of $D^0$-$\bar{D}^0$ 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 non-zero, mixing will occur. The Standard Model expectation for the size of both is $\lesssim 10^{-3}$ [3, 4].

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

$$
\tau_m \equiv \left| \frac{q}{p} \right| \quad \text{and} \quad \varphi_f \equiv \arg \left( \frac{q}{p} A_f \right) ,
$$

(2)

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

$D^0$-$\bar{D}^0$ mixing will alter the decay time distribution of $D^0$ and $\bar{D}^0$ 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 [3]

$$
\begin{align*}
\tau^+ &= \tau^0 \left[ 1 + \tau_m \left( y \cos \varphi_f - x \sin \varphi_f \right) \right]^{-1} \\
\tau^- &= \tau^0 \left[ 1 + \tau_m^{-1} \left( y \cos \varphi_f + x \sin \varphi_f \right) \right]^{-1} ,
\end{align*}
$$

(3)

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

$$
Y = \frac{\tau^0}{\langle \tau \rangle} - 1 \quad \Delta Y = \frac{\tau^0}{\langle \tau \rangle} A_r ,
$$

(4)

where $\langle \tau \rangle = (\tau^+ + \tau^-)/2$ and $A_r = (\tau^+ - \tau^-)/(\tau^+ + \tau^-)$. Both $Y$ and $\Delta Y$ are zero if there is no $D^0$-$\bar{D}^0$ 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 $\Delta Y$ obtained from a 91 fb$^{-1}$ data sample collected on or near the $Y(4S)$ 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 [3]. 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 $\bar{D}^0$ 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 $\pi^-\pi^+$ and include the decay $D^* \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^0$ to suppress backgrounds and distinguish $D^0$ from $\bar{D}^0$. These three samples were used to measure $Y$ and $\Delta Y$. 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 $\mu$m high and 120 $\mu$m 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 $\sigma_t$ for each $D^0$ candidate were calculated using the $D^0$ and IP vertex fits. The world average $D^0$ mass $\bar{m}_{D}$ 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 $\sigma_t$, 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 $D^* \rightarrow D^0\pi^+$ is characterized by a $\pi^+$ of low momentum ($\pi_\pi$). To increase acceptance, $\pi_\pi$ candi-
date tracks were not required to include DCH measurements. To improve momentum resolution, a vertex fit was used to constrain each \(\pi_s\) 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 (\(\delta m\)) peaked near 145.4 MeV/c\(^2\). Backgrounds were suppressed by discarding \(D^{*+}\) candidates with a value of \(\delta m\) that deviated more than 1 (2.5) MeV/c\(^2\) from the peak for those \(\pi_s\) 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\(^2\) 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 \(\sigma_t\), 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 \(A_T\).

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 \(\delta m\) sideband (151 < \(\delta m\) < 159 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 \(\tau^0\), \(\langle \tau \rangle\), and \(A_T\) fit parameters were hidden until the analysis method and systematic uncertainties were finalized.

Potential biases in \(Y\) and \(\Delta Y\) were investigated using Monte Carlo (MC) samples produced by a GEANT4-based detector simulation and processed by the same reconstruction and analysis programs as the data. To estimate the behavior of both signal and background, the
Potential inaccuracies in the simulation of tracking and alignment that have a strong influence on \( \Delta Y \) did not make a large contribution to \( Y \) and \( \Delta Y \). Efforts to reduce these uncertainties are still underway; therefore, a value of \( \tau^0 \) is not reported in this letter. A subsample of the data was used to verify that \( \tau^0 \) is consistent within uncertainties with the world average \( [1] \).

The systematic uncertainties in \( Y \) and \( \Delta Y \) are summarized in Table III. The separate results for each sample are listed in Table III with combined values that assume the same value of \( \varphi_f \) 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 \( \Delta Y \) is considerably smaller than in \( Y \).

In summary, we have obtained a value of \( Y = (0.8 \pm 0.4 \text{ (stat.)} \pm 0.5 \text{ (syst.)}) \% \) that is consistent with no mixing and is at least twice as precise as previous measurements.
TABLE III: Summary of $Y$ and $\Delta Y$ results. The first error is statistical; the second, systematic.

| Sample          | $Y$ (%) | $\Delta Y$ (%) |
|-----------------|---------|----------------|
| $K^-K^+$        | $1.5 \pm 0.8 \pm 0.5$ | $-1.3 \pm 0.8 \pm 0.2$ |
| $\pi^-\pi^+$   | $1.7 \pm 1.2 \pm 1.6$ | $0.3 \pm 1.1 \pm 0.2$ |
| Untagged $K^-K^+$ | $0.2 \pm 0.5 \pm 0.4$ | $--$ |
| Combined        | $0.8 \pm 0.4 \pm 0.5$ | $-0.8 \pm 0.6 \pm 0.2$ |

of this type [10, 11, 12, 13], all of which assumed $CP$ conservation. We also obtain for the first time a measurement of $\Delta Y = (-0.8 \pm 0.6 \text{(stat.)} \pm 0.2 \text{(syst.)})\%$.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from the A. P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

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[14] Unless otherwise noted, statements involving $D^0$ mesons and their decay modes are intended to apply in addition to their charged conjugates.