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

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We present evidence for $D^0$-$\bar{D}^0$ mixing in $D^0 \to K^+\pi^-$ decays from 384 fb$^{-1}$ of $e^+e^-$ colliding-beam data recorded near $\sqrt{s} = 10.6$ GeV with the B A B A R detector at the PEP-II storage rings at SLAC. We find the mixing parameters $\rho' = -0.22 \pm 0.30$ (stat.) $\pm 0.21$ (syst.) $\times 10^{-3}$ and $\gamma' = [9.7 \pm 4.4$ (stat.) $\pm 3.1$ (syst.)$] \times 10^{-3}$, and a correlation between them of $-0.94$. This result is inconsistent with the no-mixing hypothesis with a significance of 3.9 standard deviations. We
We present evidence for charm-meson ($D^0$-$\bar{D}^0$) mixing. This work complements results in the neutral $K$ [1, 2], $B$ [3, 4], and $B_s$ [5, 6] systems. Although precise predictions are difficult, $D^0$-$\bar{D}^0$ mixing in the Standard Model (SM) is expected at the 1% level or less [7–12]. Our result is consistent with this expectation and previous experimental limits [13–18]. By observing the wrong-sign decay $D^0 \rightarrow K^+\pi^-$ [19], we determine $R_D$, the ratio of doubly Cabibbo-suppressed to Cabibbo-favored decay rates, and the mixing parameters $x'^2$ and $y'$. The SM predicts effects well below the sensitivity of this experiment. The latter can be produced via the doubly Cabibbo-suppressed (DCS) decay $D^0 \rightarrow K^+\pi^-$ or via mixing followed by a CF decay $D^0 \rightarrow \bar{D}^0 \rightarrow K^+\pi^-$. The DCS decay has a small rate $R_D$ of order $\tan^4 \theta_C \approx 0.3\%$ relative to CF decay. We distinguish $D^0$ and $\bar{D}^0$ by their production in the decay $D^{*+} \rightarrow \pi^+D^0$ where the $\pi^+_c$ is referred to as the “slow pion”. In RS decays the $\pi^+_c$ and $\pi^-_c$ are consistent with this expectation and previous experiments. The SM predicts effects well below the sensitivity of this experiment. For each $D^0$, Cabibbo-favored (CF) decay $D^0 \rightarrow K^+\pi^-$ and the wrong-sign (WS) decay $D^0 \rightarrow K^+\pi^-$. The latter can be produced via the doubly Cabibbo-suppressed (DCS) decay $D^0 \rightarrow K^+\pi^-$ or via mixing followed by a CF decay $D^0 \rightarrow \bar{D}^0 \rightarrow K^+\pi^-$. The DCS decay has a small rate $R_D$ of order $\tan^4 \theta_C \approx 0.3\%$ relative to CF decay. We distinguish $D^0$ and $\bar{D}^0$ by their production in the decay $D^{*+} \rightarrow \pi^+D^0$ where the $\pi^+_c$ is referred to as the “slow pion”. In RS decays the $\pi^+_c$ and kaon have opposite charges, while in WS decays the charges are the same. The time dependence of the WS decay rate is used to separate the contributions of DCS decays from $D^0$-$\bar{D}^0$ mixing. The $D^0$ and $\bar{D}^0$ mesons are produced as flavor eigenstates, but evolve and decay as mixtures of the eigenstates $D_1$ and $D_2$ of the Hamiltonian, with masses and widths $M_1$, $\Gamma_1$ and $M_2$, $\Gamma_2$, respectively. Mixing is characterized by the mass and lifetime differences $\Delta M = M_1 - M_2$ and $\Delta \Gamma = \Gamma_1 - \Gamma_2$. Defining the parameters $x = \Delta M / \Gamma$ and $y = \Delta \Gamma / 2\Gamma$, where $\Gamma = (\Gamma_1 + \Gamma_2)/2$, we approximate the time dependence of the WS decay of a meson produced as a $D^0$ at time $t = 0$ in the limit of small mixing ($|x|, |y| \ll 1$) and CP conservation as

$$\frac{T_{WS}(t)}{e^{-\Gamma t}} \propto R_D + \sqrt{R_D y'} \left( \Gamma t + \frac{x'^2 + y'^2}{4} \right)^2,$$

where $x' = x \cos \delta_{K\pi} + y \sin \delta_{K\pi}$, $y' = -x \sin \delta_{K\pi} + y \cos \delta_{K\pi}$, and $\delta_{K\pi}$ is the strong phase between the DCS and CF amplitudes. We study both CP-conserving and CP-violating cases. For the CP-conserving case, we fit for the parameters $R_D$, $x'^2$, and $y'$. To search for CP violation, we apply Eq. (1) to $D^0$ and $\bar{D}^0$ samples separately, fitting for the parameters \{$R_D^\pm$, $x'^2\pm$, $y'^\pm$\} for $D^0$ (+) decays and $\bar{D}^0$ (-) decays.

We use $384 \text{ fb}^{-1}$ of $e^+e^-$ colliding-beam data recorded near $\sqrt{s} = 10.6 \text{ GeV}$ with the BABAR detector [20] at the PEP-II asymmetric-energy storage rings. We select $D^0$ candidates by pairing oppositely-charged tracks with a $K^+\pi^\pm$ invariant mass $m_{K\pi}$ between 1.81 and 1.92 GeV/c$^2$, requiring each track to have at least 12 coordinates in the drift chamber (DCH). Each pair is characterized by $K^+\pi^\pm$ using a likelihood-based particle identification algorithm. The identification efficiency for kaons (pions) is about 85% (95%); the misidentification rate of kaons (pions) as pions (kaons) is about 2% (6%).

To obtain the proper decay time $t$ and its error $\delta t$ for each $D^0$ candidate, we refit the $K^+$ and $\pi^\pm$ tracks, constraining them to originate from a common vertex. We also require the $D^0$ and $\pi^+_c$ to originate from a common vertex, constrained by the position and size of the $e^+e^-$ interaction region. We require the $\pi^+_c$ to have a momentum in the laboratory frame greater than 0.1 GeV/c and in the $e^+e^-$ center-of-mass (CM) frame below 0.45 GeV/c. We require the $\chi^2$ probability of the vertex-constrained combined fit $P(\chi^2)$ to be at least 0.1%, and the $m_{D^*+} - m_{K\pi}$ mass difference $\Delta m$ to satisfy $0.14 < \Delta m < 0.16 \text{ GeV/c}^2$.

To remove $D^0$ candidates from $B$-meson decays and to reduce combinatorial backgrounds, we require each $D^0$ to have a momentum in the CM frame greater than $2.5 \text{ GeV/c}$, and $-2 < t < 4 \text{ ps}$ and $\delta t < 0.5 \text{ ps}$ (the most probable value of $\delta t$ for signal events is 0.16 ps). For $D^{*+}$ candidates sharing one or more tracks with other $D^{*+}$ candidates, we retain only the candidate with the highest $P(\chi^2)$. After applying all criteria, we keep approximately 1,229,000 RS and 64,000 WS $D^0$ and $\bar{D}^0$ candidates. To avoid potential bias, we finalized our data selection criteria and the procedures for fitting and extracting the statistical limits without examining the mixing results.

The mixing parameters are determined in an unbinned, extended maximum-likelihood fit to the RS and WS data samples over the four observables $m_{K\pi}$, $\Delta m$, $t$, and $\delta t$. The fit is performed in several stages. First, RS and WS signal and background shape parameters are determined from a fit to $m_{K\pi}$ and $\Delta m$, and are not varied in subsequent fits. Next, the $D^0$ proper-time resolution function and lifetime are determined in a fit to the RS data using $m_{K\pi}$ and $\Delta m$ to separate the signal and background components. We fit to the WS data sample using three different models. The first model assumes both CP conservation and the absence of mixing, and only measures $R_D$. The second model allows for mixing, but assumes no CP violation, and the third model allows for both mixing and CP violation.
The RS and WS \(\{m_{K\pi}, \Delta m\}\) distributions are described by four components: signal, random \(\pi^+_s\), misreconstructed \(D^0\) and combinatorial background. Signal has a characteristic peak in both \(m_{K\pi}\) and \(\Delta m\). The random \(\pi^+_s\) component models reconstructed \(D^0\) decays combined with a random slow pion and has the same shape in \(m_{K\pi}\) as signal events, but does not peak in \(\Delta m\). Misreconstructed \(D^0\) events have one or more of the \(D^0\) decay products either not reconstructed or reconstructed with the wrong particle hypothesis. They peak in \(\Delta m\), but not in \(m_{K\pi}\). For RS events, most of these are semileptonic decays \(D^0 \rightarrow K^-\ell^+\nu\) with the charged lepton misidentified as a pion. For WS events, the main contributor is RS \(D^0 \rightarrow K^-\pi^+\) decays where the \(K^-\) and the \(\pi^+\) are misidentified as \(\pi^-\) and \(K^+\), respectively. Combinatorial background events are those not described by the above components; they do not exhibit any peaking structure in \(m_{K\pi}\) or \(\Delta m\).

The functional forms of the probability density functions (PDFs) for the signal and background components are chosen based on studies of Monte Carlo (MC) samples. However, all parameters are determined from two-dimensional likelihood fits to data over the full \(1.81 < m_{K\pi} < 1.92\) GeV/c\(^2\) and \(0.14 < \Delta m < 0.16\) GeV/c\(^2\) region.

We fit the RS and WS data samples simultaneously with shape parameters describing the signal and random \(\pi^+_s\) components shared between the two data samples. We find \(1,141, 500 \pm 1, 200\) RS signal events and \(4,030 \pm 90\) WS signal events. The dominant background component is the random \(\pi^+_s\) background. Projections of the WS data and fit are shown in Fig. 1.

![Figure 1](image)

**FIG. 1:** a) \(m_{K\pi}\) for wrong-sign (WS) candidates with \(0.1445 < \Delta m < 0.1465\) GeV/c\(^2\) and b) \(\Delta m\) for WS candidates with \(1.843 < m_{K\pi} < 1.883\) GeV/c\(^2\). The fitted PDFs are overlaid. The shaded regions represent the different background components.

The measured proper-time distribution for the RS signal is described by an exponential function convolved with a resolution function whose parameters are determined by the fit to the data. The resolution function is the sum of three Gaussians with widths proportional to the estimated event-by-event proper-time uncertainty \(\delta t\). The random \(\pi^+_s\) background is described by the same proper-time distribution as signal events, since the slow pion has little weight in the vertex fit. The proper-time distribution of the combinatorial background is described by a sum of two Gaussians, one of which has a power-law tail to account for a small long-lived component. The combinatorial background and real \(D^0\) decays have different \(\delta t\) distributions, as determined from data using a background-subtraction technique [21] based on the fit to \(m_{K\pi}\) and \(\Delta m\).

The fit to the RS proper-time distribution is performed over all events in the full \(m_{K\pi}\) and \(\Delta m\) region. The PDFs for signal and background in \(m_{K\pi}\) and \(\Delta m\) are used in the proper-time fit with all parameters fixed to their previously determined values. The fitted \(D^0\) lifetime is found to be consistent with the world-average lifetime [22].

The measured proper-time distribution for the WS signal is modeled by Eq. (1) convolved with the resolution function determined in the RS proper-time fit. The random \(\pi^+_s\) and misreconstructed \(D^0\) backgrounds are described by the RS signal proper-time distribution since they are real \(D^0\) decays. The proper-time distribution for WS data is shown in Fig. 2. The fit results with and without mixing are shown as the overlaid curves.

![Figure 2](image)

**FIG. 2:** a) The proper-time distribution of combined \(D^0\) and \(D^0\) WS candidates in the signal region \(1.843 < m_{K\pi} < 1.883\) GeV/c\(^2\) and \(0.1445 < \Delta m < 0.1465\) GeV/c\(^2\). The result of the fit allowing (not allowing) mixing but not CP violation is overlaid as a solid (dashed) curve. Background components are shown as shaded regions. b) The points represent the difference between the data and the no-mixing fit. The solid curve shows the difference between fits with and without mixing.

The fit with mixing provides a substantially better description of the data than the fit with no mixing. The significance of the mixing signal is evaluated based on the change in negative log likelihood with respect to the minimum. Figure 3 shows confidence-level (CL) contours
The central value (point) and confidence-level (CL) contours for $1 - \text{CL} = 0.317$ ($1\sigma$), $4.55 \times 10^{-2}$ ($2\sigma$), $2.70 \times 10^{-3}$ ($3\sigma$), $6.33 \times 10^{-5}$ ($4\sigma$) and $5.73 \times 10^{-7}$ ($5\sigma$), calculated from the change in the value of $-2\ln \mathcal{L}$ compared with its value at the minimum. Systematic uncertainties are included. The no-mixing point is shown as a plus sign (+).

Allowing for the possibility of CP violation, we calculate the values of $R_D = \sqrt{R_D^+ R_D^-}$ and $A_D = (R_D^+ - R_D^-)/(R_D^+ + R_D^-)$ listed in Table I, from the fitted $R_D^\pm$ values. The best fit in each case is more than three standard deviations away from the no-mixing hypothesis. All cross checks indicate that the high level of agreement between the separate $D^0$ and $\bar{D}^0$ fits is a coincidence.

As a cross-check of the mixing signal, we perform independent $\{m_{K\pi}, \Delta m\}$ fits with no shared parameters for intervals in proper time selected to have approximately equal numbers of RS candidates. The fitted WS branching fractions are shown in Fig. 4 and are seen to increase with time. The slope is consistent with the measured mixing parameters and inconsistent with the no-mixing hypothesis.

We have validated the fitting procedure on simulated data samples using both MC samples with the full detector simulation and large parameterized MC samples. In all cases we have found the fit to be unbiased. As a further cross-check, we have performed a fit to the RS data proper-time distribution allowing for mixing in the signal component; the fitted values of the mixing parameters are consistent with no mixing. The correlations among parameters determined at different stages of the fit are low. In addition we have found the staged fitting approach to give the same solution and confidence regions as a simultaneous fit in which all parameters are allowed to vary.

In evaluating systematic uncertainties in $R_D$ and the mixing parameters we have considered variations in the fit model and in the selection criteria. We have also considered alternative forms of the $m_{K\pi}, \Delta m$, proper time, and $\delta t$ PDFs. We varied the $t$ and $\delta t$ requirements. In addition, we considered variations that keep or reject all $D^{\pm}$ candidates sharing tracks with other candidates.

For each source of systematic error, we compute the significance $s_i^2 = 2 \left[ \ln \mathcal{L}(x_i^2, y_i') - \ln \mathcal{L}(x_i^2, y_i') \right] / 2.3$, where $(x_i^2, y_i')$ are the parameters obtained from the standard fit, $(x_i^2, y_i')$ the parameters from the fit including the $i^{th}$ systematic variation, and $\mathcal{L}$ the likelihood of the standard fit. The factor 2.3 is the 68% confidence confidence

![Figure 3](image)

FIG. 3: The central value (point) and confidence-level (CL) contours for $1 - \text{CL} = 0.317$ ($1\sigma$), $4.55 \times 10^{-2}$ ($2\sigma$), $2.70 \times 10^{-3}$ ($3\sigma$), $6.33 \times 10^{-5}$ ($4\sigma$) and $5.73 \times 10^{-7}$ ($5\sigma$), calculated from the change in the value of $-2\ln \mathcal{L}$ compared with its value at the minimum. Systematic uncertainties are included. The no-mixing point is shown as a plus sign (+).

![Figure 4](image)

FIG. 4: The WS branching fractions from independent $\{m_{K\pi}, \Delta m\}$ fits to slices in measured proper time (points). The dashed line shows the expected wrong-sign rate as determined from the mixing fit shown in Fig. 2. The $\chi^2$ with respect to expectation from the mixing fit is 1.5; for the no-mixing hypothesis (a constant WS rate), the $\chi^2$ is 24.0.

| Fit type | Parameter | Fit Results ($10^{-3}$) |
|----------|-----------|-------------------------|
| No CP viol. or mixing | $R_D$ | $3.03 \pm 0.16 \pm 0.10$ |
| No CP violation | $x^2$ | $-0.22 \pm 0.30 \pm 0.21$ |
| CP | $y'$ | $9.7 \pm 4.4 \pm 3.1$ |
| CP | $A_D$ | $-21 \pm 52 \pm 15$ |
| CP violation allowed | $x'^{+}$ | $-0.24 \pm 0.43 \pm 0.30$ |
| CP | $y'^+$ | $9.8 \pm 6.4 \pm 4.5$ |
| CP violation allowed | $x'^{-}$ | $-0.20 \pm 0.41 \pm 0.29$ |
| CP | $y'^-$ | $9.6 \pm 6.1 \pm 4.3$ |

TABLE I: Results from the different fits. The first uncertainty listed is statistical and the second systematic.
level for 2 degrees of freedom. To estimate the significance of our results in \((x'^2, y')\), we reduce \(-2\Delta \ln \mathcal{L}\) by a factor of \(1 + \sum s_i^2 = 1.3\) to account for systematic errors. The largest contribution to this factor, 0.06, is due to uncertainty in modeling the long decay time component from other \(D\) decays in the signal region. The second largest component, 0.05, is due to the presence of a non-zero mean in the proper time signal resolution PDF. The mean value is determined in the RS proper time fit to be 3.6 fs and is due to small misalignments in the detector. The error of \(15 \times 10^{-3}\) on \(A_D\) is primarily due to uncertainties in modeling the differences between \(K^+\) and \(K^-\) absorption in the detector.

We have presented evidence for \(D^0-\bar{D}^0\) mixing. Our result is inconsistent with the no-mixing hypothesis at a significance of 3.9 standard deviations. We measure \(y' = [9.7 \pm 4.4 \text{ (stat.)} \pm 3.1 \text{ (syst.)}] \times 10^{-3}\), while \(x'^2\) is consistent with zero. We find no evidence for \(CP\) violation and measure \(R_D\) to be \([0.303 \pm 0.016 \text{ (stat.)} \pm 0.010 \text{ (syst.)}]\)%. The result is consistent with SM estimates for mixing.

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