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

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We present evidence for D^0-$\overline{D}^0$ mixing in $D^0 \to K^+\pi^-$ decays from $384\,\mathrm{fb}^{-1}$ of e^+e^- colliding-beam data recorded near $\sqrt{s} = 10.6\,\mathrm{GeV}$ with the *BABAR* detector at the PEP-II storage rings at SLAC. We find the mixing parameters $x'^2 = [-0.22 \pm 0.30\ (\mathrm{stat.}) \pm 0.21\ (\mathrm{syst.})] \times 10^{-3}$ and $y' = [9.7 \pm 4.4\ (\mathrm{stat.}) \pm 3.1\ (\mathrm{syst.})] \times 10^{-3}$, 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

measure $R_{\rm D}$, the ratio of doubly Cabibbo-suppressed to Cabibbo-favored decay rates, to be $[0.303 \pm 0.016\ (\text{stat.}) \pm 0.010\ (\text{syst.})]\%$. We find no evidence for *CP* violation.

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We present evidence for charm-meson (D^0-$\overline{D}^0$) 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-$\overline{D}^0$ 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 $D^0 \to K^+\pi^-$ [19], we determine $R_{\rm D}$, the ratio of doubly Cabibbo-suppressed to Cabibbo-favored decay rates, and the mixing parameters x'^2 and y'.

The charm sector is the only place where the contributions to *CP* violation of down-type quarks in the mixing diagram can be explored. We compare results for D^0 and $\overline{D}^0$ decays but find no evidence for *CP* violation. The SM predicts effects well below the sensitivity of this experiment.

We study the right-sign (RS), Cabibbo-favored (CF) decay $D^0 \to K^-\pi^+$ and the wrong-sign (WS) decay $D^0 \to K^+\pi^-$. The latter can be produced via the doubly Cabibbo-suppressed (DCS) decay $D^0 \to K^+\pi^-$ or via mixing followed by a CF decay $D^0 \to \overline{D}^0 \to K^+\pi^-$. The DCS decay has a small rate $R_{\rm D}$ of order $\tan^4\theta_C \approx 0.3\%$ relative to CF decay. We distinguish D^0 and $\overline{D}^0$ by their production in the decay $D^{*+} \to \pi_{\rm s}^+ D^0$ where the $\pi_{\rm s}^+$ is referred to as the "slow pion". In RS decays the $\pi_{\rm s}^+$ 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-$\overline{D}^0$ mixing.

The D^0 and $\overline{D}^0$ 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, Γ_1 and M_2, Γ_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

$$\frac{T_{\rm WS}(t)}{e^{-\Gamma t}} \propto R_{\rm D} + \sqrt{R_{\rm D}}\, y'\, \Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\,, \qquad (1)$$

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 $R_{\rm D}$, x'^2, and y'. To search for *CP* violation, we apply Eq. (1) to D^0 and $\overline{D}^0$ samples separately, fitting for the parameters $\{R_{\rm D}^{\pm}, x'^{2\pm}, y'^{\pm}\}$ for D^0 (+) decays and $\overline{D}^0$ (−) 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 $K^{\mp}\pi^{\pm}$ invariant mass $m_{K\pi}$ between 1.81 and $1.92\,\text{GeV}/c^2$, requiring each track to have at least 12 coordinates in the drift chamber (DCH). Each pair is identified as $K^{\mp}\pi^{\pm}$ 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 δt for each D^0 candidate, we refit the $K^{\mp}$ and $\pi^{\pm}$ tracks, constraining them to originate from a common vertex. We also require the D^0 and $\pi_{\rm s}^+$ to originate from a common vertex, constrained by the position and size of the e^+e^- interaction region. We require the $\pi_{\rm s}^+$ to have a momentum in the laboratory frame greater than $0.1\,\text{GeV}/c$ and in the e^+e^- center-of-mass (CM) frame below $0.45\,\text{GeV}/c$. We require the χ^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 Δm 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 $2.5\,\text{GeV}/c$. We require $-2 < t < 4\,\text{ps}$ and $\delta t < 0.5\,\text{ps}$ (the most probable value of δt 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 $\overline{D}^0$ 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 $m_{K\pi}$, Δm, t, and δt. 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 Δm, 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 Δm 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 $R_{\rm D}$. 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 π_s^+, misreconstructed D^0 and combinatorial background. Signal has a characteristic peak in both $m_{K\pi}$ and Δm. The random π_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 Δm. 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 Δm, but not in $m_{K\pi}$. For RS events, most of these are semileptonic decays $D^0 \to K^-\ell^+\nu$ with the charged lepton misidentified as a pion. For WS events, the main contributor is RS $D^0 \to K^-\pi^+$ decays where the K^- and the π^+ are misidentified as π^- 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 Δm.

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 $1.81 < m_{K\pi} < 1.92\,\mathrm{GeV}/c^2$ and $0.14 < \Delta m < 0.16\,\mathrm{GeV}/c^2$ region.

We fit the RS and WS data samples simultaneously with shape parameters describing the signal and random π_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 π_s^+ background. Projections of the WS data and fit are shown in Fig. 1.

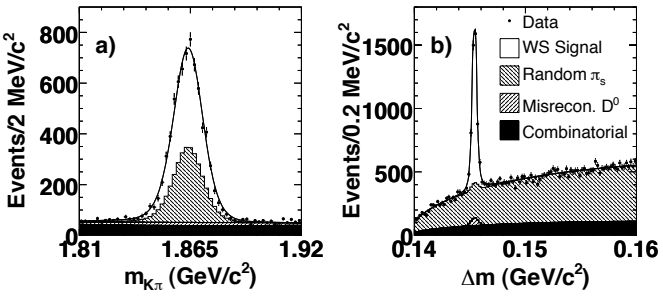

FIG. 1: a) $m_{K\pi}$ for wrong-sign (WS) candidates with $0.1445 < \Delta m < 0.1465\,\mathrm{GeV}/c^2$, and b) Δm for WS candidates with $1.843 < m_{K\pi} < 1.883\,\mathrm{GeV}/c^2$. The fitted PDFs are overlaid. The shaded regions represent the different background components.

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 δt. The random π_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 δt distributions, as determined from data using a background-subtraction technique [21] based on the fit to $m_{K\pi}$ and Δm.

The fit to the RS proper-time distribution is performed over all events in the full $m_{K\pi}$ and Δm region. The PDFs for signal and background in $m_{K\pi}$ and Δm 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 π_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.

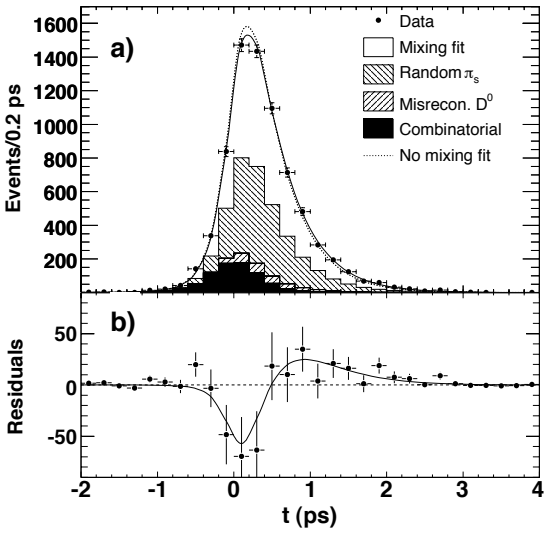

FIG. 2: a) The proper-time distribution of combined D^0 and $\overline{D}^0$ WS candidates in the signal region $1.843 < m_{K\pi} < 1.883\,\mathrm{GeV}/c^2$ and $0.1445 < \Delta m < 0.1465\,\mathrm{GeV}/c^2$. The result of the fit allowing (not allowing) mixing but not *CP* violation is overlaid as a 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

calculated from the change in log likelihood ($-2\Delta \ln \mathcal{L}$) in two dimensions (x'^2 and y') with systematic uncertainties included. The likelihood maximum is at the unphysical value of $x'^2 = -2.2 \times 10^{-4}$ and $y' = 9.7 \times 10^{-3}$. The value of $-2\Delta \ln \mathcal{L}$ at the most likely point in the physically allowed region ($x'^2 = 0$ and $y' = 6.4 \times 10^{-3}$) is 0.7 units. The value of $-2\Delta \ln \mathcal{L}$ for no-mixing is 23.9 units. Including the systematic uncertainties, this corresponds to a significance equivalent to 3.9 standard deviations ($1 - \mathrm{CL} = 1 \times 10^{-4}$) and thus constitutes evidence for mixing. The fitted values of the mixing parameters and R_D are listed in Table I. The correlation coefficient between the x'^2 and y' parameters is -0.94.

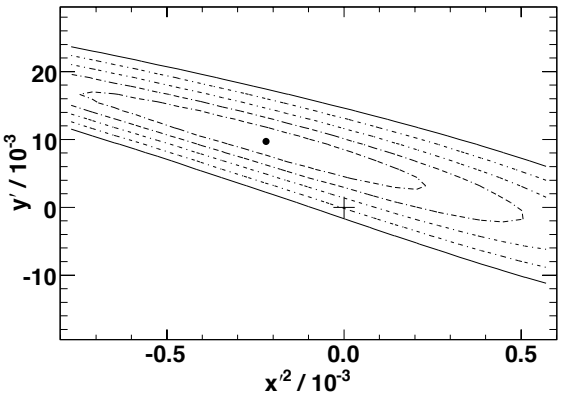

FIG. 3: The central value (point) and confidence-level (CL) contours for $1 - \mathrm{CL} = 0.317$ (1σ), 4.55×10^{-2} (2σ), 2.70×10^{-3} (3σ), 6.33×10^{-5} (4σ) and 5.73×10^{-7} (5σ), calculated from the change in the value of $-2 \ln \mathcal{L}$ compared with its value at the minimum. Systematic uncertainties 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 $\overline{D}^0$ 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.

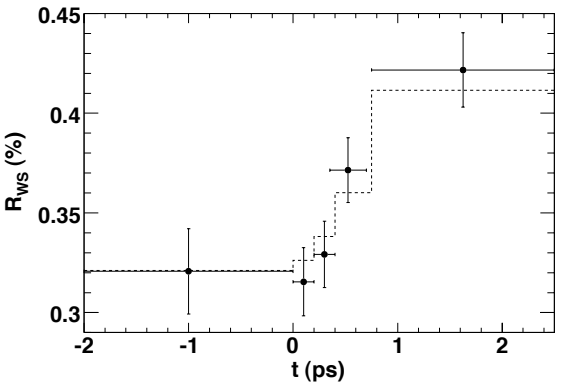

FIG. 4: The WS branching fractions from independent $\{m_{K\pi}, \Delta m\}$ fits to slices in measured proper time (points). The dashed line shows the expected wrong-sign rate as determined from the mixing fit shown in Fig. 2. The χ^2 with respect to expectation from the mixing fit is 1.5; for the no-mixing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

TABLE I: Results from the different fits. The first uncertainty listed is statistical and the second systematic.

Fit type	Parameter	Fit Results ($/10^{-3}$)
No *CP* viol. or mixing	R_D	$3.53 \pm 0.08 \pm 0.04$
No *CP* violation	R_D	$3.03 \pm 0.16 \pm 0.10$
	x'^2	$-0.22 \pm 0.30 \pm 0.21$
	y'	$9.7 \pm 4.4 \pm 3.1$
CP violation allowed	R_D	$3.03 \pm 0.16 \pm 0.10$
	A_D	$-21 \pm 52 \pm 15$
	x'^{2+}	$-0.24 \pm 0.43 \pm 0.30$
	y'^+	$9.8 \pm 6.4 \pm 4.5$
	x'^{2-}	$-0.20 \pm 0.41 \pm 0.29$
	y'^-	$9.6 \pm 6.1 \pm 4.3$

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 $m_{K\pi}$, Δm, proper time, and δt PDFs. We varied the t and δt requirements. In addition, we considered variations that keep or reject all D^{*+} candidates sharing tracks with other candidates.

For each source of systematic error, we compute the significance $s_i^2 = 2\left[\ln \mathcal{L}(x'^2, y') - \ln \mathcal{L}(x'^2_i, y'_i)\right]/2.3$, where (x'^2, y') are the parameters obtained from the standard fit, (x'^2_i, 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

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 $1 + \Sigma s_i^2 = 1.3$ 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 nonzero 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 15×10^{-3} on $A_{\rm D}$ is primarily due to uncertainties in modeling the differences between K^+ and K^- absorption in the detector.

We have presented evidence for D^0-$\overline{D}^0$ 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 $R_{\rm D}$ 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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