January 2007
BABAR-PUB-06/049, SLAC-PUB-12036
hep-ex/0608006

Search for D^0-$\overline{D}^0$ Mixing and Branching-Ratio Measurement in the Decay $D^0 \to K^+\pi^-\pi^0$

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Submitted to Physical Review Letters

Work supported in part by the US Department of Energy contract DE-AC02-76SF00515

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(Dated: January 5, 2007)

We analyze 230.4 fb^{-1} of data collected with the *BABAR* detector at the PEP-II e^+e^- collider at SLAC to search for evidence of D^0-$\overline{D}^0$ mixing using regions of phase space in the decay $D^0 \to K^+\pi^-\pi^0$. We measure the time-integrated mixing rate $R_M = (0.023\ ^{+0.018}_{-0.014}\,(\text{stat.}) \pm 0.004\,(\text{syst.}))\%$, and $R_M < 0.054\%$ at the 95% confidence level, assuming *CP* invariance. The data are consistent with no mixing at the 4.5% confidence level. We also measure the branching ratio for $D^0 \to K^+\pi^-\pi^0$ relative to $D^0 \to K^-\pi^+\pi^0$ to be $(0.214 \pm 0.008\,(\text{stat.}) \pm 0.008\,(\text{syst.}))\%$.

PACS numbers: 14.40.Lb, 13.25.Ft, 12.15.Mm, 11.30.Er

Mixing of the strong eigenstates $|D^0\rangle$ and $|\overline{D}^0\rangle$, involving transitions of the charm quark to a down-type quark, is expected to have a very small rate in the Standard Model (SM). Accurate estimates of this rate must consider long-distance effects [1], and typical theoretical values of the time-integrated mixing rate are $R_M \sim \mathcal{O}(10^{-6}$–$10^{-4})$. The most stringent constraint to date is $R_M < 0.040\%$ at the 95% confidence level [2]. Because SM D mixing involves only the first two quark generations to a very good approximation, the mixing-amplitude scale is set by flavor-SU(3) breaking, and *CP* violation is undetectable [1].

We search for the process $|D^0\rangle \to |\overline{D}^0\rangle$ by analyzing the decay of a particle known to be created as a $|D^0\rangle$ [3]. We reconstruct the wrong-sign (WS) decay $D^0 \to K^+\pi^-\pi^0$, and we distinguish doubly Cabibbo-suppressed (DCS) contributions from Cabibbo-favored (CF) mixed contributions in the decay-time distribution. Because mixing amplitudes are small, the greatest sensitivity to mixing is found when the amplitude for a particular DCS decay is comparably small. We increase our overall sensitivity to mixing by selecting regions of phase space (*i.e.*, the Dalitz plot) where the relative number of DCS decays to CF decays is small. This technique cannot be performed with the two-body decay $D^0 \to K^+\pi^-$, and it has not been used to date. While the ratio of DCS to CF decay rates depends on position in the Dalitz plot, the mixing rate does not. From inspection of the Dalitz plots, we note that DCS decays proceed primarily through the resonance $D^0 \to K^{*+}\pi^-$, while CF decays proceed primarily through $D^0 \to K^-\rho^+$ [4].

We present the first search for D mixing in the decay $D^0 \to K^+\pi^-\pi^0$. The analysis method introduced increases experimental accessibility to interference between DCS decay and mixing without a full phase-space parameterization. Such interference effects can be used to search for new physics contributions to *CP* violation.

The two mass eigenstates

$$|D_{A,B}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \tag{1}$$

generated by mixing dynamics have different masses ($m_{A,B}$) and widths ($\Gamma_{A,B}$), and we parameterize the mixing process with the quantities

$$x \equiv 2\frac{m_B - m_A}{\Gamma_B + \Gamma_A}, \qquad y \equiv \frac{\Gamma_B - \Gamma_A}{\Gamma_B + \Gamma_A}. \tag{2}$$

If *CP* is not violated, then $|p/q| = 1$. For a nonleptonic multibody WS decay, the time-dependent decay rate, $\Gamma_{\rm WS}(t)$, relative to a corresponding right-sign (RS) rate, $\Gamma_{\rm RS}(t)$, is approximated by [5]

$$\frac{\Gamma_{\rm WS}(t)}{\Gamma_{\rm RS}(t)} = \tilde{R}_D + \alpha\tilde{y}'\sqrt{\tilde{R}_D}\,(\Gamma t) + \frac{\tilde{x}'^2 + \tilde{y}'^2}{4}(\Gamma t)^2 \tag{3}$$
$$0 \le \alpha \le 1.$$

The tilde indicates quantities that have been integrated over any choice of phase-space regions. $\tilde{R}_D$ is the integrated DCS branching ratio, $\tilde{y}' = y\cos\tilde{\delta} - x\sin\tilde{\delta}$ and $\tilde{x}' = x\cos\tilde{\delta} + y\sin\tilde{\delta}$, where $\tilde{\delta}$ is an integrated strong-phase difference between the CF and the DCS decay amplitudes, α is a suppression factor that accounts for strong-phase variation over the regions, and Γ is the average width. The time-integrated mixing rate $R_M = (\tilde{x}'^2 + \tilde{y}'^2)/2 = (x^2 + y^2)/2$ is independent of decay mode.

We search for *CP*-violating effects by fitting to the $D^0 \to K^+\pi^-\pi^0$ and $\overline{D}^0 \to K^-\pi^+\pi^0$ samples separately. We consider *CP* violation in the interference between the DCS channel and mixing, parameterized by an integrated *CP*-violating–phase difference $\tilde{\phi}$, as well as *CP* violation in mixing, parameterized by $|p/q|$. We assume *CP* invariance in the DCS and CF decay rates. The substitutions

$$\alpha\tilde{y}' \to |p/q|^{\pm 1}\,(\alpha\tilde{y}'\cos\tilde{\phi} \pm \beta\tilde{x}'\sin\tilde{\phi}) \tag{4}$$
$$(x^2 + y^2) \to |p/q|^{\pm 2}\,(x^2 + y^2) \tag{5}$$

are applied to Eq. 3, using $(+)$ for $\Gamma(\overline{D}^0 \to K^-\pi^+\pi^0)/\Gamma(D^0 \to K^-\pi^+\pi^0)$ and $(-)$ for the charge-conjugate ratio. The parameter β is a suppression factor that accounts for ϕ variation in the selected regions.

We use 230.4 fb^{-1} of data collected with the *BABAR* detector [6] at the PEP-II e^+e^- collider at SLAC. The production vertices of charged particles are measured with a silicon-strip detector (SVT), and their momenta are measured by the SVT and a drift chamber (DCH) in a 1.5 T magnetic field. Particle types are identified using energy deposition measurements from the SVT and DCH along with information from a Cherenkov-radiation detector. The energies of photons are measured by an electromagnetic calorimeter. All selection criteria were finalized before searching for evidence of mixing in the data. Selection criteria were determined from both study of the RS sample and past experience with other charm samples [7].

We reconstruct the decay $D^{*+} \to D^0\pi_s^+$ and determine the flavor of the D^0 candidate from the charge of the low-momentum pion denoted by $\pi_s^\pm$. We require $\pi_s^\pm$

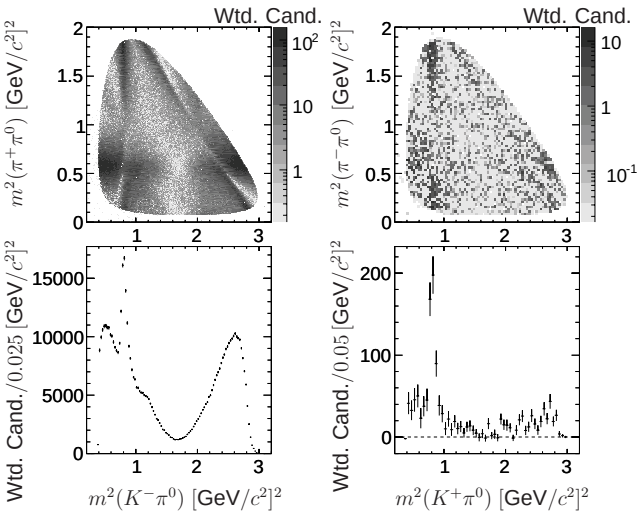

FIG. 1: Dalitz plots and projections for RS (left) and WS (right) data. An additional selection is made to reduce peaking background in the events shown here, and no σ_t selection is made. A statistical background subtraction [11] and a phase-space dependent efficiency correction have been applied (*i.e.*, candidates have been weighted).

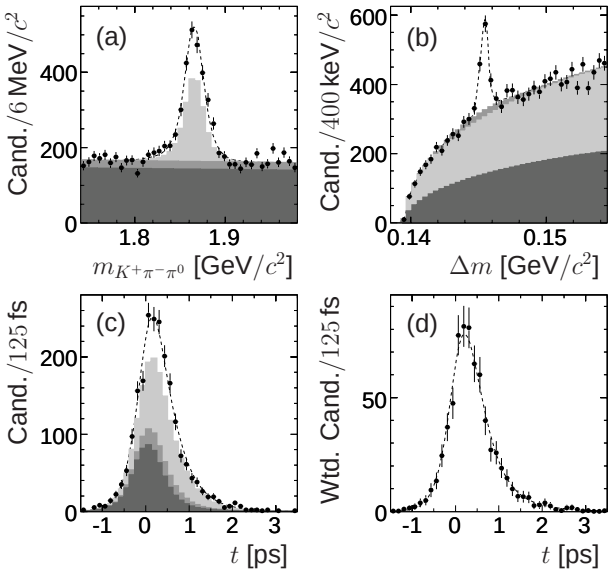

FIG. 2: Distributions of WS data (points with error bars) with fitted PDFs (dashed line) overlaid. The $m_{K\pi\pi^0}$ distribution (a) requires $0.1444 < \Delta m < 0.1464\,\mathrm{GeV}/c^2$; the Δm distribution (b) requires $1.85 < m_{K\pi\pi^0} < 1.88\,\mathrm{GeV}/c^2$; and the t distribution (c) requires both mass selections. The data points in (d) show the t distribution after applying a channel-likelihood signal projection [11, 12], and the signal PDF is overlaid. The error bars in (d) reflect Poissonian signal fluctuations only. In (a)–(d), the white regions represent signal events, the light gray misassociated $\pi_s^\pm$ events, the medium gray correctly associated $\pi_s^\pm$ with misreconstructed D^0 events, and the dark gray remaining combinatorial background.

candidates to have momentum transverse to the beam axis $p_t > 120\,\mathrm{MeV}/c$. We require D^0 candidates to have center-of-mass momenta greater than $2.4\,\mathrm{GeV}/c$, and the charged D^0 daughters must satisfy a likelihood-based particle-identification selection. The identification efficiency for both K and π is 90%, and the misidentification rate is 3% (1%) for K (π) candidates. We require photons from π^0 decays to have a laboratory energy $E_\gamma > 100\,\mathrm{MeV}$, and π^0 candidates to have a laboratory momentum $p_{\pi^0} > 350\,\mathrm{MeV}/c$ and a mass-constrained–fit χ^2 probability > 0.01. The experimental width of the π^0-mass peak is $\sigma_{m(\gamma\gamma)} \approx 6\,\mathrm{MeV}/c^2$. We accept candidates with an invariant mass $1.74 < m_{K\pi\pi^0} < 1.98\,\mathrm{GeV}/c^2$ and an invariant mass difference $0.140 < \Delta m < 0.155\,\mathrm{GeV}/c^2$, where $\Delta m \equiv m_{K\pi\pi^0\pi_s} - m_{K\pi\pi^0}$. We enhance contributions from $D^0 \to K^-\rho^+$ and reduce the ratio of DCS to CF decays by excluding events with two-body invariant masses in the ranges $850 < m(K\pi^\pm, K\pi^0) < 950\,\mathrm{MeV}/c^2$. Figure 1 shows the Dalitz plots for these decays.

The D^{*+} mass, D^0 mass, and D^0 decay time are derived from a track-vertex fit [8]. A mass constraint is applied to the π^0 candidate, and the D^{*+}-decay vertex is constrained to the beamspot region, of size $(\sigma_x, \sigma_y, \sigma_z) \approx (150\,\mu\mathrm{m}, 10\,\mu\mathrm{m}, 7\,\mathrm{mm})$. We select events for which the fit χ^2 probability > 0.01. From this fit, a D^0 decay time, t, and uncertainty, σ_t, are calculated using the three-dimensional flight path. The full covariance matrix, including correlations between the D^{*+} and D^0 vertices, is used in the σ_t estimate. For signal events, the typical value of σ_t is near 0.23 ps. We accept decays with $\sigma_t < 0.5\,\mathrm{ps}$. The D^0 lifetime is $(410.1 \pm 1.5)\,\mathrm{fs}$ [9].

We first extract the signal yields from a two-dimensional, unbinned, extended maximum likelihood fit to the $m_{K\pi\pi^0}$ and Δm distributions, performed on the RS and WS samples simultaneously. The signal-shape parameters of the probability density function (PDF) describing the WS sample are precisely determined by the large RS sample, and all associated systematic uncertainties are suppressed. The width of the Δm peak is uncorrelated with the width of the $m_{K\pi\pi^0}$ peak, dominated by π^0-momentum resolution, to first order. However, there is a second-order correlation in the signal between the two distributions. Thus, the signal PDF has a width in Δm that varies quadratically with $m_{K\pi\pi^0}$. This feature significantly reduces the signal yield uncertainty.

Three background categories are included in the likelihood: (1) correctly reconstructed D^0 candidates with a misassociated π_s^+, (2) D^{*+} decays with a correctly associated π_s^+ and a misreconstructed D^0, and (3) remaining combinatorial backgrounds. The first category has distributions in $m_{K\pi\pi^0}$ and t of RS signal decays and is distinguished using Δm. The second category, peaking in Δm and distinguished using $m_{K\pi\pi^0}$, has a t distribution similar to RS signal with a different characteristic lifetime.

TABLE I: Signal-candidate yields determined by the two-dimensional fit to the $(m_{K\pi\pi^0}, \Delta m)$ distributions for the WS and RS samples. Yields are shown (a) for the selected phase-space regions used in this analysis and (b) for the entire allowed phase-space region. Uncertainties are those calculated from the fit, and no efficiency corrections have been applied.

		D^0 Cand.	$\overline{D}^0$ Cand.
(a)	WS	$(3.84 \pm 0.36) \times 10^2$	$(3.79 \pm 0.36) \times 10^2$
	RS	$(2.518 \pm 0.006) \times 10^5$	$(2.512 \pm 0.006) \times 10^5$
(b)	WS	$(7.5 \pm 0.5) \times 10^2$	$(8.1 \pm 0.5) \times 10^2$
	RS	$(3.648 \pm 0.007) \times 10^5$	$(3.646 \pm 0.007) \times 10^5$

The third category does not peak in either $m_{K\pi\pi^0}$ or Δm and has a t distribution empirically described by a Gaussian with a power-law tail. Although the functional forms of the background PDFs are motivated by simulations, all shape parameters are obtained from a fit to the data. The $m_{K\pi\pi^0}$ and Δm projections of the two-dimensional fit to the WS sample are shown in Fig. 2(a,b).

The signal yields from the fit to the $(m_{K\pi\pi^0}, \Delta m)$ plane are listed in Table I. Considering the entire allowed phase space, and without the σ_t selection, we measure the branching ratio for $D^0 \to K^+\pi^-\pi^0$ relative to the decay $D^0 \to K^-\pi^+\pi^0$ to be $(0.214 \pm 0.008\,(\text{stat.}) \pm 0.008\,(\text{syst.}))\%$. This result is consistent with previous measurements [10] of this quantity and is significantly more precise. For this measurement, a phase-space dependent efficiency correction is applied to account for the different resonant populations in CF and DCS decays. The average efficiency of the WS sample relative to the RS samples is 97%. Phase-space dependent π^0 selection efficiencies dominate the systematic uncertainty.

The fitted shape parameters from $m_{K\pi\pi^0}$ and Δm are used to determine the signal probability of each event in a three-dimensional likelihood, $\mathcal{L}$, that is optimized in a one-dimensional fit to t. The RS signal PDF in t is represented by an exponential function convolved with a three-Gaussian detector-resolution function. The Gaussians have a common mean, but different widths. The width of each Gaussian is a scale factor multiplied by σ_t, and σ_t is determined for each event. The three different scale factors, as well as the fraction of events described by each Gaussian, are determined from the fit to the data. We find a D^0 lifetime consistent with the nominal value.

The WS PDF in t is based on Eq. 3 convolved with the same resolution function as in the RS PDF. The D^0 lifetime and resolution scale factors, determined by the fit to the RS t distribution, are fixed. We fit the WS PDF to the t distribution allowing yields and background-shape parameters to vary. The fit to the t distribution is shown for the WS sample in Fig. 2(c,d).

The results of the decay-time fit, with and without the assumption of *CP* conservation, are listed in Table II. The statistical uncertainty of a particular parameter is obtained by finding its extrema for $\Delta \ln \mathcal{L} = 0.5$. Contours of constant $\Delta \ln \mathcal{L} = 1.15, 3$, enclosing two-dimensional coverage probabilities of 68.3% and 95.0%, respectively, are shown in Fig. 3. With a Bayesian interpretation of $\mathcal{L}$, we find an upper limit $R_M < 0.054\%$ at the 95% confidence level, assuming *CP* conservation.

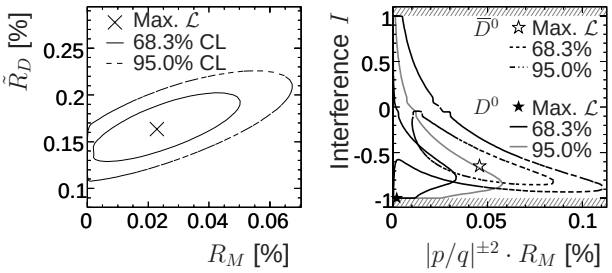

FIG. 3: Contours of constant $\Delta \ln \mathcal{L} = 1.15, 3$, defining 68.3% and 95.0% confidence levels, respectively. The contours on the left are in terms of the integrated mixing rate, R_M, and doubly Cabibbo-suppressed rate, $\tilde{R}_D$, assuming *CP* invariance. The contours on the right are in terms of R_M and the normalized interference $I = (\alpha\tilde{y}' \cos\tilde{\phi} \pm \beta\tilde{x}' \sin\tilde{\phi})/\sqrt{x^2+y^2}$, for the D^0 and $\overline{D}^0$ samples separately. On the left, the upward slope of the contour indicates negative interference; on the right, the hatched regions are physically forbidden.

In one dimension, $\Delta \ln \mathcal{L}$ changes its behavior near $R_M = 0$ because the interference term (the term linear in t in Eq. 3) becomes unconstrained. Therefore, we estimate the consistency of the data with no mixing using a frequentist method. We generate 1000 simulated data sets with no mixing but otherwise according to the fitted PDF, each with 58,800 events representing signal and background in the quantities $m_{K\pi\pi^0}$, Δm, and t. We find 4.5% of simulated data sets have a fitted value of R_M greater than that observed in the data. Thus, the observed data are consistent with no mixing at the 4.5% confidence level.

We quantify systematic uncertainties by repeating the fits with the following elements changed, in order of significance: the background PDF shape in the $m_{K\pi\pi^0}$ distribution, the selection of events based on σ_t, the decay-time resolution function, and the measured D^0 lifetime value. Additionally, for $\tilde{R}_D$, we consider the absence of any Dalitz-plot efficiency correction. The combined systematic uncertainties are smaller than statistical uncertainties by factors of 2–4. The quantity $\beta\tilde{x}' \sin\tilde{\phi}$, which quantifies a difference between the D^0 and $\overline{D}^0$ samples, has a negligible systematic uncertainty because positively correlated effects in the two samples cancel.

As a consistency check, we perform the decay-time fit to the entire phase-space region populated by the decays $D^0 \to K^+\pi^-\pi^0$. The results are consistent with Table II, with sensitivity to R_M preserved. However, the interference term obtained is different. Figure 3 indicates that

TABLE II: Mixing results assuming *CP* conservation (D^0 and $\overline{D}^0$ samples are not separated) and manifestly permitting *CP* violation (D^0 and $\overline{D}^0$ samples are fit separately). The first listed uncertainty is statistical, and the second is systematic. Quantities that have been integrated over the selected phase-space regions are indicated with tildes. $\tilde{R}_D$ is not reported when allowing for *CP* violation because precise $\pi_s^\pm$ efficiency asymmetries are unknown.

CP conserved		*CP* violation allowed	
R_M	$(0.023\ ^{+0.018}_{-0.014} \pm 0.004)\%$		$(0.010\ ^{+0.022}_{-0.007} \pm 0.003)\%$
$\tilde{R}_D$	$(0.164\ ^{+0.026}_{-0.022} \pm 0.012)\%$		
$\alpha\tilde{y}'$	$-0.012\ ^{+0.006}_{-0.008} \pm 0.002$	$\alpha\tilde{y}' \cos\tilde{\phi}$	$-0.012\ ^{+0.006}_{-0.007} \pm 0.002$
		$\beta\tilde{x}' \sin\tilde{\phi}$	$0.003\ ^{+0.002}_{-0.005} \pm 0.000$
		$\lvert p/q \rvert$	$2.2\ ^{+1.9}_{-1.0} \pm 0.1$

both D^0 and $\overline{D}^0$ samples prefer a large negative interference term when the phase space is restricted to suppress DCS contributions. By contrast, when the interference term is integrated over the entire Dalitz plot, it is found to be consistent with zero, with uncertainties comparable to those in this analysis. The variation of the interference effect in different phase-space regions motivates a detailed phase-space analysis of this mode in the future.

In summary, we find that the data are consistent with the no-mixing hypothesis at the 4.5% confidence level, and we set an upper limit $R_M < 0.054\%$ at the 95% confidence level. We measure the branching ratio for $D^0 \to K^+\pi^-\pi^0$ relative to $D^0 \to K^-\pi^+\pi^0$ to be $(0.214 \pm 0.008\,(\text{stat.}) \pm 0.008\,(\text{syst.}))\%$.

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), MEC (Spain), and PPARC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

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