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


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25Ecole Polytechnique, Laboratoire Leprince-Ringuet, F-91128 Palaiseau, France
26University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
27Dipartimento di Fisica and INFN, Università di Ferrara, I-44100 Ferrara, Italy
28Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy
29Dipartimento di Fisica and INFN, Università di Genova, I-16146 Genova, Italy
30Harvard University, Cambridge, Massachusetts 02138, USA
31Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, D-69120 Heidelberg, Germany
32Imperial College London, London, SW7 2AZ, United Kingdom
33University of Iowa, Iowa City, Iowa 52242, USA
34Iowa State University, Ames, Iowa 50011-3160, USA
35Johns Hopkins University, Baltimore, Maryland 21218, USA
36Institut für Experimentelle Kernphysik, Universität Karlsruhe, D-76021 Karlsruhe, Germany
37Laboratoire de l’Accélérateur Linéaire, IN2P3-CNRS et Université Paris-Sud 11, Centre Scientifique d’Orsay, B.P. 34, F-91898 ORSAY Cedex, France
38Lawrence Livermore National Laboratory, Livermore, California 94550, USA
39University of Liverpool, Liverpool L69 7ZE, United Kingdom
40Queen Mary, University of London, E1 4NS, United Kingdom
41University of London, Royal Holloway, and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
42University of Louisville, Louisville, Kentucky 40292, USA
43University of Manchester, Manchester M13 9PL, United Kingdom
44University of Maryland, College Park, Maryland 20742, USA
45University of Massachusetts, Amherst, Massachusetts 01003, USA
46Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
47McGill University, Montréal, Québec, Canada H3A 2T8
48Dipartimento di Fisica and INFN, Università di Milano, I-20133 Milano, Italy
49University of Mississippi, University, Mississippi 38677, USA
50Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
51Mount Holyoke College, South Hadley, Massachusetts 01075, USA
52Dipartimento di Scienze Fisiche and INFN, Università di Napoli Federico II, I-80126, Napoli, Italy
53NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
54University of Notre Dame, Notre Dame, Indiana 46556, USA
55Ohio State University, Columbus, Ohio 43210, USA
56University of Oregon, Eugene, Oregon 97403, USA
57Dipartimento di Fisica and INFN, Università di Padova, I-35131 Padova, Italy
58Laboratoire de Physique Nucléaire et de Hautes Energies, Universités Paris VI et VII, F-75252 Paris, France
59University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
60Dipartimento di Fisica and INFN, Università di Perugia, I-06100 Perugia, Italy
61Dipartimento di Fisica, Scuola Normale Superiore and INFN, Università di Pisa, I-56127 Pisa, Italy
62Prairie View A&M University, Prairie View, Texas 77446, USA
63Princeton University, Princeton, New Jersey 08544, USA
64Dipartimento di Fisica and INFN, Università di Roma La Sapienza, I-00185 Roma, Italy
65University of Rostock, D-18051 Rostock, Germany
66Rutherford Appleton Laboratory, Chilton, Didcot, Oxford, OX11 0QX, United Kingdom
67DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
68University of South Carolina, Columbia, South Carolina 29208, USA
69Stanford Linear Accelerator Center, Stanford, California 94309, USA
70Stanford University, Stanford, California 94305-4060, USA
71State University of New York, Albany, New York 12222, USA
72University of Tennessee, Knoxville, Tennessee 37996, USA
73University of Texas at Austin, Austin, Texas 78712, USA
74University of Texas at Dallas, Richardson, Texas 75083, USA
75Dipartimento di Fisica Sperimentale and INFN, Università di Torino, I-10125 Torino, Italy
76Dipartimento di Fisica and INFN, Università di Trieste, 1-34127 Trieste, Italy
77IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
78University of Victoria, Victoria, British Columbia, Canada V8W 3P6
79Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
80University of Wisconsin, Madison, Wisconsin 53706, USA
81Yale University, New Haven, Connecticut 06511, USA
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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 $D^{0}$-$\bar{D}^{0}$ mixing using regions of phase space in the decay $D^{0} \rightarrow K^{*} \pi^{0}$. We measure the time-integrated mixing rate $R_{M} = (0.023^{+0.003}_{-0.012} \text{(stat.)} \pm 0.004 \text{(syst.)}) \%$, 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 $D^{0} \rightarrow K^{*} \pi^{0} \rightarrow D^{0} \rightarrow K^{-} \pi^{+} \pi^{0}$ to be $(0.214 \pm 0.008 \text{(stat.)} \pm 0.008 \text{(syst.)})\%$.

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Mixing of the strong eigenstates $|D^{0}\rangle$ and $|\bar{D}^{0}\rangle$, 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 $R_{M} \sim O(10^{-6}-10^{-4})$. 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 $|D^{0}\rangle \rightarrow |\bar{D}^{0}\rangle$ by analyzing the decay of a particle known to be created as a $|D^{0}\rangle$ [3]. We reconstruct the wrong-sign (WS) decay $D^{0} \rightarrow K^{+} \pi^{-} \pi^{0}$, 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 small. This technique cannot be performed with the two-body decay $D^{0} \rightarrow K^{+} \pi^{-}$, 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 $D^{0} \rightarrow K^{+}\pi^{-}\pi^{0}$, while CF decays proceed primarily through $D^{0} \rightarrow K^{-}\rho^{+}$ [4].

We present the first search for $D$ mixing in the decay $D^{0} \rightarrow K^{+} \pi^{-} \pi^{0}$. The analysis method introduces increased 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

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

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

$$x = \frac{2m_{B} - m_{A}}{\Gamma_{B} + \Gamma_{A}}, \quad y = \frac{\Gamma_{B} - \Gamma_{A}}{\Gamma_{B} + \Gamma_{A}}.$$  \hspace{1cm} (2)

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

$$\frac{\Gamma_{WS}(t)}{\Gamma_{RS}(t)} = R_{D} + \alpha\gamma' \sqrt{R_{D}(\Gamma(t)) + \frac{x^{2} + y^{2}}{4}(\Gamma(t))^{2}}, \quad 0 \leq \alpha \leq 1.$$  \hspace{1cm} (3)

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

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

$$\alpha\gamma' \rightarrow |p/q|^{-1}(\alpha\gamma' \cos \phi \pm \beta\tilde{\chi} \sin \phi)$$  \hspace{1cm} (4)

$$(x^{2} + y^{2}) \rightarrow |p/q|^{-2}(x^{2} + y^{2})$$  \hspace{1cm} (5)

are applied to Eq. (3), using (+) for $\Gamma(\bar{D}^{0} \rightarrow K^{-}\pi^{+}\pi^{0})/\Gamma(D^{0} \rightarrow K^{-}\pi^{+}\pi^{0})$ and (−) for the charge-conjugate ratio. The parameter $\beta$ is a suppression factor that accounts for $\phi$ 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 $D^{*+} \rightarrow D^{0}\pi^{+}$ and determine the flavor of the $D^{0}$ candidate from the charge of the low-
momentum pion denoted by $\pi_{K}^+$. We require $\pi_{K}^+$ candidates to have momentum transverse to the beam axis $p_{t} > 120$ MeV/c. We require $D^0$ candidates to have center-of-mass momenta greater than 2.4 GeV/c, and the charged $D^0$ daughters must satisfy a likelihood-based particle-identification selection. The identification efficiency for both $K$ and $\pi$ is 90%, and the misidentification rate is 3% (1%) for $K$ ($\pi$) candidates. We require photons from $\pi^0$ decays to have a laboratory energy $E_{\gamma} > 100$ MeV, and $\pi^0$ candidates to have a laboratory momentum $p_{\pi^0} > 350$ MeV/c and a mass-constrained-fit $\chi^2$ probability $>0.01$. The experimental width of the $\pi^0$-mass peak is $\sigma_{m(\gamma\gamma)} = 6$ MeV/c$^2$. We accept candidates with an invariant mass $1.74 < m_{K\pi\pi} < 1.98$ GeV/c$^2$ and an invariant mass difference $0.140 < \Delta m < 0.155$ GeV/c$^2$, where $\Delta m = m_{K\pi\pi} - m_{K\pi\pi}^0$. We enhance contributions from $D^0 \rightarrow K^-\pi^+\pi^-$ and reduce the ratio of DCS to CF decays by excluding events with two-body invariant masses in the ranges $850 < m(K\pi^+ \pi^-)$, $m(K\pi^0) < 950$ MeV/c$^2$. Figure 1 shows the Dalitz plots for these decays.

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

We first extract the signal yields from a two-dimensional, unbinned, extended maximum likelihood fit to the $m_{K\pi\pi}$ and $\Delta m$ 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 $\Delta m$ peak is uncorrelated with the width of the $m_{K\pi\pi}$ peak, dominated by $\pi^0$-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 $\Delta m$ that varies quadratically with $m_{K\pi\pi}$. 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 $\pi^+$, (2) $D^{\pm}$ decays with a correctly associated $\pi^+$ and a misreconstructed $D^0$, and (3) remaining combinatorial backgrounds. The first category has distributions in $m_{K\pi\pi}$ and $t$ of RS signal decays and is distinguished using $\Delta m$. The second category, peaking in $\Delta m$ and distinguished using $m_{K\pi\pi}$, has a $t$ distribution similar to RS signal with a different characteristic lifetime. The third category does not peak in either $m_{K\pi\pi}$ or $\Delta m$ 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 $m_{K\pi\pi}$ and $\Delta m$ projections of the two-dimensional fit to the WS sample are shown in Fig. 2(a) and 2(b).

The signal yields from the fit to the $(m_{K\pi\pi}, \Delta m)$ plane are listed in Table I. Considering the entire allowed phase space, and without the $\sigma_t$ selection, we measure the branching ratio for $D^0 \rightarrow K^-\pi^+\pi^-$ relative to the decay $D^0 \rightarrow K^-\pi^+\pi^0$ to be $(0.214 \pm 0.008(stat.) \pm 0.008(syst.))\%$. 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

![Figure 1](image-url)  
**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 $\sigma_t$ selection is made. A statistical background subtraction [11] and a phase-space dependent efficiency correction have been applied (i.e., candidates have been weighted).

| TABLE I. Signal-candidate yields determined by the two-dimensional fit to the $(m_{K\pi\pi}, \Delta m)$ 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. |
|-----------------|-----------------|
|                  | $D^0$ Candidate  | $\bar{D}^0$ Candidate |
| (a)              | (b)             |
| WS               | $(3.84 \pm 0.36) \times 10^2$ | $(3.79 \pm 0.36) \times 10^2$ |
| $(2.518 \pm 0.006) \times 10^5$ | $(2.512 \pm 0.006) \times 10^5$ |
| RS               | $(7.5 \pm 0.5) \times 10^2$ | $(8.1 \pm 0.5) \times 10^2$ |
| $(3.648 \pm 0.007) \times 10^5$ | $(3.646 \pm 0.007) \times 10^5$ |
dimensional fit to

t
used to determine the signal probability of each event in a
by an exponential function convolved with a three-

RS samples is 97%. Phase-space dependent $\pi^0$ selection
efficiencies dominate the systematic uncertainty.

The fitted shape parameters from $m_{K\pi\pi^0}$ and $\Delta m$ are
used to determine the signal probability of each event in a
three-dimensional likelihood, $L$, 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 $\sigma_i$, and $\sigma_i$
are determined for each event. The three different scale fac-
tors, 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 pa-
rameters to vary. The fit to the $t$ distribution is shown for
the WS sample in Fig. 2(c) and 2(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 $\Delta \ln L = 0.5$. Contours of con-
stant $\Delta \ln L = 1.15$, 3, enclosing two-dimensional cover-
age probabilities of 68.3% and 95.0%, respectively, are
shown in Fig. 3. With a Bayesian interpretation of $L$, we
find an upper limit $R_M < 0.054%$ at the 95% confidence
level, assuming CP conservation.

In one dimension, $\Delta \ln L$ changes its behavior near
$R_M = 0$ because the interference term [the term linear in
$t$ in Eq. (3)] becomes unconstrained. Therefore, we esti-
mate 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 58800 events representing signal and back-
ground in the quantities $m_{K\pi\pi^0}$, $\Delta m$, 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 sig-
nificance: the background PDF shape in the $m_{K\pi\pi^0}$
distribution, the selection of events based on $\sigma_i$, the decay-time
resolution function, and the measured $D^0$ lifetime value.
Additionally, for $R_D$, we consider the absence of any
Dalitz-plot efficiency correction. The combined systematic
uncertainties are smaller than statistical uncertainties by

![Figure 2](image_url)

**TABLE II.** Mixing results assuming CP conservation ($D^0$ and $\bar{D}^0$ samples are not separated) and manifestly permitting CP violation ($D^0$ and $\bar{D}^0$ 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. $\bar{R}_D$ is not reported when allowing for CP violation because precise $\pi^0$ efficiency asymmetries are unknown.

<table>
<thead>
<tr>
<th>CP conserved</th>
<th>CP violation allowed</th>
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<tbody>
<tr>
<td>$R_M = (0.023^{+0.018}_{-0.014} \pm 0.004)$%</td>
<td>$R_M = (0.010^{+0.022}_{-0.007} \pm 0.003)$%</td>
</tr>
<tr>
<td>$\bar{R}<em>D = (0.164^{+0.026}</em>{-0.022} \pm 0.012)$%</td>
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<tr>
<td>$\alpha \pi^0 = -0.012^{+0.006}_{-0.008} \pm 0.002$</td>
<td>$\alpha \pi^0 \cos \phi = -0.012^{+0.006}_{-0.007}$ ± 0.002</td>
</tr>
<tr>
<td>$\beta \pi^0 \sin \phi = 0.003^{+0.002}_{-0.002} \pm 0.000$</td>
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<td>p/q</td>
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[3] Unless otherwise stated, particle types and decay processes imply also their charge conjugates.


FIG. 3. Contours of constant $\Delta \ln \mathcal{L} = 1.15$, 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 $I = (\alpha y^\prime \cos \phi \pm \beta z^\prime \sin \phi)/\sqrt{x^2 + y^2}$, for the $D^0$ and $\bar{D}^0$ samples separately. On the left, the upward slope of the contour indicates negative interference; on the right, the hatched regions are physically forbidden.

The quantity $\beta z^\prime \sin \phi$, which quantifies a difference between the $D^0$ and $\bar{D}^0$ 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 $D^0 \rightarrow K^+ \pi^- \pi^0$. The results are consistent with Table II, with sensitivity to $R_M$ preserved. However, the interference term obtained is different. Figure 3 indicates that both $D^0$ and $\bar{D}^0$ 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 $D^0 \rightarrow K^+ \pi^- \pi^0$ relative to $D^0 \rightarrow K^- \pi^+ \pi^0$ to be $(0.214 \pm 0.008 \text{(stat.)} \pm 0.008 \text{(syst.)})\%$.

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