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SEARCH FOR D^0-$\overline{D}^0$ MIXING WITH THE *BABAR* EXPERIMENT

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The results of searches for D^0-$\overline{D}^0$ mixing in the decays $D^0 \to K^+\pi^-\pi^0$ and $D^0 \to K^+\pi^-\pi^+\pi^-$, using $230\,\text{fb}^{-1}$ of e^+e^- collisions collected from the *BABAR* detector at the PEP-II storage ring at SLAC, are presented. The combination of results from these analyses yields a value for the time-integrated mixing rate $R_M = (0.020\ ^{+0.011}_{-0.010}(\text{stat.}))\%$, and an upper limit $R_M < 0.042\%$ at the 95% confidence level. The data in these analyses are consistent with the no-mixing hypothesis at the 2.1% confidence level.

Keywords: Charm; Mixing; Lifetime; CP Violation; Cabibbo Suppressed.

1. Introduction

Although K^0-$\overline{K}^0$ mixing and B^0-$\overline{B}^0$ mixing are well established, D^0-$\overline{D}^0$ mixing has not yet been observed. As this particular mixing phenomenon is sensitive to new physics in a complementary manner to the K and B systems, it is an essential test of the completeness of the Standard Model. However, unlike B-mixing phenomena, which can be accurately calculated in the Standard Model from box diagrams, D-mixing phenomena are difficult to calculate because of dominant contributions from long-distance effects. A thorough review of D mixing is given in Ref. 1, and recent experimental results are discussed in Ref. 2.

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 $|p/q| = 1$. The time-integrated mixing rate is approximately

$$R_M = (x^2 + y^2)/2. \tag{3}$$

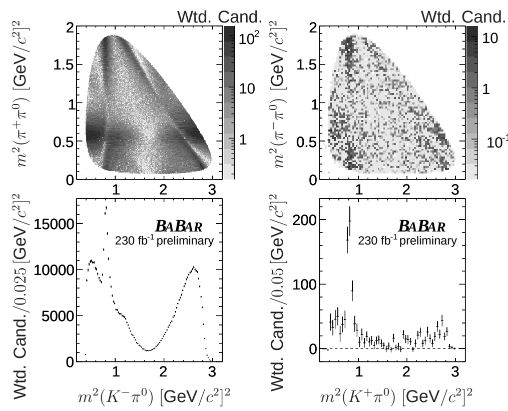

Fig. 1. Dalitz plots and projections for the decays $D^0 \to K^-\pi^+\pi^0$ (left) and $D^0 \to K^+\pi^-\pi^0$ (right). A statistical background subtraction[9] and a phase-space dependent efficiency correction have been applied (*i.e.*, candidates have been weighted).

This is a useful quantity that can be compared among different experimental analyses.

Using $230\,\text{fb}^{-1}$ of e^+e^- collisions collected from the *BABAR* detector at the PEP-II storage ring at SLAC, we have searched for evidence of D mixing in the decays $D^0 \to K^+\pi^-\pi^0$ and $D^0 \to K^+\pi^-\pi^+\pi^-$ by analyzing the decay-time distributions[3,4]. Although the branching ratio of $D^0 \to K^+\pi^-\pi^0$ to $D^0 \to K^-\pi^+\pi^0$ has been measured previously[5,6], this is the first

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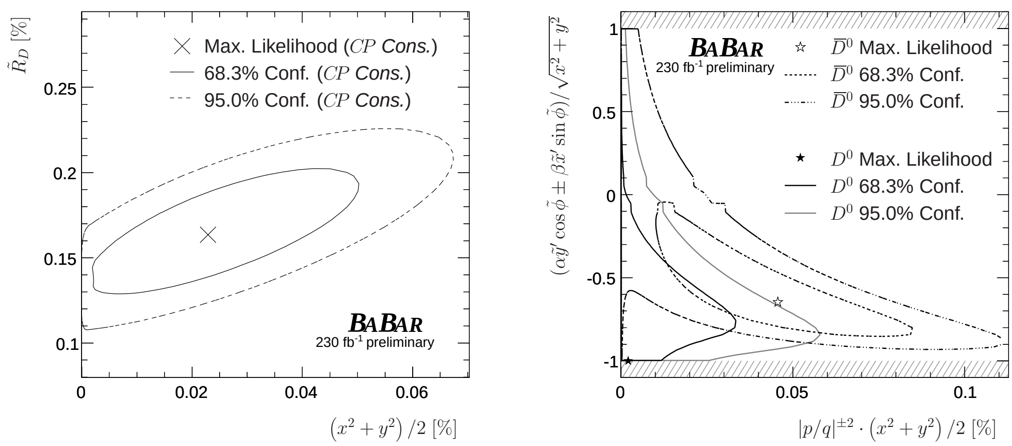


Fig. 2. Contours of constant $\Delta \ln \mathcal{L} = 1.15, 3$ from the analysis of $D^0 \to K^+\pi^-\pi^0$, defining 68.3% and 95.0% confidence levels, respectively. The contours on the left are in terms of the integrated mixing rate, $R_M = (x^2 + y^2)/2$, and doubly Cabibbo-suppressed rate, $\tilde{R}_D$, assuming *CP* invariance. The contours on the right are in terms of $|p/q|^{\pm 2} \cdot R_M$ and the normalized interference between the mixing and doubly Cabibbo-suppressed amplitudes, for the D^0 and $\overline{D}^0$ samples separately.

search for mixing in $D^0 \to K^+\pi^-\pi^0$. Similarly, the branching ratio of $D^0 \to K^+\pi^-\pi^+\pi^-$ to $D^0 \to K^-\pi^+\pi^+\pi^-$ has been measured previously[6,7,8], but only one previous search for mixing in the decay $D^0 \to K^+\pi^-\pi^+\pi^-$ has been performed[7].

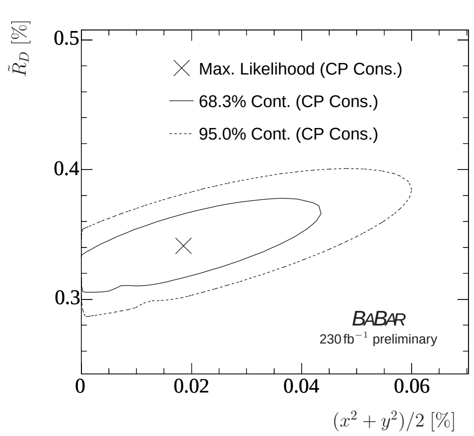
In each of the individual analyses, two similar final states are reconstructed. The mode of most interest, described as the wrong-sign (WS) mode, has both doubly Cabibbo-suppressed contributions and contributions from mixing. These two processes may be distinguished in the decay-time distribution. The second mode reconstructed, the right-sign (RS) mode, is Cabibbo favored, and is used as a normalization mode.

2. Analysis of $D^0 \to K^+\pi^-\pi^0$

Our analysis of $D^0 \to K^+\pi^-\pi^0$ is described in Ref. 3. The final state of the decay $D^0 \to K^+\pi^-\pi^0$ may be reached through intermediate resonances, and these resonances may be observed in the Dalitz plot for this mode. We perform the mixing analysis in a region of the Dalitz plot where we expect to find the largest amplitude from mixing. The Dalitz plots are shown in Fig. 1. We observe that the Cabibbo-favored RS decay $D^0 \to K^-\pi^+\pi^0$ populates the Dalitz plot differently from the WS decay. Because the amplitude for decay following mixing is predominantly Cabibbo favored, we expect the mixing amplitude to populate the Dalitz plot as the RS mode does. Since we observe a dominant contribution from $D^0 \to K^-\rho^+$ in the RS sample, consistent with previous measurements[10], we enhance our sensitivity to the mixing amplitude by rejecting candidates with two-body invariant masses in the ranges $850 < m(K\pi^\pm, K\pi^0) < 950\,\mathrm{MeV}/c^2$, corresponding to K^* resonances. Contours

Table 1. Mixing-rate central values assuming *CP* conservation. The first listed uncertainty is statistical, and the second (if present) is systematic.

Mode	R_M
$D^0 \to K^+\pi^-\pi^0$	$(0.023\ ^{+\,0.018}_{-\,0.014} \pm 0.004)$ %
$D^0 \to K^+\pi^-\pi^+\pi^-$	$(0.019\ ^{+\,0.016}_{-\,0.015} \pm 0.002)$ %
Combined	$(0.020\ ^{+\,0.011}_{-\,0.010})$ %



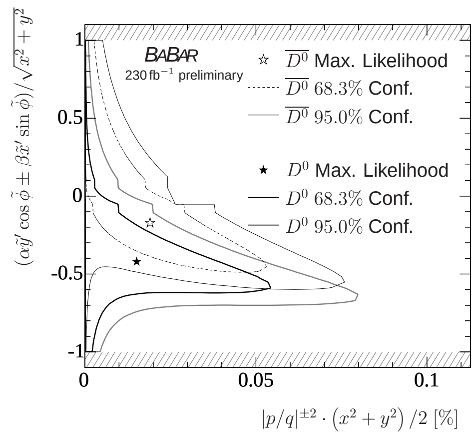


Fig. 3. Contours of constant $\Delta \ln \mathcal{L} = 1.15, 3$ from the analysis of $D^0 \to K^+\pi^-\pi^+\pi^-$, defining 68.3% and 95.0% confidence levels, respectively. The contours on the left are in terms of the integrated mixing rate, $R_M = (x^2+y^2)/2$, and doubly Cabibbo-suppressed rate, $\tilde{R}_D$, assuming *CP* invariance. The contours on the right are in terms of $|p/q|^{\pm 2} \cdot R_M$ and the normalized interference between the mixing and doubly Cabibbo-suppressed amplitudes, for the D^0 and $\overline{D}^0$ samples separately.

enclosing two-dimensional coverage probabilities of 68.3% and 95.0%, both in terms of the mixing rate R_M and the doubly Cabibbo-suppressed rate $\tilde{R}_D$, and in terms of R_M and the interference between the two amplitudes, are shown in Fig. 2.

3. Analysis of $D^0 \to K^+\pi^-\pi^+\pi^-$

Our analysis of $D^0 \to K^+\pi^-\pi^+\pi^-$ is described in Ref. 4. This final state also proceeds through intermediate resonances. However, we do not attempt to optimize the sensitivity to mixing in this analysis by selecting phase-space regions.

We note two experimental advantages to using this mode compared to using $D^0 \to K^+\pi^-\pi^0$. First, the signal-to-background ratio is almost twice as large, resulting in a better statistical separation of signal from background when fitting to the sample. Second, the decay-time resolution is better. For the decay $D^0 \to K^+\pi^-\pi^0$, the mean value of the decay-time distribution is 0.43 ps, and a typical value is 0.23 ps; for $D^0 \to K^+\pi^-\pi^+\pi^-$, the mean is 0.29 ps and a typical value is 0.16 ps. For comparison, the D^0 lifetime is (410.1 ± 1.5) fs[11]. Contours enclosing two-dimensional coverage probabilities of 68.3% and 95.0%, both in terms of the mixing rate R_M and the doubly Cabibbo-suppressed rate $\tilde{R}_D$, and in terms of R_M and the interference between the two amplitudes, are shown in Fig. 3.

Table 2. Central values of *CP* violation in mixing. The first listed uncertainty is statistical, and the second is systematic.

Mode	$\lvert p/q \rvert$
$D^0 \to K^+\pi^-\pi^0$	$2.2\ ^{+\ 1.9}_{-\ 1.0} \pm 0.1$
$D^0 \to K^+\pi^-\pi^+\pi^-$	$1.1\ ^{+\ 4.0}_{-\ 0.6} \pm 0.1$

Table 3. Mixing-rate central values 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.

Mode	R_M
$D^0 \to K^+\pi^-\pi^0$	$(0.010\ ^{+\ 0.022}_{-\ 0.007} \pm 0.003)$ %
$D^0 \to K^+\pi^-\pi^+\pi^-$	$(0.017\ ^{+\ 0.017}_{-\ 0.016} \pm 0.003)$ %

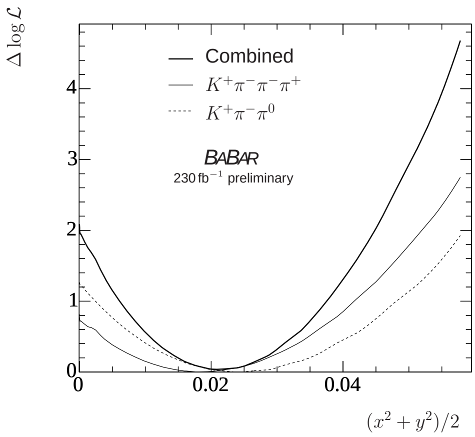


Fig. 4. $\Delta \ln \mathcal{L}$ as a function of R_M for separate and combined results of $D^0 \to K^+\pi^-\pi^0$ and $D^0 \to K^+\pi^-\pi^+\pi^-$. (On the axis, the natural logarithm is denoted log.)

4. Results and Summary

The central values we obtain for the mixing rate R_M, with and without the assumption of *CP* invariance, and for $|p/q|$, parameterizing *CP* violation in mixing, are given in Tables 1–3. We multiply the likelihood functions from the individual analyses to obtain combined results. These $\Delta \ln \mathcal{L}(R_M)$ curves are shown in Fig 4. We extract a central value and an uncertainty from the combined curve using the same procedure as for each individual result. With this method, we find $R_M = (0.020\,^{+0.011}_{-0.010})\%$, where the uncertainty is statistical only. We determine the upper limit $R_M < 0.042\%$ at the 95% confidence level, and we find the combined data are consistent with the no-mixing hypothesis at the 2.1% confidence level, as determined from the $\Delta \ln \mathcal{L}(R_M)$ curve.

In the future, we hope to combine these results with those from other modes and from other experiments.

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