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

(December 31, 1999)

Abstract

We report on a search for $D^0 - \overline{D}^0$ mixing made by studying the ‘wrong-sign’ process $D^0 \rightarrow K^+\pi^-$. The data come from an integrated luminosity of 9.0 fb$^{-1}$ of $e^+e^-$ collisions at $\sqrt{s} \approx 10$ GeV recorded with the CLEO II.V detector. We measure the time integrated rate of the ‘wrong-sign’ process $D^0 \rightarrow K^+\pi^-$ relative to that of the Cabibbo-favored process $\overline{D}^0 \rightarrow K^+\pi^-$ to be $R = (0.332^{+0.063}_{-0.065} \pm 0.040)\%$. We study $D^0 \rightarrow K^+\pi^-$ as a function of decay time to distinguish direct doubly Cabibbo-suppressed decay from $D^0 - \overline{D}^0$ mixing. The amplitudes that describe $D^0 - \overline{D}^0$ mixing, $x'$ and $y'$, are consistent with zero. At the 95% C.L. and without assumptions concerning charge-parity (CP) violating parameters, we find $(1/2)x'^2 < 0.041\%$ and $-5.8% < y' < 1.0\%$. 

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Studies of the evolution of a $K^0$ or $B_d^0$ into the respective anti-particle, a $\overline{K}^0$ or $\overline{B}_d^0$, have guided the form and content of the Standard Model, and permitted useful estimates of the masses of the charm $[1,2]$ and top quark $[3,4]$ prior to their direct observation. In this Letter, we present the results of a search for the evolution of the $D^0$ into the $\overline{D}^0$ $[5]$. Our principal motivation is to observe new physics outside the Standard Model.

A $D^0$ can evolve into a $\overline{D}^0$ through on-shell intermediate states, such as $K^+K^-$ with mass, $m_{K^+K^-} = m_{D^0}$, or through off-shell intermediate states, such as those that might be present due to new physics. We denote the amplitude through the former (latter) states by $-iy(x)$, in units of $\Gamma_{D^0}/2$ $[3]$. Many predictions for $x$ in the $D^0 \rightarrow \overline{D}^0$ amplitude have been made $[6]$. The Standard Model contributions are suppressed to $|x| \approx \tan^2 \theta_C \approx 5\%$ because $D^0$ decay is Cabibbo-favored; the GIM $[8]$ cancellation could further suppress $|x|$ down to $10^{-6} - 10^{-2}$. Many non-Standard Models predict $|x| > 1\%$. Contributions to $x$ at this level could result from the presence of new particles with masses as high as 100-1000 TeV $[9,10]$. Signatures of new physics include $|x| \gg |y|$, or charge-parity (CP) violating interference between $x$ and $y$, or between $x$ and a direct decay amplitude. In order to assess the origin of a $D^0 \rightarrow \overline{D}^0$ mixing signal, the effects described by $y$ must be distinguished from those described by $x$.

The wrong-sign (WS) process, $D^0 \rightarrow K^+\pi^-$, can proceed either through direct doubly Cabibbo-suppressed decay (DCSD), or through state-mixing followed by the Cabibbo-favored decay (CFD), $D^0 \rightarrow \overline{D}^0 \rightarrow K^+\pi^-$. Both processes could contribute to the time integrated WS rate $R = (f + \overline{f})/2$, and the inclusive CP asymmetry $A = (f - \overline{f})/(f + \overline{f})$, where $f = \Gamma(D^0 \rightarrow K^+\pi^-)/\Gamma(\overline{D}^0 \rightarrow K^+\pi^-)$, and $\overline{f}$ is defined by the application of charge-conjugation to $f$.

To disentangle the processes that could contribute to $D^0 \rightarrow K^+\pi^-$, we study the distribution of WS final states as a function of the proper decay time $t$ of the $D^0$. We describe the proper decay time in units of the mean $D^0$ lifetime, $\tau_{D^0} = 415 \pm 4\,\text{fs}$ $[11]$. The differential WS rate is $[12,13]$

$$r(t) \equiv [R_D + \sqrt{R_D}y/t + \frac{1}{4}(x^2 + y^2)^2]e^{-t}. \quad (1)$$

The modified mixing amplitudes $x'$ and $y'$ in Eqn. $[1]$ are given by $y' \equiv y \cos \delta - x \sin \delta$, $x' \equiv x \cos \delta + y \sin \delta$ and $R_M \equiv \frac{1}{2}(x'^2 + y'^2) = \frac{1}{2}(x^2 + y^2)$ where $\delta$ is a possible strong phase between the DCSD and CFD amplitudes. The symbol $R_D$ ($R_M$) represents the DCSD (mixing) rate relative to the CFD rate. There are theoretical arguments that $\delta$ is small $[14]$, which have recently been questioned $[15]$.

The influence of each of $x'$, $y'$, and $R_D$ on $r(t)$ in Eqn. $[1]$ is distinguishable. Such behavior is complementary to the time dependence of the decay rate to CP eigenstates such as $D^0 \rightarrow K^+K^-$ that is primarily sensitive to $y$, or that of $D^0 \rightarrow K^+\ell^-\nu_\ell$ that is sensitive to $R_M$ alone.

We characterize the violation of CP in state-mixing, direct decay, and the interference between those two processes, respectively, by the real-valued parameters $A_M$, $A_D$, and $\phi$, where, to leading order, both $x'$ and $y'$ are scaled by $(1 \pm A_M/2)$, $R_D \rightarrow R_D (1 \pm A_D)$, $\delta \rightarrow \delta \pm \phi$ in Eqn. $[1,13]$. The plus (minus) sign is used for an initial $D^0$ ($\overline{D}^0$).

Our data were accumulated between Feb. 1996 and Feb. 1999 from an integrated luminosity of 9.0 fb$^{-1}$ of $e^+e^-$ collisions at $\sqrt{s} \approx 10\,\text{GeV}$ provided by the Cornell Electron Storage
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We reconstruct candidates for the decay sequence \( D^{*+} \rightarrow \pi^+_s D^0, \) \( D^0 \rightarrow K^\mp \pi^\pm . \) The charge of the slow pion (\( \pi^+_s \) or \( \pi^-_s \)) identifies the charm state at \( t = 0 \) as either \( D^0 \) or \( \overline{D}^0 \). We require the \( D^{*+} \) momentum, \( p_{D^{*+}} \), to exceed 2.2 GeV, and we require the \( D^0 \) to produce either the final state \( K^+\pi^- \) (WS) or \( K^-\pi^+ \) (right-sign (RS)). The broad features of the reconstruction are similar to those employed in the recent CLEO measurement of the \( D \) meson lifetimes [13].

The SVX provides precise measurement of the charged particle trajectories, or ‘tracks,’ in three dimensions [20]. We are thus able to refit the \( K^+ \) and \( \pi^- \) tracks with a requirement that they form a common vertex in three dimensions, and require that the confidence level (C.L.) of the refit exceed 0.01%. We use the trajectory of the \( K^+\pi^- \) system and the position of the CESR luminous region to obtain the \( D^0 \) production point. We refit the \( \pi^+_s \) track with a requirement that the trajectory intersect the \( D^0 \) production point, and require that the confidence level of the refit exceed 0.01%.

We reconstruct the energy released in the \( D^{*+} \rightarrow \pi^+_s D^0 \) decay as \( Q \equiv M^* - M - m_\pi \), where \( M^* \) is the reconstructed mass of the \( \pi^+_s K^+\pi^- \) system, \( M \) is the reconstructed mass of the \( K^+\pi^- \) system, and \( m_\pi \) is the charged pion mass. The addition of the \( D^0 \) production point to the \( \pi^+_s \) trajectory, as well as track-fitting improvements, yields the resolution \( \sigma_Q = 190 \pm 6 \) keV [21]. The use of helium-propane, in addition to improvements in track-fitting, yields the resolution \( \sigma_M = 6.4 \pm 0.1 \) MeV [21]. These resolutions are better than those of earlier studies [22][23], and permit improved suppression of background processes.

Candidates must pass two kinematic requirements designed to suppress backgrounds from \( D^0 \rightarrow \pi^+\pi^- \), \( D^0 \rightarrow K^+K^- \), \( D^0 \rightarrow \) multibody, and from cross-feed between WS and RS decays. We evaluate the mass \( M \) for \( D^0 \rightarrow K^+\pi^- \) candidates under the three alternate hypotheses \( D^0 \rightarrow \pi^+\pi^- \), \( D^0 \rightarrow K^+K^- \), and \( D^0 \rightarrow \pi^+K^- \). If any one of the three masses falls within \( 4 \sigma \) [20] of the nominal \( D^0 \) mass [11], the \( D^0 \rightarrow K^+\pi^- \) candidate is rejected. A conjugate requirement is made for the RS decays. The second kinematic requirement rejects asymmetric \( D^0 \) decays where the pion candidate has low momentum with the requirement that \( \cos \theta^* > -0.8 \) where \( \theta^* \) is the angle of the pion candidate in the \( D^0 \) rest frame with respect to the \( D^0 \) boost. The relative efficiency for the CFD to pass the two kinematic requirements is 84% and 91%, respectively.

We require the specific ionization \( (dE/dx) \) measured in the drift chamber for each charged track agree to within \( 3\sigma \) of the expected value; this is a loose criterion, and we vary the \( dE/dx \) requirement for systematic studies.

We reconstruct \( t \) using only the vertical \((y)\) component of the flight distance of the \( D^0 \) candidate. This reconstruction is effective because the vertical extent of the \( e^+e^- \) luminous region has \( \sigma_y = 7 \mu m \) [27]. The resolution on the \( D^0 \) decay point \((x^e, y^e, z^e)\) is typically 40 \( \mu m \) in each dimension. We measure the centroid of the luminous region \((x_b, y_b, z_b)\) with hadronic events in blocks of data with integrated luminosities of several pb\(^{-1}\), and an error on \( y_b \) that is less than 5 \( \mu m \). We reconstruct \( t \) as \( t = M/p_y \times (y_b - y_0)/(c\tau_{D^0}) \) where \( p_y \) is the \( y \) component of the total momentum of the \( K^+\pi^- \) system. The error in \( t \), \( \sigma_t \), is typically 0.4 (in \( D^0 \) lifetimes), although when the \( D^0 \) direction is near the horizontal plane, \( \sigma_t \) can be

The data were taken with the CLEO II multipurpose detector [17], upgraded in 1995 when a silicon vertex detector (SVX) was installed [18] and the drift chamber gas was changed from argon-ethane to helium-propane. The upgraded configuration is named CLEO II.V.
large; we reject 12% of the CFD by requiring $\sigma_t < 3/2$. Studies of the plentiful RS sample allow us to determine our resolution function [19], and show that biases are negligible for the WS results.

Our signal for the WS process $D^0 \rightarrow K^+\pi^-$ is shown in Fig. 1. We determine the background levels by performing a fit to the two-dimensional region of $0 < Q < 10$ MeV versus $1.76 < M < 1.97$ GeV that has an area 135 times larger than our signal region. Event samples generated by the Monte Carlo (MC) method and fully simulated in our detector [28] corresponding to 90 fb$^{-1}$ of integrated luminosity are used to estimate the background shapes in the $Q-M$ plane. The normalizations of the background components with distinct distributions in the $Q-M$ plane are allowed to vary in the fit to the data. The background distributions and normalizations in the $D^0$ and $\bar{D}^0$ samples are consistent and constrained to be identical. We describe the signal shape in the $Q-M$ plane with the RS data that is within 4$\sigma$ [26] of the nominal CFD value. The results of the fit are displayed in Fig. 1 and summarized in Table I.

TABLE I. Fitted event yields in a region of 2$\sigma$ [26] centered on the CFD $Q$ and $M$ values. The total number of candidates is 82. The estimated background is $37.2 \pm 1.8$. The bottom row describes the normalization sample.

| Component | Yield       |
|-----------|-------------|
| $D^0 \rightarrow K^+\pi^-$ (WS) | $44.8^{+9.7}_{-8.7}$ |
| random $\pi^+_s$, $\bar{D}^0 \rightarrow K^+\pi^-$ | $16.0 \pm 1.6$ |
| $e^+e^- \rightarrow e\bar{e}$ bkgd. | $17.6 \pm 0.8$ |
| $e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$ bkgd. | $3.6 \pm 0.4$ |
| $\bar{D}^0 \rightarrow K^+\pi^-$ (RS) | $13527 \pm 116$ |

The proper decay time distribution is shown in Fig. 2 for WS candidates that are within 2$\sigma$ [26] of the CFD signal value in the $Q-M$ plane. We performed maximum-likelihood fits in bins that are 1/20 of the $D^0$ lifetime. The background levels are constrained to the levels determined in the fit to the $Q-M$ plane. We use the resolution function in $t$ to describe the $e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$ backgrounds, and an exponential, folded with the resolution function, to describe the $e^+e^- \rightarrow e\bar{e}$ backgrounds. The distribution in $t$ of the RS data is used to represent the random $\pi^+_s$, $\bar{D}^0 \rightarrow K^+\pi^-$ background [24]. The WS signal is described by Eqn. 1, either modified to describe all three forms of CP violation (Fit A), without modification to describe mixing alone (Fit B), or with the mixing parameters constrained to be zero (Fit C). The effect of our resolution is always included.

The reliability of our fit depends upon the simulation of the decay time distribution of the background in the signal region. A comparison of the proper time for the data and MC samples for several sideband regions yields a $\chi^2 = 4.4$ for 8 degrees of freedom and supports the accuracy of the background simulation [21].

Our principal results concerning mixing are determined from Fit A. The one-dimensional, 95% confidence intervals for $x', y'$ and $R_D$, determined by an increase in negative log likelihood ($-\ln L$) of 1.92, are given in Table II. The fits are consistent with an absence of both mixing and CP violation. The small change in likelihood when mixing and CP violation are allowed could be a statistical fluctuation, or an emerging signal.
induced asymmetries in CFD limits the relative systematic error on $A \equiv A_D$ of earlier studies \cite{23,24}, is uniform as a function of $x^\prime$. We also include the statistical uncertainty on the MC determination of the proper time for the $e^+e^\rightarrow q\bar{q}$ backgrounds \cite{23}, is uniform as a function of $D^0$ decay time. Many classes of systematic error cancel due to the similarity of the events that comprise the numerators and denominators of $R$ and $A$. The dominant systematic errors stem from potential misunderstanding of the shapes and acceptances for our backgrounds. We vary the selection criteria to estimate these systematic errors from the data. The level and composition of the backgrounds are sensitive to the requirements on momentum magnitude and direction, and $dE/dx$ of the charged particle trajectories and contribute $\pm 0.018\%$, $\pm 0.018\%$ and $\pm 0.026\%$, respectively, to the systematic error in $R_D$. We also include the statistical uncertainty on the MC determination of the proper time for the $e^+e^\rightarrow q\bar{q}$ backgrounds \cite{23} in the systematic error. We assess a total systematic error on $R_D$, $x^\prime$ and $y^\prime$ of $\pm 0.040\%$, $\pm 0.2\%$ and $\pm 0.3\%$, respectively. A study of detector-induced and event-reconstruction-induced asymmetries in CFD limits the relative systematic error on $A$ to $< 1\%$.

We make contours in the two-dimensional plane of $y^\prime$ versus $x^\prime$ that contain the true value of $x^\prime$ and $y^\prime$ with 95\% confidence, for Fit A and Fit B. The contour is where $-\ln L$ increases from the best fit value by 3.0. All fit variables other than $x^\prime$ and $y^\prime$ are allowed to vary to best fit values at each point on the contour. The interior of the contour is the tightly cross-hatched region near the origin of Fig. 3. The limits are not substantially degraded when the most general CP violation is allowed, in part because our acceptance, unlike that of earlier studies \cite{23,24}, is uniform as a function of $D^0$ decay time.

Many classes of systematic error cancel due to the similarity of the events that comprise the numerators and denominators of $R$ and $A$. The dominant systematic errors stem from potential misunderstanding of the shapes and acceptances for our backgrounds. We vary the selection criteria to estimate these systematic errors from the data. The level and composition of the backgrounds are sensitive to the requirements on momentum magnitude and direction, and $dE/dx$ of the charged particle trajectories and contribute $\pm 0.018\%$, $\pm 0.018\%$ and $\pm 0.026\%$, respectively, to the systematic error in $R_D$. We also include the statistical uncertainty on the MC determination of the proper time for the $e^+e^\rightarrow q\bar{q}$ backgrounds \cite{23} in the systematic error. We assess a total systematic error on $R_D$, $x^\prime$ and $y^\prime$ of $\pm 0.040\%$, $\pm 0.2\%$ and $\pm 0.3\%$, respectively. A study of detector-induced and event-reconstruction-induced asymmetries in CFD limits the relative systematic error on $A$ to $< 1\%$.
If we assume that $\delta$ is small, then $x' \approx x$ and we can indicate the impact of our work in limiting predictions of $D^0-\overline{D}^0$ mixing from extensions to the Standard Model. The 95% C.L. interval for $x$ from Fit A has some inconsistency with eighteen of the predictions tabulated in Ref. [7]. A new model [32] invokes SUSY to account for the value of $\epsilon'/\epsilon$ [33] and estimates $D^0-\overline{D}^0$ mixing with $x = 0.6\%$, somewhat below our sensitivity. Another analysis [34] notes that SUSY could induce $A_D \sim 30\%$, just below our sensitivity.

In conclusion, our data are consistent with no $D^0-\overline{D}^0$ mixing. We limit the mixing amplitudes, $x'$ and $y'$, to be $(1/2)x'^2 < 0.041\%$ and $-5.8\% < y' < 1.0\%$ at the 95% C.L., without assumptions concerning CP violating parameters. We have observed $44.8^{+9.7}_{-8.7}$ candidates for the decay $D^0 \rightarrow K^+\pi^-$ corresponding to $R = (0.332^{+0.063}_{-0.065} \pm 0.040)\%$. We observe no evidence for CP violation. These results are a substantial advance in sensitivity to the phenomena that contribute to the wrong-sign process $D^0 \rightarrow K^+\pi^-$. 

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[29] The mean decay time of the $e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$ and $c\bar{c}$ background is determined from the MC sample to be 2.6 ± 6.6 fs and 408.6 ± 27.3 fs, respectively. From the RS data sample, we determine $\tau_{D^0} = 400.7 ± 3.9$ fs without assessment of the systematic uncertainty. This result does not supersede [19]. From the MC sample, we determine, $\tau_{D^0} = 416.0 ± 1.6$ fs, consistent with the input value of 415 fs.

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FIG. 1. Signal for the WS process $D^0 \rightarrow K^+\pi^-$. The data are the full circles with error bars, the projection of the fit for the signal is cross-hatched, and the projections of the fit for the backgrounds from charm and light quark production are single-hatched. For part a), $M$ is within $2\sigma$ [26] of the CFD value, and for b), $Q$ is within $2\sigma$ [26] of the CFD value.
FIG. 2. Distribution in proper decay time for $D^0 \rightarrow K^+\pi^-$ candidates, and the best fit of type A, described in Table II. The data are shown as the full circles with error bars. The cross-hatched region is the sum of the fit contribution from the direct $D^0 \rightarrow K^+\pi^-$ decay and the fit contribution from the destructive interference with mixing, which is shown in the region with single, vertical hatching. The fit contributions from backgrounds charm and light quark production are shown in single, diagonal hatching.
FIG. 3. Allowed regions, at 95% C.L., in the $y'$ vs. $x'$ plane. The entire kidney shaped region, filled with tight cross-hatching, is allowed under Fit A of Table II, while Fit B, in which CP violation is assumed, allows the smaller region, which is overlayed and filled with looser cross-hatching. The allowed regions from studies comparable to Fit A, using $D^0 \rightarrow K^+\pi^-$ [30], for which we assume $\delta = 0$, and $D^0 \rightarrow K^+\ell^-(\bar{\nu}_\ell)$ [31], are shown as single-hatched regions. The Bayesian approach is used [11].
$D^{*+} \rightarrow D^0 \pi^+, D^0 \rightarrow K^+ \pi^-$

(a) (b)

CLEO II.V
(9.0 fb$^{-1}$)

Q (MeV) $M (\text{GeV/c}^2)$

Events / 400keV

Events / 6.5MeV
$D^{*+} \rightarrow D^0 \pi^+, \quad D^0 \rightarrow K^+ \pi^-$

(a)

Events / 400keV

$Q$ (MeV)

(b)

Events / 6.5MeV

$M$ (GeV/c$^2$)

CLEO II.V

(9.0 fb$^{-1}$)
CLEO II.V

\[ D^{*+} \rightarrow D^0 \pi^+, \ D^0 \rightarrow K^+ \pi^- \]

- **Events** / **$D^0$ Lifetimes**
- **$D^0 \rightarrow K^+ \pi^-$**
- **$D^0 \rightarrow \bar{D}^0 \rightarrow K^+ \pi^-$**
- **Charm**
- **uds**
- **Interference**