Search for $D^0\overline{D}^0$ Mixing in Semileptonic Decay Modes

E. M. Aitala,[8] S. Amato,[1] J. C. Anjos,[1] J. A. Appel,[5] D. Ashery,[14] S. Banerjee,[5] I. Bediaga,[1] G. Blaylock,[2] S. B. Bracker,[15] P. R. Burchat,[13] R. A. Burnstein,[6] T. Carter,[5] H. S. Carvalho,[1] N. K. Copty,[12] I. Costa,[1] L. M. Cremaldi,[8] C. Darling,[18] K. Denisenko,[5] A. Fernandez,[11] P. Gagnon,[2] S. Gerzon,[14] C. Gobel,[1] K. Gounder,[8] A. M. Halling,[5] G. Herrera,[4] G. Hurvits,[14] C. James,[5] P. A. Kasper,[6] S. Kwan,[5] D. C. Langs,[10] J. Leslie,[2] B. Lundberg,[5] S. MayTal-Beck,[14] B. Meadows,[3] J. R. T. de Mello Neto,[1] R. H. Milburn,[16] J. M. de Miranda,[1] A. Napier,[16] A. Nguyen,[7] A. B. d'Oliveira,[3,11] K. O'Shaughnessy,[2] K. C. Peng,[6] L. P. Perera,[3] M. V. Purohit,[12] B. Quinn,[8] S. Radeztsky,[17] A. Rafatian,[8] N. W. Reay,[7] J. J. Reidy,[8] A. C. dos Reis,[1] H. A. Rubin,[6] A. K. S. Santha,[3] A. F. S. Santoro,[1] A. J. Schwartz,[10] M. Sheaff,[17] R. A. Sidwell,[7] A. J. Slaughter,[18] M. D. Sokoloff,[3] N. R. Stanton,[7] K. Stenson,[17] K. Sugano,[2] D. J. Summers,[8] S. Takach,[18] K. Thorne,[5] A. K. Tripathi,[9] S. Watanabe,[17] R. Weiss-Babai,[14] J. Wiener,[10] N. Witchey,[7] E. Wolin,[18] D. Yi,[8] S. Yoshida,[7] R. Zaliznyak,[13] and C. Zhang[7]

(Fermilab E791 Collaboration)

[1]*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[2]*University of California, Santa Cruz, California 95064*
[3]*University of Cincinnati, Cincinnati, Ohio 45221*
[4]*CINVESTAV, Mexico*
[5]*Fermilab, Batavia, Illinois 60510*
[6]*Illinois Institute of Technology, Chicago, Illinois 60616*
[7]*Kansas State University, Manhattan, Kansas 66506*
[8]*University of Mississippi, University, Mississippi 38677*
[9]*The Ohio State University, Columbus, Ohio 43210*
[10]*Princeton University, Princeton, New Jersey 08544*
[11]*Universidad Autonoma de Puebla, Mexico*
[12]*University of South Carolina, Columbia, South Carolina 29208*
[13]*Stanford University, Stanford, California 94305*
[14]*Tel Aviv University, Tel Aviv, Israel*
[15]*317 Belsize Drive, Toronto, Canada*
[16]*Tufts University, Medford, Massachusetts 02155*
[17]*University of Wisconsin, Madison, Wisconsin 53706*
[18]*Yale University, New Haven, Connecticut 06511*
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We report the result of a search for $D^0\overline{D}^0$ mixing in the data from hadroproduction experiment E791 at Fermilab. We use the charge of the pion from the strong decay $D^{*+} \rightarrow D^0\pi^+$ (and charge conjugate) to identify the charm quantum number of the neutral D at production, and the charge of the lepton and the kaon in the semileptonic decays $D^0 \rightarrow Ke\nu$ and $K\mu\nu$ to identify the charm at the time of decay. No evidence of mixing is seen. We set a 90% confidence level upper limit on mixing of $r < 0.50\%$, where $r = \Gamma(D^0 \rightarrow \overline{D}^0 \rightarrow K^+l^-\overline{\nu}_l)/\Gamma(D^0 \rightarrow K^-l^+\nu_l)$. [S0031-9007(96)01122-2]

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The predicted rate of $D^0\overline{D}^0$ mixing in the standard model [1] is several orders of magnitude below the sensitivity of current experiments. However, several theoretical extensions to the Standard Model (e.g., theories with a heavy fourth-generation quark with $-1/3$ charge, scalar leptoquark bosons, or flavor-changing neutral Higgs bosons) predict $D^0\overline{D}^0$ mixing rates high enough to be measurable by existing experiments, making it interesting to search for this process [2]. The mixing rate is parametrized as $r = \Gamma(D^0 \rightarrow \overline{D}^0 \rightarrow \overline{f})/\Gamma(D^0 \rightarrow f)$, where f is the final decay state used to identify the charm quantum number of the neutral D at the time of decay. We report here a limit on r using semileptonic decays in the data from Fermilab experiment E791.

Many experiments have used hadronic D^0 decays to search for mixing. For example, Fermilab experiment E691 studied $D^0\overline{D}^0$ mixing by looking for the decay chain $D^{*+} \rightarrow \pi^+D^0$, followed by $D^0 \rightarrow \overline{D}^0 \rightarrow K^+\pi^-$ or $K^+\pi^-\pi^+\pi^-$ [3]. A wrong-sign charged K from the neutral D decay (e.g., $D^0 \rightarrow \overline{D}^0 \rightarrow K^+\pi^-$) can be a signature of mixing. However, a wrong-sign K can also come from doubly-Cabibbo-suppressed (DCS) decays in which a D^0 decays directly into the wrong-sign kaon (e.g., $D^0 \rightarrow K^+\pi^-$). Moreover, the DCS amplitude can interfere with the mixing amplitude, reducing the

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sensitivity to mixing [4] even though the mixing, DCS, and interference terms in principle can be separated statistically using decay-time information. E691 reported a 90% confidence level (C.L.) limit on r of 0.37% assuming no interference between DCS and mixing amplitudes. For worst-case interference, their limit is 1.9% in the $K\pi$ mode and 0.7% in the $K\pi\pi\pi$ mode. E791 has used the $K\pi$ and $K\pi\pi\pi$ modes to study $D^0\overline{D}^0$ mixing under a variety of assumptions on interference and CP violation, including the most general, with sensitivities comparable to those reported in this paper [5]. CLEO II has observed a wrong-sign signal in the mode $D \rightarrow K\pi$, and measures the ratio of the wrong-sign to right-sign decays to be $(0.77 \pm 0.25 \pm 0.25)\%$ [6]. However, an unambiguous mixing signal cannot be established from the CLEO result because of the lack of decay-time information.

An alternate way to make a mixing measurement is to use semileptonic decays to tag the charm of the neutral D at the time of decay. There is no DCS amplitude in these decays, eliminating the complications of interference. Fermilab experiment E615 searched for mixing by looking for pairs of muons with the same charge in a single event [7]. Same-sign muons could come from the semileptonic decays of a D meson (D^0 or D^+) and a $\overline{D}^0$ that has oscillated into a D^0. E615 obtained a 90% C.L. upper limit on r of 0.56% using specific assumptions for charm production cross sections and D branching fractions.

In this Letter we report the result of a mixing search using reconstructed semileptonic decays of the D^0 in the data sample of hadroproduction experiment E791 at Fermilab. We observe a large signal for the right-sign (RS) decay chain $D^{*+} \rightarrow \pi^+ D^0 \rightarrow \pi^+(K^- l^+ \nu_l)$, where l is an e or a μ, in which the charge of the π is the same as the charge of the lepton from the neutral D decay (charge conjugate modes are implied throughout this paper). We search for mixing in wrong-sign (WS) D^{*+} decay candidates in which the charge of the π is opposite that of the charged lepton. These candidates could correspond to the decay chain $D^{*+} \rightarrow \pi^+ D^0 \rightarrow \pi^+ \overline{D}^0 \rightarrow \pi^+(K^+ l^- \overline{\nu}_l)$. We look for two signatures of mixing in the WS sample—a peak in Q value $[Q \equiv M(Kl\nu\pi) - M(D^0) - M(\pi)]$ at about 5.8 MeV and the characteristic distribution in proper decay time t. Assuming mixing is small, the time evolution of the mixed D's is given by $dN/dt \propto t^2 e^{-\Gamma t}$, where Γ is the D^0 decay rate.

The E791 experiment [8] recorded 2×10^{10} events from 500 GeV$/c$ π^- interactions in five thin targets (one platinum, four diamond) separated by gaps of 1.34 to 1.39 cm. Precision vertex and tracking information was provided by 23 silicon microstrip detectors and 35 drift chamber planes. Momentum was measured using two dipole magnets. Two segmented threshold Cerenkov counters provided $\pi/K/p$ separation in the 6–60 GeV$/c$ momentum range [9].

A segmented lead and liquid-scintillator calorimeter is used to identify electrons from their energy deposition and transverse shower shape. For the cuts used in this analysis, the typical probabilities that a π or a K is misidentified as an electron are 1.6% and 0.8%, respectively. All misidentification probabilities are obtained from the large E791 sample of $D^+ \rightarrow K^-\pi^+\pi^+$ decays, in which the kaons and pions can be identified by their charge alone. Muon identification is provided by two planes of scintillation counters located behind shower-absorbing calorimeters and steel shielding with a total thickness equivalent to 15 proton interaction lengths. All muon candidates are required to have momentum greater that 10 GeV$/c$ to reduce background from decays in flight, and to leave a signal in the expected scintillation counters, allowing for multiple scattering. For the cuts used in this analysis, the typical probabilities that a π or a K is misidentified as a μ are 3.6% and 4.6%, respectively.

To reduce background, a candidate D^0 decay vertex is required to be separated from the production vertex by at least $8\sigma_z$, where σ_z is the error on the separation between the two vertices (average value $\sim$580 μm). The decay vertex is required to be at least 3σ away from the edge of the nearest solid material, where σ is the error on the separation. The minimum parent mass, defined as $M_{\rm min} = p_T + \sqrt{p_T^2 + M_{Kl}^2}$, where p_T is the transverse momentum of the Kl with respect to the direction of flight of the D^0 and M_{Kl} is the invariant mass of the Kl candidates [10], is required to be in the range 1.6 to 2.1 GeV$/c^2$. The $M_{\rm min}$ distribution for Monte Carlo signal events has a cusp at the D^0 mass and falls rapidly at lower values of $M_{\rm min}$, whereas background rises as $M_{\rm min}$ decreases. We also require the invariant mass of the Kl candidate M_{Kl} to be in the range 1.15 to 1.80 GeV$/c^2$. The lower cut on M_{Kl} reduces noncharm background and the upper cut on M_{Kl} removes feedthrough from $D^0 \rightarrow K\pi$ decays into the RS sample, in which the π is misidentified as a lepton. We require the transverse momentum of the lepton with respect to the direction of flight of the candidate D^0 to be greater than 0.2 GeV$/c$ and that of the hadron to be greater than 0.4 GeV$/c$, since charm decay products tend to have larger such transverse momenta than background tracks. The π^+ track from the D^{*+} is required to be consistent with belonging to the primary vertex and to have momentum greater than 2 GeV$/c$.

To eliminate feedthrough of the $K\pi$ mode into the wrong-sign sample through double misidentification of the hadrons (the K misidentified as a lepton and the π misidentified as a K), we require $|M_{\pi K} - M_{D^0}| > 30$ MeV$/c^2$ (typical σ of the D^0 mass peak in the $K\pi$ mode is 15 MeV$/c^2$), where $M_{\pi K}$ is the invariant mass of the Kl candidate when the K is assigned the π mass and the l is assigned the K mass.

Additional cuts are applied to $K\mu\nu$ candidates because kaons and pions are more likely to be misidentified as muons than as electrons due to punchthrough and decays in flight. If the muon track is positively identified as a kaon in the Cherenkov detectors, the decay vertex is rejected. Feedthrough from the mode $D^0 \to K^-K^+$ is eliminated by the requirement $|M_{KK} - M_{D^0}| > 30$ MeV$/c^2$, where M_{KK} is the invariant mass of the Kl candidate when both tracks are assigned the K mass. We also demand that there be one and only one D^* candidate (Q value < 80 MeV$/c^2$) in each event in the $K\mu\nu$ sample. An event is rejected if more than one D^* candidate is found.

Since there is an undetected neutrino in a semileptonic decay, the D^0 momentum cannot be reconstructed directly. However, using the measured positions of the primary and secondary vertices, the measured K and l momenta, and assuming the parent particle mass is that of a D^0, one can solve for the neutrino momentum up to a twofold ambiguity. The solution resulting in higher D^0 momentum is used for all events. Monte Carlo (MC) studies indicate that it gives a better estimate of the true momentum for the selected sample. From MC, we determine that the root mean square (rms) deviation between the calculated and true D^0 momenta is about 15%. This also causes smearing in the calculated proper decay time. The effect of this smearing is discussed below. Having obtained the D^0 momentum, we calculate the invariant mass of the D^{*+} candidate and the proper decay time of the D^0 candidate. The final Q-value distributions for $Ke\nu$ and $K\mu\nu$ candidates are shown in Fig. 1.

To search for mixing signals, separate unbinned maximum likelihood fits are performed on the $Ke\nu$ and $K\mu\nu$ samples using the Q value and proper decay time t for each event. The expected Q-value signal shape in WS data is obtained directly from fits to the large, kinematically identical RS signal. It is parametrized by asymmetric Gaussian distributions, broader on the high Q side, with widths σ decreasing with longer proper decay time t, $\sigma(t) = \sqrt{(\sigma_0)^2 + (C/t)^2}$. This t dependence arises because the D^0 direction is measured better for decays at greater distances. The Q-value distribution of the background under the D^* peak is described by the spectrum which results from combining a D^0 candidate from one event with pions from other events to form random D^0-π mass combinations (dotted histograms in Fig. 1).

When smearing is neglected, the measured proper decay-time spectrum of a mixing signal is proportional to $t^2\epsilon(t)e^{-\Gamma t}$, where $\epsilon(t)$ is the t-dependent detector efficiency. This spectrum is obtained by multiplying the measured distribution [crosses in Figs. 2(a) and 2(b)] of background-subtracted RS data [$\propto \epsilon(t)e^{-\Gamma t}$] by the mean value of t^2 in each bin. The t distribution of the non-D^* background is obtained from data events in the Q-value sideband with $25 < Q < 60$ MeV$/c^2$. Distributions of t in the three Q-value sidebands $20 < Q < 30$, $40 < Q < 50$, and $60 < Q < 70$ MeV$/c^2$ are identical within statistical errors. Therefore the background decay-time distribution is constant across the Q-value spectrum, as expected if most background is due to real D^0's combined with random pions. Sideband t dependence thus can be and is used to model the background in the signal region.

From the fits, we find $N_{\rm RS} = 1237 \pm 45$ RS events and $N_{\rm mix} = 4.4^{+11.8}_{-10.5}$ WS mixed events in the $Ke\nu$ samples, and $N_{\rm RS} = 1267 \pm 44$ RS events and $N_{\rm mix} =$

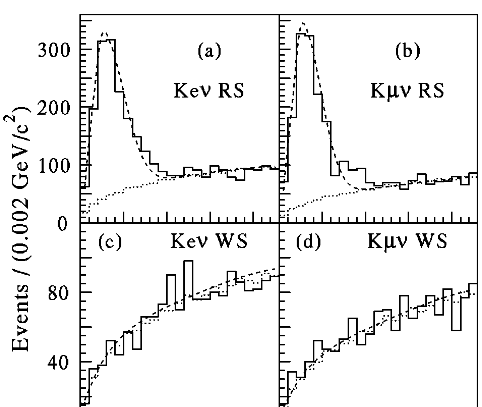

FIG. 1. The Q-value distributions for (a) $Ke\nu$ RS, (b) $K\mu\nu$ RS, (c) $Ke\nu$ WS, and (d) $K\mu\nu$ WS candidates. The solid line histograms show the data Q-value distributions, the dashed lines are the projections of the fit in Q value, and the dotted lines show the Q-value distribution obtained from combining a D^0 from one event and π from another, normalized to the number of events with $Q > 0.025$ GeV$/c^2$ in the respective histograms.

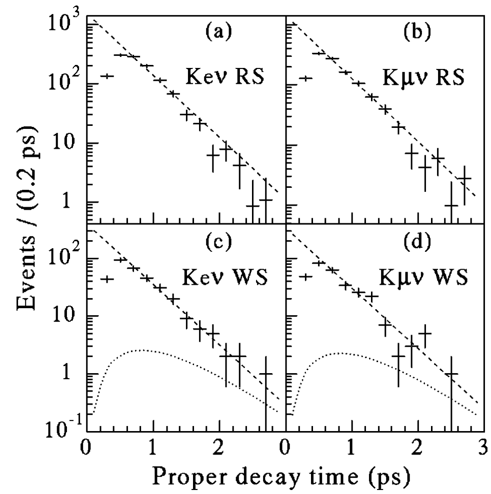

FIG. 2. Dependence of RS and WS signals on proper decay time t. Crosses represent the measured decay-time distributions for (a) $Ke\nu$ and (b) $K\mu\nu$ background-subtracted RS signals, and for (c) $Ke\nu$ and (d) $K\mu\nu$ WS signal region ($Q < 0.015$ GeV$/c^2$). The dashed line in all histograms is the expected D^0 decay-time distribution uncorrected for detector acceptance, normalized to the number of events with $t > 0.7$ ps (where acceptance is uniform). The dotted lines in (c) and (d) represent the expected decay-time distributions uncorrected for detector acceptance for $Ke\nu$ and $K\mu\nu$ mixing signals, corresponding to our 90% C.L. limit in each mode.

$1.8^{+12.1}_{-11.0}$ WS mixed events in the $K\mu\nu$ samples. There is no indication of a mixing signal.

The mixing rate is $r = (N_{\rm mix}/N_{\rm RS})\alpha$, where α accounts for the dependence of detector acceptance on t and the different t dependences of mixed and unmixed decays. Since vertex reconstruction efficiency is low at small t, the detector is more efficient at finding the longer-lived mixed decays. Specifically $\alpha \equiv [\Gamma \int_0^\infty \epsilon(t) e^{-\Gamma t} dt]/[\frac{1}{2}\Gamma^3 \int_0^\infty \epsilon(t) t^2 e^{-\Gamma t} dt]$. It is measured from the background-subtracted RS decay-time distribution $[\propto \epsilon(t) e^{-\Gamma t}]$. Values of α are 0.44 ± 0.02 for the $Ke\nu$ mode and 0.46 ± 0.02 for the $K\mu\nu$ mode.

We measure the mixing rate to be $r = (0.16^{+0.42}_{-0.37})\%$ for the $Ke\nu$ mode and $r = (0.06^{+0.44}_{-0.40})\%$ for the $K\mu\nu$ mode. Taking the weighted average of these two statistically independent results, we get an average mixing rate of $r = (0.11^{+0.30}_{-0.27})\%$. This gives an upper limit for $D^0\overline{D}{}^0$ mixing of $r < 0.50\%$ at the 90% confidence level (corresponding to the point where the log-likelihood changes by 0.82) [11].

Since right- and wrong-sign data samples are selected using identical criteria, most systematic uncertainties cancel in the mixing rate. Two possibly significant sources of systematic error, the time resolution for a mixing signal and feedthrough of hadronic decays, remain.

The decay-time distribution used in the fit for mixed events is proportional to $\epsilon(t) t^2 e^{-\Gamma t}$, which is valid only if the decay times are measured exactly. Because of finite resolution of the detector and the choice of one of the two neutrino momentum solutions, the measured mixed decay-time distribution differs slightly from the distribution used in the fit. The rms deviation of the measured t from the true one is about 15%. MC studies indicate that the effect of this smearing in proper decay time on the final result is less than 10% of the statistical error and hence is ignored.

Feedthrough of hadronic decays into the semileptonic sample is expected to come mainly from modes such as $D^0 \rightarrow K^-\pi^+\pi^0$ in which an undetected neutral hadron approximates the kinematics of a missing neutrino, and a hadron is misidentified as a lepton. Misidentified hadronic decays have two possible effects: (1) Feedthrough into the WS signal would give a false mixing signal; (2) feedthrough into the RS signal would inflate the denominator of the mixing rate, thus overestimating our sensitivity to mixing. WS feedthrough requires K-π misidentification as well as hadron-lepton misidentification. Another source of feedthrough into the WS sample is doubly misidentified semileptonic decays (in which the hadron is misidentified as a lepton and the lepton is misidentified as a kaon). We see no WS signal and make no correction for this effect. RS feedthrough has been modeled by Monte Carlo simulation and shown to be about 3% of the RS signal. No correction is made for this effect.

To check our fitting procedure and to look for possible systematic effects in our sensitivity, we added fixed numbers M ($M = 10$, 20, 30, 40; the typical fit error on our $N_{\rm mix}$ is 10) of simulated mixed events to the wrong-sign data sample and refit. These fits found a mixing rate systematically (10–15)% higher than the correct value, mainly due to an overestimate of the correction factor α, which is a result of our choice of the neutrino momentum resulting in higher D^0 momentum. We conservatively choose not to correct for this systematic overestimate of mixing rate.

In summary, we have searched for $D^0\overline{D}{}^0$ mixing using $D^{*+} \rightarrow \pi^+ D^0 \rightarrow \pi^+ \overline{D}{}^0 \rightarrow \pi^+(K^+ l^- \overline{\nu}_l)$ candidates together with decay-time information. We obtain a 90% C.L. upper limit of 0.50% on the mixing rate. This is the best model-independent limit on $D^0\overline{D}{}^0$ mixing to date.

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