CLNS 01/1763
CLEO 01-21

Lifetime Differences, Direct CP Violation and Partial Widths in D^0 Meson Decays to K^+K^- and $\pi^+\pi^-$

(CLEO Collaboration)

(6 November 2001)

Abstract

We describe several measurements using the decays $D^0 \to K^+K^-$ and $\pi^+\pi^-$. We find the ratio of partial widths, $\Gamma\left(D^0 \to K^+K^-\right)/\Gamma\left(D^0 \to \pi^+\pi^-\right)$, to be $2.96 \pm 0.16 \pm 0.15$, where the first error is statistical and the second is systematic. We observe no evidence for direct CP violation, obtaining $A_{CP}(KK) = (0.0 \pm 2.2 \pm 0.8)\%$ and $A_{CP}(\pi\pi) = (1.9 \pm 3.2 \pm 0.8)\%$. In the limit of no CP violation we measure the mixing parameter $y_{CP} = -0.012 \pm 0.025 \pm 0.014$ by measuring the lifetime difference between $D^0 \to K^+K^-$ or $\pi^+\pi^-$ and the CP neutral state, $D^0 \to K^-\pi^+$. We see no evidence for mixing.

S. E. Csorna,[1] I. Danko,[1] K. W. McLean,[1] Z. Xu,[1] R. Godang,[2] G. Bonvicini,[3] D. Cinabro,[3] M. Dubrovin,[3] S. McGee,[3] A. Bornheim,[4] E. Lipeles,[4] S. P. Pappas,[4] A. Shapiro,[4] W. M. Sun,[4] A. J. Weinstein,[4] D. E. Jaffe,[5] R. Mahapatra,[5] G. Masek,[5] H. P. Paar,[5] D. M. Asner,[6] T. S. Hill,[6] R. J. Morrison,[6] H. N. Nelson,[6] R. A. Briere,[7] G. P. Chen,[7] T. Ferguson,[7] H. Vogel,[7] J. P. Alexander,[8] C. Bebek,[8] K. Berkelman,[8] F. Blanc,[8] V. Boisvert,[8] D. G. Cassel,[8] P. S. Drell,[8] J. E. Duboscq,[8] K. M. Ecklund,[8] R. Ehrlich,[8] L. Gibbons,[8] B. Gittelman,[8] S. W. Gray,[8] D. L. Hartill,[8] B. K. Heltsley,[8] L. Hsu,[8] C. D. Jones,[8] J. Kandaswamy,[8] D. L. Kreinick,[8] M. Lohner,[8] A. Magerkurth,[8] H. Mahlke-Krüger,[8] T. O. Meyer,[8] N. B. Mistry,[8] E. Nordberg,[8] M. Palmer,[8] J. R. Patterson,[8] D. Peterson,[8] J. Pivarski,[8] D. Riley,[8] H. Schwarthoff,[8] J. G. Thayer,[8] D. Urner,[8] B. Valant-Spaight,[8] G. Viehhauser,[8] A. Warburton,[8] M. Weinberger,[8] S. B. Athar,[9] P. Avery,[9] C. Prescott,[9] H. Stoeck,[9] J. Yelton,[9] G. Brandenburg,[10] A. Ershov,[10] D. Y.-J. Kim,[10] R. Wilson,[10] K. Benslama,[11] B. I. Eisenstein,[11] J. Ernst,[11] G. E. Gladding,[11] G. D. Gollin,[11] R. M. Hans,[11] I. Karliner,[11] N. Lowrey,[11] M. A. Marsh,[11] C. Plager,[11] C. Sedlack,[11] M. Selen,[11] J. J. Thaler,[11] J. Williams,[11] K. W. Edwards,[12] A. J. Sadoff,[13] R. Ammar,[14] A. Bean,[14] D. Besson,[14] X. Zhao,[14] S. Anderson,[15] V. V. Frolov,[15] Y. Kubota,[15] S. J. Lee,[15] R. Poling,[15] A. Smith,[15] C. J. Stepaniak,[15] J. Urheim,[15] S. Ahmed,[16] M. S. Alam,[16] L. Jian,[16] L. Ling,[16] M. Saleem,[16] S. Timm,[16] F. Wappler,[16] A. Anastassov,[17] E. Eckhart,[17] K. K. Gan,[17] C. Gwon,[17] T. Hart,[17] K. Honscheid,[17] D. Hufnagel,[17] H. Kagan,[17] R. Kass,[17] T. K. Pedlar,[17] J. B. Thayer,[17] E. von Toerne,[17] M. M. Zoeller,[17] S. J. Richichi,[18] H. Severini,[18] P. Skubic,[18] S.A. Dytman,[19] V. Savinov,[19] S. Chen,[20] J. W. Hinson,[20] J. Lee,[20] D. H. Miller,[20] V. Pavlunin,[20] E. I. Shibata,[20] I. P. J. Shipsey,[20] D. Cronin-Hennessy,[21] A.L. Lyon,[21] W. Park,[21] E. H. Thorndike,[21] T. E. Coan,[22] Y. S. Gao,[22] F. Liu,[22] Y. Maravin,[22] I. Narsky,[22] R. Stroynowski,[22] J. Ye,[22] M. Artuso,[23] C. Boulahouache,[23] K. Bukin,[23] E. Dambasuren,[23] G. Majumder,[23] R. Mountain,[23] T. Skwarnicki,[23] S. Stone,[23] J.C. Wang,[23] H. Zhao,[23] S. Kopp,[24] M. Kostin,[24] and A. H. Mahmood[25]

[1]Vanderbilt University, Nashville, Tennessee 37235
[2]Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
[3]Wayne State University, Detroit, Michigan 48202
[4]California Institute of Technology, Pasadena, California 91125
[5]University of California, San Diego, La Jolla, California 92093
[6]University of California, Santa Barbara, California 93106
[7]Carnegie Mellon University, Pittsburgh, Pennsylvania 15213
[8]Cornell University, Ithaca, New York 14853
[9]University of Florida, Gainesville, Florida 32611
[10]Harvard University, Cambridge, Massachusetts 02138
[11]University of Illinois, Urbana-Champaign, Illinois 61801
[12]Carleton University, Ottawa, Ontario, Canada K1S 5B6
and the Institute of Particle Physics, Canada
[13]Ithaca College, Ithaca, New York 14850
[14]University of Kansas, Lawrence, Kansas 66045
[15]University of Minnesota, Minneapolis, Minnesota 55455
[16]State University of New York at Albany, Albany, New York 12222

[17]Ohio State University, Columbus, Ohio 43210
[18]University of Oklahoma, Norman, Oklahoma 73019
[19]University of Pittsburgh, Pittsburgh, Pennsylvania 15260
[20]Purdue University, West Lafayette, Indiana 47907
[21]University of Rochester, Rochester, New York 14627
[22]Southern Methodist University, Dallas, Texas 75275
[23]Syracuse University, Syracuse, New York 13244
[24]University of Texas, Austin, Texas 78712
[25]University of Texas - Pan American, Edinburg, Texas 78539

The structure of the Standard Model has been guided by measurements of mixing and CP violation in the neutral K and B meson sectors. The Standard Model predictions for the rate of mixing and CP violation in the charm sector are small, with the largest predictions in both cases being $\mathcal{O}(0.01)$, and most predictions being $\mathcal{O}(0.001)$ [1]. Observation of CP violation above the 1% level would be strong evidence for physics outside the Standard Model.

The SU(3) flavor symmetry predicts $\Gamma\left(D^0 \to K^+K^-\right)/\Gamma\left(D^0 \to \pi^+\pi^-\right) = 1$ [2], while the previously measured value is 2.80 ± 0.20 [4]. This deviation is most likely caused by large final state interactions. These can also give rise to a large strong phase differences between mixing and Cabibbo-suppressed D^0 decays that give rise to the same final states [3]. A measure of CP violation in these decays, the direct CP violation asymmetry, is proportional to the amount of CP violation in the decays and the sine of the strong phase difference. The Standard Model suggests that CP violation in these decays is small since the higher-order diagrams are suppressed, however, new physics can enhance the rate of CP violation. In this paper we present the most precise measurement to date of the ratio of partial widths, $\Gamma\left(D^0 \to K^+K^-\right)/\Gamma\left(D^0 \to \pi^+\pi^-\right)$ [5]. We also present our search for direct CP violation in these decays.

In the absence of CP violation, the D meson mass eigenstates $D_{1,2}$ are also CP eigenstates. The decay of a D^0 to a CP eigenstate, such as K^+K^- or $\pi^+\pi^-$, has a purely exponential lifetime characteristic of the associated mass eigenstate. Therefore, in the limit of no CP violation, we can write the time-dependent rate of a D^0 decaying to a CP eigenstate, f, as $R(t) \propto \exp\left[-t\Gamma \cdot (1 - y_{CP}\eta_{CP})\right]$, where $CP \mid f\rangle = \eta_{CP} \mid f\rangle$, Γ is the average D^0 width, $y_{CP} = y = \Delta\Gamma/2\Gamma$, and $\Delta\Gamma$ is the width difference between the two mass eigenstates [6]. We can measure y_{CP} simply by measuring the ratio of lifetimes of the D^0 decaying to a CP eigenstate (τ_{CP+}) and a CP neutral state such as $K^-\pi^+$ (τ). Then $y_{CP} = \tau/\tau_{CP+} - 1$. We have used $\tau = (\tau_{CP+} + \tau_{CP-})/2$, and assumed that the lifetime difference is small so that the $K^+\pi^-$ lifetime distribution can be fit with a single exponential.

The data were collected using the CLEO II.V upgrade [7] of the CLEO II detector [8] between February 1996 and February 1999 at the Cornell Electron Storage Ring (CESR). The data correspond to 9.0 fb^{-1} of e^+e^- collisions near $\sqrt{s} \approx 10.6$ GeV. The detector consisted of cylindrical tracking chambers and an electromagnetic calorimeter immersed in a 1.5 Tesla axial magnetic field, surrounded by muon chambers. The reconstruction of displaced vertices from charm decays was made possible by the addition of a silicon vertex detector (SVX) in CLEO II.V. We utilized this improved resolution in previous searches for D^0–$\overline{D^0}$ mixing [9] and in measurements of charmed particle lifetimes [10]. The charged particle trajectories were fit using a Kalman filter technique that takes into account energy loss as the particles pass through the material of the beam pipe and detector [11].

The events are selected by searching for the decay chain $D^{*+} \to D^0\pi_s^+$, with subsequent decays of the D^0 to K^+K^-, $\pi^+\pi^-$, or $K^-\pi^+$. The charge of the slow pion, π_s^+, from the D^{*+} decay is a tag of the initial D^0 flavor. Additionally, we separate signal from background using the energy release in the D^{*+} decay, $Q \equiv M^* - M - M_\pi$, where M^* is the candidate D^{*+} invariant mass, M is the candidate D^0 invariant mass, and M_π is the pion mass.

All pairs of oppositely-charged tracks of good quality are used to form D^0 candidates assuming four particle assignments: K^+K^-, $K^+\pi^-$, π^+K^-, and $\pi^+\pi^-$. The D^0 candidate is retained if any of the particle assignments has an invariant mass within 35 MeV of the D^0

mass. The D^0 daughters are constrained to come from a common vertex, and the confidence level from this constraint must be greater than 0.01%. A pion candidate with at least two SVX hits in both the r–ϕ and r–z layers is combined with the D^0 candidate to form a D^{*+}. The slow pion candidate is refit by constraining it to come from the intersection of the beam spot and the projection of the D^0 momentum vector. This dramatically reduces the mismeasurement of the pion momentum due to multiple scattering in the beam pipe and first layer of silicon. The resulting Q distribution has a width of approximately 190 keV. The candidate is retained if the confidence level for the refit is greater than 0.01%, Q is less than 25 MeV, and the D^{*+} momentum is greater than 2.2 GeV/c. Finally, we require $|\cos\theta^*| < 0.8$, where $\cos\theta^*$ is the angle in the D^0 rest frame between a D^0 daughter and the D^0 direction in the lab frame. The signal is flat in $\cos\theta^*$, while the backgrounds are highly peaked at $|\cos\theta^*| \approx 1$. Particle identification using specific ionization is not required since the different mass hypotheses are separated by greater than 8.5 standard deviations.

The partial width measurements are obtained from binned maximum likelihood fits to the Q distribution of the D^{*+} decay. We fit in bins of momentum to eliminate potential bias due to mismodeling of the D^{*+} momentum spectrum in Monte Carlo. The finite statistics of the fitting shapes are included in the statistical uncertainty of the fit. The signal shape is taken from the $K^-\pi^+$ data sample, while the background shape is determined from Monte Carlo. All of the modes have approximately the same signal shape since the Q resolution is dominated by multiple scattering of the slow pion. We also fit the D^0 mass distribution as a check.

We first fit the $K\pi$ data outside of the signal region to obtain the background normalization. To obtain $R_{\pi\pi} = \Gamma\left(D^0 \to \pi^+\pi^-\right)/\Gamma\left(D^0 \to K^-\pi^+\right)$ we fit the Q distributions for the ratio of signal yields between the $\pi\pi$ and $K\pi$ channels, and for the normalization of the background, where we have used the signal shape and background parameters determined from the $K\pi$ data and Monte Carlo samples, respectively. To obtain $R_{KK} = \Gamma\left(D^0 \to K^+K^-\right)/\Gamma\left(D^0 \to K^-\pi^+\right)$ we fit the Q distributions as we did for $R_{\pi\pi}$, however we add an additional component from pseudoscalar-vector decay (PV) background, where the shape is taken from Monte Carlo and the normalization is allowed to float. The PV background is primarily from $D^0 \to K^-\rho^+$, $\rho^+ \to \pi^+\pi^0$ where the π^0 is nearly at rest. This background forms a broad peak in Q. The PV background is negligible in the $\pi\pi$ and $K\pi$ final states.

In order to maintain statistical independence, we use two different sets of Monte Carlo events. One sample is only used to determine the fitting shapes. We fit the data and the second Monte Carlo sample simultaneously to correct for small differences in acceptance between the normalization and signal modes. The results of the fits are $R_{KK} = 0.1037 \pm 0.0038$ and $R_{\pi\pi} = 0.0355 \pm 0.0017$ from approximately 20,000 $K^-\pi^+$, 1900 K^+K^-, and 710 $\pi^+\pi^-$ events.

The systematic uncertainty due to the fitting shapes is assessed by performing a series of fits using different assumptions for the background and also several fits to the D^0 mass distribution. We estimate systematic uncertainties of 0.0017 and 0.001 due to the fitting shapes in the KK and $\pi\pi$ modes, respectively. We vary the bin sizes, Q fit range, Q signal region and candidate D^0 mass requirement, and form a combined systematic uncertainty of 0.0005 due to these variations.

We also estimate systematic uncertainties associated with some of the event selection requirements by doing the analysis without those requirements. The variations we observe are 0.0009 in R_{KK} and 0.00095 in $R_{\pi\pi}$ from removing the vertex confidence level requirement, and 0.00032 in R_{KK} and 0.00016 in $R_{\pi\pi}$ from removing the track quality requirement.

We use the $K\pi$ data sample to study the effect of any mismodeling in the simulation of the fragmentation and the detector acceptance. For the fragmentation modeling we estimate a systematic uncertainty of 0.0014 for R_{KK} and 0.0005 for $R_{\pi\pi}$. We obtain relative corrections and uncertainties due to mismodeling of the detector acceptance of $(-2.4 \pm 1.1)\%$ for R_{KK} and $(+2.4 \pm 2.7)\%$ for $R_{\pi\pi}$. We apply these corrections and sum all of the systematic uncertainties in quadrature to obtain the final results $R_{KK} = \Gamma\left(D^0 \to K^+K^-\right)/\Gamma\left(D^0 \to K^-\pi^+\right) = 0.1040 \pm 0.0033 \pm 0.0027$ and $R_{\pi\pi} = \Gamma\left(D^0 \to \pi^+\pi^-\right)/\Gamma\left(D^0 \to K^-\pi^+\right) = 0.0351 \pm 0.0016 \pm 0.0017$, where the first error is statistical and the second is systematic. These results are the most precise determinations of R_{KK} and $R_{\pi\pi}$ to date [4].

We can combine the results, accounting for cancellations and correlations among the uncertainties to calculate $R_{KK}/R_{\pi\pi} = 2.96 \pm 0.16(\mathrm{stat}) \pm 0.15(\mathrm{syst})$. This result agrees with the world average value of 2.80 ± 0.20 [4].

We can use the same procedure to search for the direct CP asymmetries

$$A_{CP} = \frac{\Gamma\left(D^0 \to f\right) - \Gamma\left(\overline{D^0} \to f\right)}{\Gamma\left(D^0 \to f\right) + \Gamma\left(\overline{D^0} \to f\right)},$$

where f can be K^+K^- or $\pi^+\pi^-$. The charge of the slow pion from the D^{*+} decay serves as an unbiased tag of the D^0 flavor since charm quarks are produced in quark–antiquark pairs at CESR and fragmentation and the D^* decay are strong processes, which conserve CP.

We measure the CP asymmetry in the same manner as the partial width analysis described above apart from the following changes. The K^+K^- and $\pi^+\pi^-$ data are separated into D^0 and $\overline{D^0}$ samples based on the charge of the slow pion. However, we still normalize by the entire $K\pi$ sample to eliminate possible bias from any asymmetry in $D^0 \to K^-\pi^+$ decay. The D^{*+} momentum requirement is altered to be greater than 2.0 GeV/c since acceptance differences between modes are no longer an issue. The candidate D^0 mass requirement is tightened to ± 15 MeV of the nominal D^0 mass, which reduces the backgrounds by about a factor of two.

We fit the data in the same manner as in the partial width analysis, modified as described above. The KK and $\pi\pi$ Q distributions and fit results are shown in Figure 1. From the fits we find 1512 ± 47 $D^0 \to K^+K^-$ events, 1511 ± 47 $\overline{D^0} \to K^+K^-$ events, 579 ± 26 $D^0 \to \pi^+\pi^-$ events, and 557 ± 26 $\overline{D^0} \to \pi^+\pi^-$ events, and obtain $A_{CP}^{KK} = 0.001 \pm 0.022$ and $A_{CP}^{\pi\pi} = 0.020 \pm 0.032$.

The sources of possible systematic error for the CP asymmetry measurement are the shapes used for fitting and a charge dependent slow pion acceptance. To assess the systematic uncertainty from the fitting shapes we perform fits in which we vary the candidate D^0 mass window, remove the vertex confidence level requirement, vary the width of the $K\pi$ signal region and the Q fit region, alter the number of bins, and split the $K\pi$ sample into two according to the charge of the associated slow pion and fit the two samples separately. We use 1/2 of the largest variation in each case, and then sum them in quadrature to obtain a systematic uncertainty due to the fitting shape of 0.0068 for A_{CP}^{KK} and 0.0069 for $A_{CP}^{\pi\pi}$.

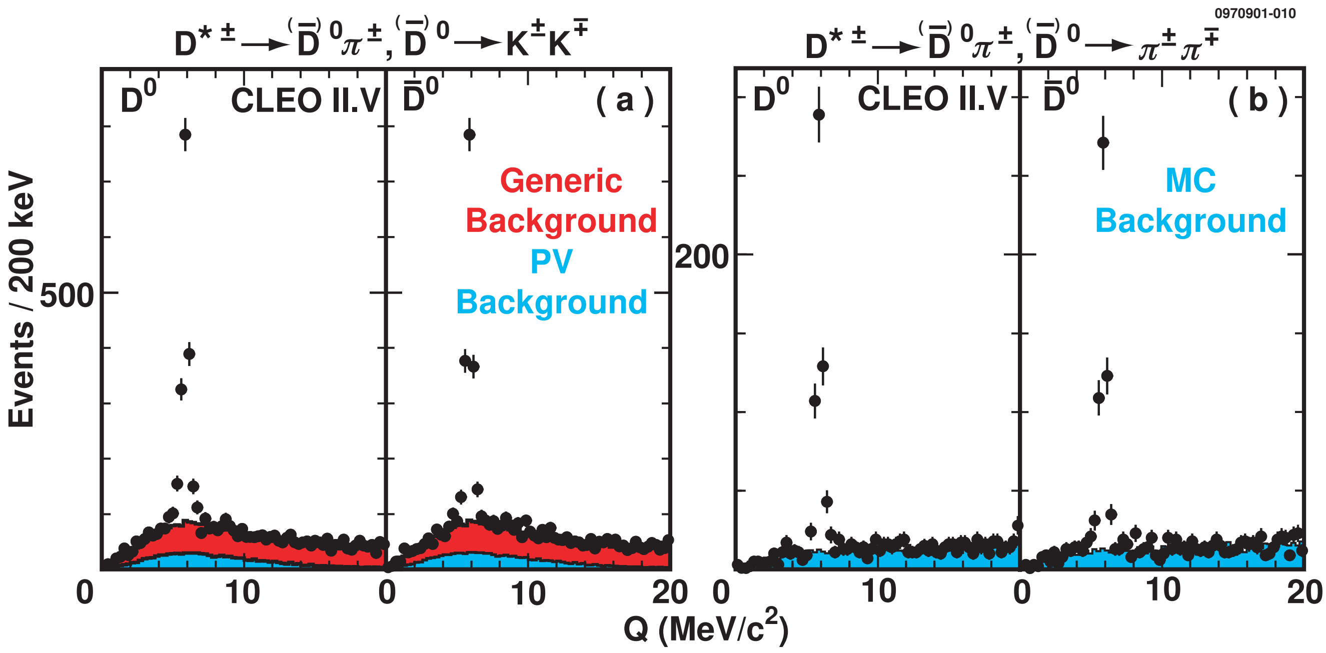

FIG. 1. The $D^* \to D\pi_s$ Q distributions for a) $D^0 \to K^+K^-$ and $\overline{D^0} \to K^+K^-$ candidates and b) $D^0 \to \pi^+\pi^-$ and $\overline{D^0} \to \pi^+\pi^-$ candidates. The points are the data and the histograms are the background fits.

A difference in slow pion acceptance for positive and negative pions can come from a number of different sources. The interaction cross section of pions with matter is different for positive and negative pions. We use the known composition of the CLEO detector and the interaction cross sections to calculate the induced asymmetry as a function of momentum. We find that the bias to the asymmetry is less than 0.2%. We use the pions from K^0_S decays to search for a momentum-dependent charge bias in pion acceptance. We select the pions from K^0_S decay similarly to the method used to select the slow pions from D^{*+} decay. We compare the observed difference between the momentum spectrum for the positive and negative legs of the K^0_S, over the region of slow pion momenta from $D^{*+} \to D^0\pi^+$ decay, to estimate the acceptance difference for positive and negative pions to be less than 0.07%.

We have looked for a momentum-independent charge bias in track finding by generating single track Monte Carlo randomly distributed in θ, ϕ, and momentum, between 0 and 3 GeV/c. We see no significant bias, and limit the momentum independent acceptance bias to be less than 0.48%. We translate these limits on acceptance differences and track finding biases into limits on our observed asymmetry based on the statistics of our observed data sample.

Charm quarks are expected to be produced with a small forward-backward asymmetry in e^+e^- annihilations at $\sqrt{s} \approx 10.6$ GeV due to the interference between the photon and Z^0. The center of the luminous region was not exactly at the center of the detector, so this, coupled with the forward-backward asymmetry, induces an acceptance asymmetry. From a study of the $K^+\pi^-$ data and Monte Carlo samples we find an acceptance bias of $0.014 \pm 0.014\%$. We correct for the bias and assign the statistical error as a systematic uncertainty.

Summing all of the systematic uncertainties in quadrature and applying the correction mentioned above we arrive at the final result of $A_{CP}^{KK} = (0.0 \pm 2.2 \pm 0.8)\%$ and $A_{CP}^{\pi\pi} = (1.9 \pm 3.2 \pm 0.8)\%$. We see no evidence of direct CP violation in these decays. This is the most precise measurement of these CP asymmetries to date [4,12].

As noted earlier we can measure the normalized mixing parameter y_{CP} by measuring the lifetime ratio between $D^0 \to K^-\pi^+$ and D^0 decay to a CP eigenstate, such as K^+K^- or $\pi^+\pi^-$: $y_{CP} = \tau/\tau_{CP+} - 1$. In the limit of no CP violation in the D meson sector y_{CP} is equivalent to y. We use the same data sample described above, using the decay length and momentum to determine the proper decay time. We modify the event selection criteria slightly for this analysis. We require the candidate D^0 momentum to be greater than 2.3 GeV/c. We tighten the requirement on the vertex confidence level of the D^0 candidate to be greater than 0.1%. Furthermore, we place an extra requirement on the data: the D^0 candidate masses obtained with the three other particle assignments to the two daughters must be more than four standard deviations away from the nominal D^0 mass.

We select events with a Q value within 1 MeV of the nominal value and fit their candidate D^0 mass spectrum with a binned maximum likelihood fit to the sum of two Gaussians for the signal, constrained to the same central value, and a first order polynomial for the background. The data and fit results are shown in Figure 2. The fit values are converted into a mass dependent probability for signal and background and are used as an input to the lifetime fits. The other inputs to the lifetime fits are the measured proper decay time and its calculated uncertainty. For the KK and $\pi\pi$ samples we fix the ratio of areas and the ratio of widths of the two Gaussians to the values determined in the $K\pi$ fit. We perform the fits for candidate D^0 mass over the range 1.825 to 1.905 GeV, and use all of these events in the lifetime fits described below.

For the signal portion of the probability distribution function for the lifetime fits we constrain the candidate D^0 mass to a fixed value, which gives us a better measurement of y_{CP}. The value we constrain to is the weighted average of the D^0 mass determined from the $K\pi$, KK, and $\pi\pi$ events, where each is corrected by an offset determined from Monte Carlo. This offset is simply the difference between the input and measured D^0 mass for each channel in the Monte Carlo. The offsets are $+0.15 \pm 0.02$ MeV ($K\pi$), $+0.27 \pm 0.05$ MeV (KK), and $+0.10 \pm 0.09$ MeV ($\pi\pi$). The mass constraint introduces a systematic bias in the lifetime measurement, which cancels for y_{CP} which only depends on the ratio of lifetimes.

The candidate proper decay time, t, is given by

$$t = m \cdot \frac{(\vec{r}_{\rm dec} - \vec{r}_{\rm prod}) \cdot \hat{p}}{|\, \vec{p}\, |},$$

where $\vec{r}_{\rm dec}$ and $\vec{p}$ are from the D^0 candidate vertex fit. We determine $\vec{r}_{\rm prod}$ using $e^+e^- \to q\bar{q}$ ($q = udscb$) events from sets of data with integrated luminosity of several pb^{-1}. The extent of the luminous region has a Gaussian width of approximately 10 μm vertically, 300 μm horizontally, and 1 cm along the beam direction [13]. The resolution on the D^0 decay point is typically 40 μm in each dimension. The resolution in t is typically $\sigma_t = 0.4$ in units of D^0 lifetimes. We determine the proper decay time in the three dimensions separately, and combine them to arrive at the best estimate of t and σ_t.

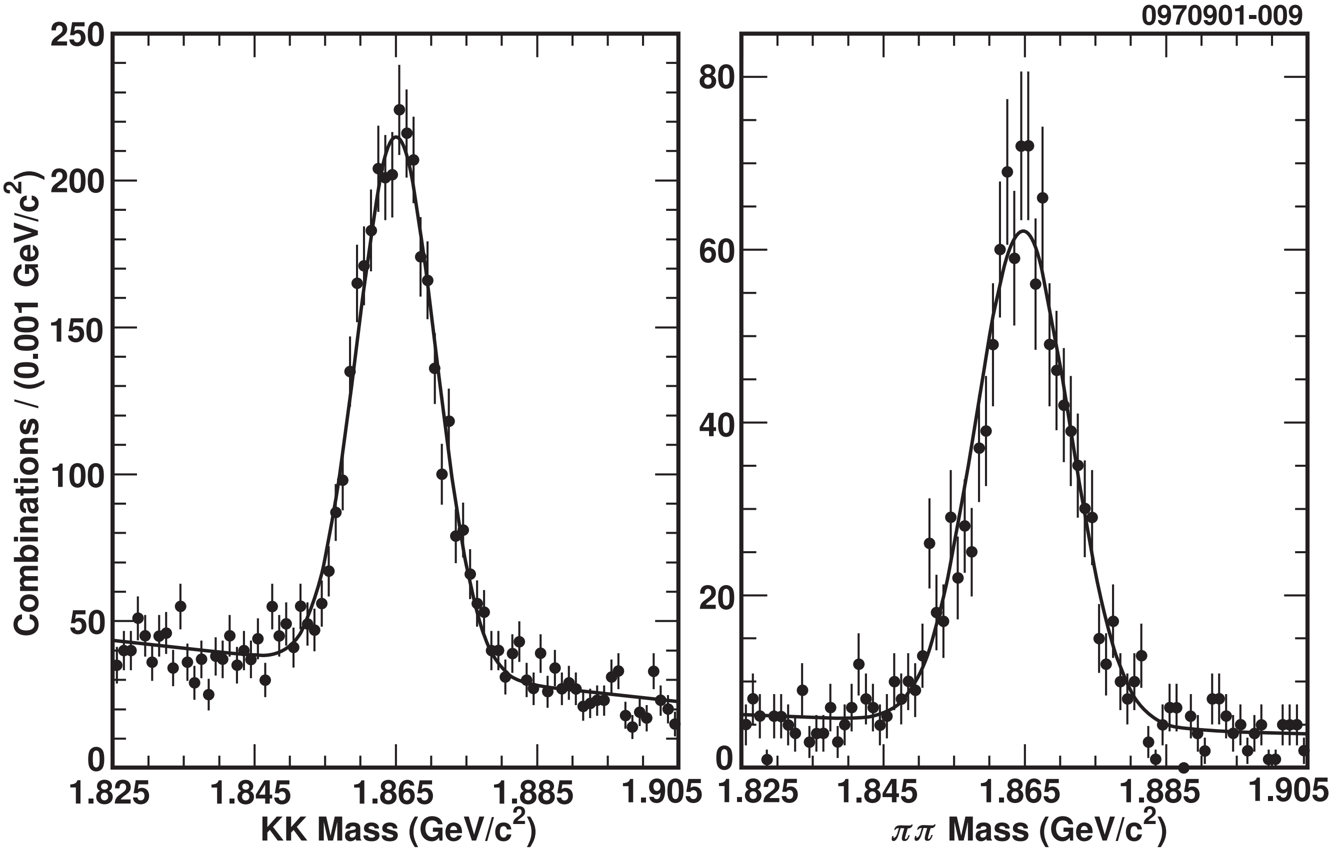

FIG. 2. The mass distribution for $D^0 \to K^+K^-$ (left) and $D^0 \to \pi^+\pi^-$ (right) candidates. The curves are the results of the fit discussed in the text.

TABLE I. Summary of the lifetime fits. The parameters are those described in the text, where $f_{\rm mis}$ is the fraction of signal in the second and third Gaussian contributions and $\sigma_{\rm mis}$ is the width of the second Gaussian. Note that we have constrained the candidates to a D^0 mass of 1.86514 GeV, the Monte Carlo corrected weighted average of the KK, $\pi\pi$, and $K\pi$ data. This mass constraint introduces a systematic bias in the lifetime measurement, which cancels for y_{CP} which only depends on the ratio of lifetimes. This technique yields the smallest uncertainty in y_{CP}, but is not optimal for measuring the absolute D^0 lifetime.

Parameter	$K\pi$	KK	$\pi\pi$
Number of signal	20272 ± 178	2463 ± 65	930 ± 37
$\tau_{\rm sig}$ (ps)	0.4046 ± 0.0036	0.411 ± 0.012	0.401 ± 0.017
Background frac. (%)	8.8 ± 0.2	50.7 ± 0.7	29.1 ± 1.3
Background life frac. (%)	81.0 ± 4.8	85.7 ± 2.9	32.2 ± 7.5
$\tau_{\rm back}$ (ps)	0.376 ± 0.030	0.436 ± 0.020	0.56 ± 0.15
$f_{\rm mis}$ (%)	3.8 ± 0.9	Fixed	Fixed
$\sigma_{\rm mis}$ (ps)	0.590 ± 0.079	Fixed	Fixed

We fit the lifetime distribution using an unbinned likelihood method. The signal probability distribution function (PDF) consists of an exponential convolved with a resolution function, composed of the sum of three parts, based on a simple, yet robust, physical model. For most events the calculated covariance matrix for the D^0 daughters is assumed to be correct to within a global scale factor, with a Gaussian resolution function of width $S \cdot \sigma_t$. The scale factor, S, accounts for any common mistake in the covariance matrices, as would be present from a deficiency in the detector material description. A few percent of the events have one or more particles that have undergone a hard scatter, rendering the extrapolated vertex errors virtually meaningless. We model the contribution from these events with a single Gaussian whose normalization and width are allowed to float in the fit. For a very small fraction of events the vertex location is extremely mismeasured. These events have a nearly flat distribution in lifetime. We model this contribution with a broad Gaussian, assigning a fixed width of 8 ps. The normalization of this contribution is allowed to float in the fit. The signal PDF is multiplied, on an event-by-event basis, by the mass-dependent signal probability from the D^0 candidate mass fit.

The background lifetime distribution contains two pieces: a prompt piece and a piece with non-zero lifetime. The component with non-zero lifetime comes from partially reconstructed charm decays. We model this component with a single exponential where the lifetime is another parameter of the fit. We expect the fitted value of the background lifetime to be consistent with the D^0 lifetime. The relative amount of background with and without lifetime is also allowed to float in the fit. Both sorts of background are convolved with a resolution function that is modeled in the same manner as the signal, but with an independent set of parameters. The background PDF is multiplied by one minus the signal probability from the mass fit.

The fit results for all events included in the fit are shown in Figure 3 and given in Table I. Small corrections to the lifetimes are computed by comparing the generated and measured

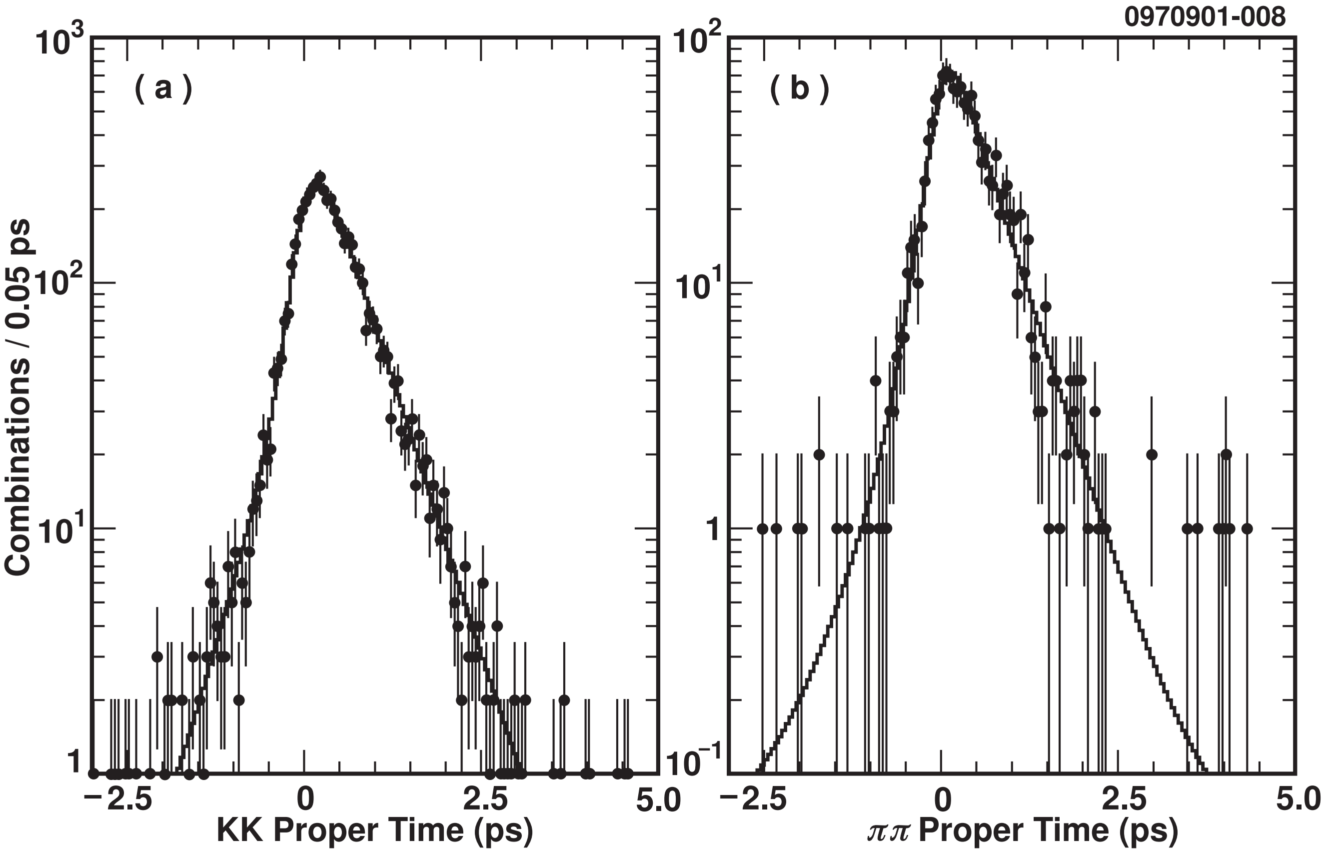

FIG. 3. The proper time distribution for all $D^0 \to K^+K^-$ (left) and $D^0 \to \pi^+\pi^-$ (right) candidates included in the fit. The curves are the fit results discussed in the text.

values in a Monte Carlo analysis on a fully simulated sample, including backgrounds, corresponding to roughly ten times the data sample. These corrections are 0.0006 ± 0.0040 ps in K^+K^-, -0.0011 ± 0.0015 ps in $K^-\pi^+$, and 0.001 ± 0.0058 ps in $\pi^+\pi^-$. Applying these corrections we obtain $y_{CP}^{KK} = -0.019 \pm 0.030 \pm 0.010$, $y_{CP}^{\pi\pi} = 0.005 \pm 0.046 \pm 0.014$, and combining them in a weighted average we calculate $y_{CP} = -0.012 \pm 0.025 \pm 0.009$, where the second error is from the Monte Carlo statistics.

We check the data for bias in several different parameters. We plot the fitted value of y_{CP} versus azimuthal angle, polar angle, date the data were collected, momentum of the candidate D^0, $\cos\theta^*$, and confidence level of the vertex constraint. We find no significant biases in any of these distributions.

The kinematics of $K\pi$, KK, and $\pi\pi$ D^0 decays are slightly different due to the different amount of kinetic energy released. This will result in the signal resolution functions being slightly different. We have constrained all of the signal resolution functions to be the same. Studying this effect in Monte Carlo and data we estimate the following systematic uncertainties: 0.007 for KK, 0.003 for $\pi\pi$, and 0.005 for the average.

We study the effects of background shape mismodeling by varying the amount and composition of the background. We perform these in data and Monte Carlo and estimate systematic uncertainties of 0.008 for KK, 0.011 for $\pi\pi$, and 0.008 for the average.

We study the effect of our treatment of the proper time outlier events, which we have modeled with a wide Gaussian of fixed width. We vary the value of the width used in the wide Gaussian and also eliminate the wide Gaussian from the resolution function and impose a maximum proper time limit instead. From these studies we estimate systematic uncertainties of 0.002 for KK, 0.001 for $\pi\pi$, and 0.002 for the average.

We investigate the bias introduced by constraining all of the events to the same D^0 mass by removing this constraint. We take the difference between the constrained and unconstrained fits as a systematic uncertainty: 0.005 in KK, 0.005 in $\pi\pi$, and 0.005 in the average. Length scale uncertainties have been studied previously by CLEO [10] and contribute negligible uncertainty to y_{CP}.

Summing all of the listed systematic uncertainties in quadrature, including the Monte Carlo statistics, we obtain the final results $y_{CP}^{KK} = -0.019 \pm 0.029 \pm 0.016$, $y_{CP}^{\pi\pi} = 0.005 \pm 0.043 \pm 0.018$ and combining the two results we obtain $y_{CP} = -0.011 \pm 0.025 \pm 0.014$, which is consistent with zero and with the average of previous measurements [14], $y_{CP} = 2.9 \pm 1.4$.

In summary, we have used the CLEO II.V data set to obtain the world's most precise measurements of $R_{KK} = \Gamma\left(D^0 \to K^+K^-\right)/\Gamma\left(D^0 \to K^-\pi^+\right) = (10.40 \pm 0.33 \pm 0.27)\%$ and $R_{\pi\pi} = \Gamma\left(D^0 \to \pi^+\pi^-\right)/\Gamma\left(D^0 \to K^-\pi^+\right) = (3.51 \pm 0.16 \pm 0.17)\%$, and the direct CP asymmetries $A_{CP}^{KK} = (0.0 \pm 2.2 \pm 0.8)\%$ and $A_{CP}^{\pi\pi} = (1.9 \pm 3.2 \pm 0.8)\%$. We have also performed a competitive measurement of the normalized mixing parameter $y_{CP} = -0.012 \pm 0.025 \pm 0.014$. In all cases the first error is statistical and the second is systematic. Our partial width measurements are consistent with the previous world average, we see no evidence for direct CP violation in Cabibbo-suppressed D^0 decays, and we measure a value of the mixing parameter y_{CP} consistent with zero.

ACKNOWLEDGMENTS

We thank A. A. Petrov for valuable discussions. We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. M. Selen thanks the PFF program of the NSF and the Research Corporation, and A.H. Mahmood thanks the Texas Advanced Research Program. This work was supported by the National Science Foundation, the U.S. Department of Energy, and the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

[1] H.N. Nelson, hep-ex/9908021; A. A. Petrov, hep-ph/0009160; I.I. Bigi, hep-ex/0104008; A. F. Falk, Y. Grossman, Z. Ligeti, A. A. Petrov, hep-ph/0110317.

[2] M. B. Einhorn and C. Quigg, Phys. Rev. D **12**, 2015 (1975).

[3] A. F. Falk, Y. Nir, A. A. Petrov, JHEP 9912, 019 (1999).

[4] Particle Data Group, D.E. Groom *et al.*, Eur. Phys. J. **C 15**, 1 (2000).

[5] Charge conjugate reactions are implied throughout, except where both are shown, as in an asymmetry definition.

[6] The parameter y is one of the standard mixing parameters, characterizing mixing through real intermediate states. Mixing through virtual intermediate states is characterized via $x = \Delta M/\Gamma$, where ΔM is the mass difference of the mass eigenstates. See T.D. Lee, R. Oehme, and C.N. Yang, Phys. Rev. **106**, 340 (1957); A. Pais and S.B. Treiman, Phys. Rev. D **12**, 2744 (1975). Our x and y are in terms of mixing amplitudes, while Pais and Treiman use the eigenvalues of the mixing Hamiltonian; both definitions agree in the limit of CP conservation. In our convention, $y > 0$ implies the real intermediate states with $CP = +1$, such as K^+K^-, make the larger contribution to y.

[7] T.S. Hill, Nucl. Instrum. Methods Phys. Res. A **418**, 32 (1998); D. Peterson, Nucl. Phys. **B** (Proc. Suppl.) **54B**, 31 (1997).

[8] Y. Kubota *et al.*, Nucl. Instrum. Methods Phys. Res. A **320**, 66 (1992).

[9] CLEO Collaboration, R. Godang *et al.*, Phys. Rev. Lett. **84**, 5038 (2000).

[10] CLEO Collaboration, G. Bonvicini *et al.*, Phys. Rev. Lett. **82**, 4586 (1999); CLEO Collaboration, A.H. Mahmood *et al.*, Phys. Rev. Lett. **86**, 2232 (2001).

[11] P. Billior, Nucl. Instrum. Methods Phys. Res., Sect. A **255**, 352 (1984).

[12] FOCUS Collaboration, J.M. Link *et al.*, Phys. Lett. B **491**, 232 (2000); Erratum-ibid. B **495**, 443 (2000).

[13] D. Cinabro *et al.*, CLNS 00/1706, hep-ph/0011075.

[14] E791 Collaboration, E.M. Aitala *et al.*, Phys. Rev. Lett. **83**, 32 (1999); FOCUS Collaboration, J.M. Link *et al.*, Phys. Lett. B **485**, 62 (2000).