Study of the Decay $D^0 \to K^+\pi^-$

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Using a large sample of photoproduced charm mesons from the FOCUS experiment at Fermilab (FNAL-E831), we observe the decay $D^0 \to K^+\pi^-$ with a signal yield of 149 $\pm$ 31 events compared to a similarly cut sample consisting of 36 760 $\pm$ 195 $D^0 \to K^-\pi^+$ events. We use the observed ratio of $D^0 \to K^+\pi^-$ to $D^0 \to K^-\pi^+$ (0.404 $\pm$ 0.085 $\pm$ 0.025)% to obtain a relationship between the D^0 mixing and doubly Cabibbo suppressed decay parameters.

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The decay $D^0 \to K^+\pi^-$ [1] may occur either via a doubly Cabibbo suppressed (DCS) decay or through the mixing of the D^0 into $\overline{D}^0$ followed by the Cabibbo favored (CF) decay $\overline{D}^0 \to K^+\pi^-$. The naive expectation for the ratio of DCS to CF branching fractions, R_{DCS}, is $\tan^4\theta_C \simeq 0.25\%$, which may be modified by final state interactions. Contributions from nonperturbative long range interactions make exact calculations of standard model charm mixing difficult, but the rate is expected to be less than 10^{-3} [2,3]. On the other hand, new physics may enhance mixing [4]. Since standard model charm sector *CP* violation is expected to be small, and current searches report negative results [5], we ignore *CP* violation in this study. Conversely, recent charm sector mixing searches hint at an effect with a rate of order 10^{-4} [6,7]; hence possible mixing effects must be considered.

Four groups [7–10] have studied the decay $D^0 \to K^+\pi^-$ and measured its branching ratio with respect to $D^0 \to K^-\pi^+$, but only the most recent result [7] by CLEO II.V is statistically significant. In addition, there is a variation of a factor of 5 among the measurements with the most recent yielding the most events and the lowest value. We present a high statistics measurement of the branching ratio with more events than any previous experiment and different systematic uncertainties.

The data were collected by the FOCUS Collaboration during the 1996–1997 Fermilab fixed target run in the Wideband Photon beam line using an upgraded version of

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the E687 spectrometer [11]. Charm particles are produced in the interaction of high energy photons ($\langle E \rangle \approx 180$ GeV) with a segmented BeO target. In the target region, charged particles are tracked by 16 layers of silicon microstrip detectors which provide excellent vertex resolution. The momentum of the charged particles is determined by measuring their deflection in two oppositely polarized, large aperture dipole magnets with five stations of multiwire proportional chambers. Particle identification is determined by three multicell threshold Čerenkov detectors, electromagnetic calorimeters, and muon counters.

I. Measurement method.—To minimize systematic effects we apply the same selection algorithm to both $D^0 \to K^+\pi^-$ and the normalizing mode $D^0 \to K^-\pi^+$. We use the sign of the soft π ($\tilde{\pi}$) from the decay $D^{*+} \to D^0\tilde{\pi}^+$ to tag the production flavor of the D meson. For the normalizing mode the charge of the $\tilde{\pi}$ is the same as the charge of the D^0 daughter π [right sign (RS)] but is opposite for the DCS or mixing mode [wrong sign (WS)].

A D^0 candidate consists of a pair of oppositely charged tracks that form a decay vertex and have a $K\pi$ invariant mass between 1.7 and 2.1 GeV$/c^2$. The D^0 candidate is used as a seed to locate a production vertex consisting of at least two charged tracks in addition to the D^0. The production vertex is required to lie within 1σ of the nearest target material and be separated from the decay vertex by at least 5 times the separation error ($\ell/\sigma_\ell > 5$). Each vertex must have a confidence level (C.L.) greater than 1% and the decay vertex tracks are required to be inconsistent when originating in the production vertex.

Highly asymmetrical $K\pi$ pairs reconstructing with the D^0 mass are more likely to be background than signal. A cut is made on asymmetry, $\mathcal{A} = |p_K - p_\pi|/|p_K + p_\pi|$, to reject these candidates. The $\mathcal{A}$ cut point is lowered linearly as the D^0 momentum decreases to achieve the best rejection of background.

For each charged track, the Čerenkov particle identification algorithm generates a set of χ^2-like variables, $W_i = -2\log(\text{likelihood})$, where i ranges over the e, π, K, and p hypotheses. We define $W_{\min}$ as the smallest W of the four hypotheses and we require $W_i - W_{\min} < 4$, where i refers to either the K or π hypothesis. The D^0 daughters must also satisfy the slightly stronger $K\pi$ separation criteria of $\Delta W_K = W_\pi - W_K > 0.5$ for the K and $\Delta W_\pi = W_K - W_\pi > -2$ for the π.

Events with the decay $D^0 \to K^-\pi^+$, where the K has been misidentified as a π and the π has been misidentified as a K, produce false WS candidates. These doubly misidentified events form a broad peak in the $K^+\pi^-$ mass distribution centered on the D^0 mass. When a real $\tilde{\pi}$ tag is present, a peak indistinguishable from the real WS signal appears in the $D^* - D$ mass difference. We treat this double misidentification background by imposing a hard Čerenkov cut on the sum $\Delta W_K + \Delta W_\pi > 8$, when the invariant mass of the $K\pi$ pair, with the K and π particle hypotheses swapped, is within 4σ of the D^0 mass.

All tracks assigned to the production vertex are considered as potential $\tilde{\pi}$ candidates. The $\tilde{\pi}$ candidate must satisfy $W_\pi - W_{\min} < 4$ and be inconsistent with being an electron from a γ conversion where the γ comes from a D^{0*} decay. This is achieved using information from the Čerenkov system, electromagnetic calorimeters, and silicon microstrip detectors.

Significant fake contributions to the WS yield arise from the decay $D^{*+} \to D^0\tilde{\pi}^+$ in which the $\tilde{\pi}$ was correctly reconstructed but the D^0 was not. In the inset in Fig. 1a we show the combined contributions from Monte Carlo (MC) generated decays $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, which are reconstructed as $K\pi$. Both the KK and $\pi\pi$ reflection peaks (below and above the D^0 mass, respectively) have tails which extend into the D^0 mass region. In the inset in Fig. 1b we plot the $K^+\pi^-$ mass contributions from MC events of all known D^0 modes, except two-body final states. The flat background in the D^0 signal region is composed primarily of partially reconstructed and doubly misidentified D^0 decays to $K^-\pi^+\pi^0$ and $K^-\ell^+\nu$. The mass difference plots (Figs. 1a and 1b) for reflected events in the D^0 signal region show peaked backgrounds in the D^* signal region. Using tighter particle identification to eliminate these backgrounds rejects about one-third of our real signal events. To avoid this we divide the RS and WS samples into 1 MeV$/c^2$ wide bins in mass difference from 139 to 179 MeV$/c^2$ and plot the $K\pi$ mass for each bin (a typical mass plot is shown in Fig. 2). The $K\pi$ mass distribution is then fit in each bin as follows: the structured reflections, KK and $\pi\pi$, are fit using line shapes obtained with the MC, the unstructured background is fit by a degree two polynomial, and the D^0 signal is fit with a Gaussian. By fitting in this way the real $D^0 \to K\pi$ decays are isolated from the correlated $\tilde{\pi}$ backgrounds.

The D^0 yields from the 80 $K\pi$ fits (40 each RS and WS) are plotted versus mass difference. The two composite mass difference distributions, shown in Fig. 3, are fit for the WS to RS branching ratio (R_{WS}). The background is fit using the following function:

$$f(\Delta m) = \alpha[(\Delta m - m_\pi)^{1/2} + \beta(\Delta m - m_\pi)^{3/2}], \quad (1)$$

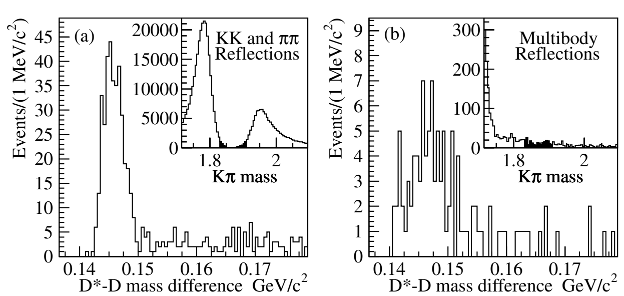

FIG. 1. Monte Carlo studies of background contamination from (a) $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ and (b) all known multibody D^0 decay modes.

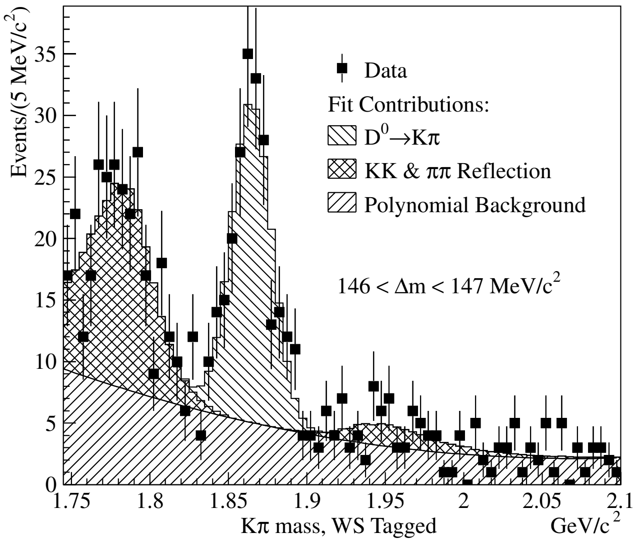

FIG. 2. A sample $K\pi$ mass fit.

where α and β are fit parameters and separate parameters (α_{RS}, β_{RS}, α_{WS}, and β_{WS}) are used to fit the RS and WS distributions. The shape of the high statistics RS signal is used to fit the WS signal. In the WS D^* signal region the full fit function is the sum of the WS background parametrization and the scaled RS signal, where the signal scale factor is R_{WS}. Modeling the WS signal in this way avoids complications arising from parametrizing the non-Gaussian signal. We obtain $R_{\mathrm{WS}} = (0.404 \pm 0.085)\%$ and find $36\,760 \pm 195$ events above background in the RS signal region corresponding to a WS yield of 149 ± 31 events.

Several sources of possible systematic errors were investigated, taking care to avoid tests correlated to possible mixing effects. Since the WS and RS modes are kinematically identical, we expect the systematic effects due to spectrometer acceptance and analysis cuts to cancel.

We looked for evidence of $D^0 \to K^-\pi^+$ doubly misidentified feedthrough by measuring R_{WS} over a wide range of cuts in $\Delta W_K + \Delta W_\pi$. The value of R_{WS} was found to be stable for cuts above four which is well below the cut of eight used in the analysis. In addition, MC studies of this cut show no evidence of feedthrough and indicate that double misidentification accounts for less than 5% of the observed WS yield at the 90% C.L.

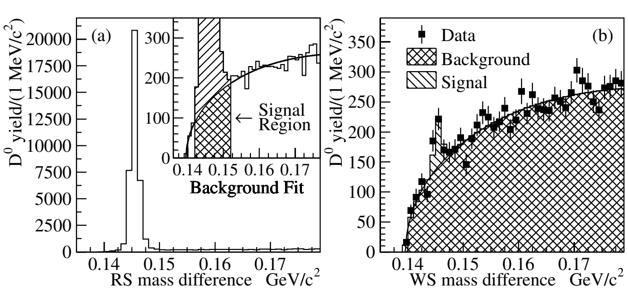

FIG. 3. (a) The RS mass difference distribution, with the inset showing a close-up of the RS background fit and signal region. (b) The WS mass difference distribution with the signal and background fit contributions shown.

We investigated various methods of fitting the mass difference background such as using a different parametrization and constraining the RS and WS shapes to be the same ($\beta_{\mathrm{RS}} = \beta_{\mathrm{WS}}$). We looked for sensitivity to the MC reflection shapes by shifting the reflection distributions by $\pm 2\ \mathrm{MeV}/c^2$, and we searched for a systematic dependence on the mass difference binning by shifting the bin centers and changing the bin widths. Finally, we tested variations on all major cuts including a momentum independent asymmetry cut and harder particle identification cuts. All such tests returned values of R_{WS} consistent with the baseline measurement.

To estimate the systematic error, measurements of R_{WS} were made with 136 different combinations of fit conditions and cut variations. Each measurement is assumed to be equally likely, and we take the statistical variance of the measurements to be the systematic error on R_{WS}. We obtain a systematic error of 0.025%.

II. R_{DCS} in the presence of mixing.—The time dependent rate for WS decays relative to the CF branching fraction is

$$R(t) = \left(R_{\mathrm{DCS}} + \sqrt{R_{\mathrm{DCS}}}\, y' t + \frac{x'^2 + y'^2}{4} t^2\right) e^{-t}, \quad (2)$$

where t is in units of the D^0 lifetime. We use the strong phase (δ) rotated convention of CLEO [7], with $y' = y\cos\delta - x\sin\delta$ and $x' = x\cos\delta + y\sin\delta$ where x and y are the usual mixing parameters, $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/2\Gamma$.

Using a large MC sample (10 times the data) of $D^0 \to K^-\pi^+$ decays generated with a pure exponential lifetime of 413 fs [12], we can calculate the expected number of WS events by reweighting each accepted MC event with a weight given by

$$W_i = \frac{N_{\mathrm{data}}}{N_{\mathrm{MC}}}\left(R_{\mathrm{DCS}} + \sqrt{R_{\mathrm{DCS}}}\, y' t_i + \frac{x'^2 + y'^2}{4} t_i^2\right), \quad (3)$$

where t_i is the generated proper time for event i, and N_{data} and N_{MC} are the number of accepted RS events, respectively, in the data and MC. Summing Eq. (3) over all accepted MC events and dividing by N_{data} we obtain

$$R_{\mathrm{WS}} = R_{\mathrm{DCS}} + \sqrt{R_{\mathrm{DCS}}}\, y'\langle t\rangle + \frac{x'^2 + y'^2}{4}\langle t^2\rangle. \quad (4)$$

The averages $\langle t\rangle$ and $\langle t^2\rangle$ are measured from the generated lifetime of the MC events accepted in the analysis. We find $\langle t\rangle = 1.578 \pm 0.008$ and $\langle t^2\rangle = 3.61 \pm 0.03$, where the errors are systematic, determined by comparing the reconstructed MC lifetime averages to the averages measured in data. Using our measured value of R_{WS} we obtain an expression for R_{DCS} as a function of the mixing parameters x' and y'.

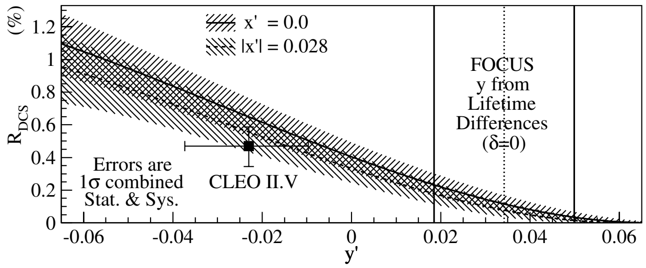

FIG. 4. R_{DCS} plotted as a function of y'. Contours are given for two values of x' covering the 95% C.L. of the CLEO II.V result.

In Fig. 4 we plot R_{DCS} as a function of y' for two values of x' that cover the CLEO [7] 95% C.L. of $|x'| < 0.028$. For comparison, the mixing measurements of CLEO and FOCUS [6] are included in Fig. 4. The CLEO result comes from a direct measurement of R_{DCS}, x', and y'. The FOCUS band represents a measurement of y from lifetime differences between CP even and CP mixed final states. The FOCUS y measurement can be directly compared only to the other results in the case of $\delta = 0$. For the CLEO and FOCUS direct mixing results to be in agreement at the 1σ level requires $\delta \gtrsim \pi/4$ [13].

III. Conclusion.—We observe a signal in the decay channel $D^0 \to K^+\pi^-$ and measure its branching ratio relative to $D^0 \to K^-\pi^+$ to be $(0.404 \pm 0.085 \pm 0.025)\%$. If charm sector mixing is significant, the doubly Cabibbo suppressed component of the branching ratio can be determined from the measured ratio by using the relation expressed in Eq. (4) and plotted in Fig. 4. If charm mixing is sufficiently small, the doubly Cabibbo suppressed branching ratio is simply equal to the measured ratio. For comparison, Table I lists the existing measurements of this branching ratio, made with the assumption of no mixing.

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TABLE I. Measurements of R_{DCS} with the assumption of no charm mixing and no CP violation.

Experiment	R_{DCS} (%) no mixing	Events
CLEO [8]	$0.77 \pm 0.25 \pm 0.25$	19.1
E791 [9]	$0.68^{+0.34}_{-0.33} \pm 0.07$	34
Aleph [10]	$1.77^{+0.60}_{-0.56} \pm 0.31$	21.3
CLEO II.V [7]	$0.332^{+0.063}_{-0.065} \pm 0.040$	44.8
This study	$0.404 \pm 0.085 \pm 0.025$	149

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