Measurements of Cabibbo-Suppressed Hadronic Decays of Charmed D^+ and D^0 Mesons

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(Received 29 April 1985)

Measurements of the branching ratios of ten Cabibbo-suppressed hadronic weak decays of the D^+ and D^0 are presented from data collected with the Mark III detector at SPEAR. In addition to the previously observed channels $D^0 \to K^-K^+$ and $\pi^-\pi^+$, we report new measurements of $D^0 \to \pi^-\pi^+\pi^0$ and $\pi^-\pi^+\pi^-\pi^+$, and $D^+ \to \bar{K}^0 K^+$, $\pi^0\pi^+$, $\bar{K}^{*0}(892)K^+$, $\phi\pi^+$, $K^-K^+\pi^+$, and $\pi^-\pi^+\pi^+$.

PACS numbers: 13.25.+m, 14.40.Jz

We present measurements of Cabibbo-suppressed hadronic weak decays of the D^+ and D^0. Measurements of D^+ and D^0 semileptonic branching fractions,[1,2] as well as direct decay-length measurements,[3] indicate a substantial difference between D^+ and D^0 lifetimes, suggesting the presence of distinct nonleptonic processes which enhance the D^0 and suppress the D^+ width.[4] Thus, a further understanding of the D-decay mechanism requires a systematic study of the hadronic decays. The measurements we report address three aspects of these decays: the contribution of Cabibbo-suppressed decays to the total widths of the D^+ and D^0, the importance of interference between final-state amplitudes in D^+ decays, and the presence of nonperturbative effects in both D^+ and D^0 decays.

The data (9.2 pb^{-1}) were collected near the peak of the $\psi(3770)$ resonance with the Mark III detector[5] at the e^+e^- storage ring SPEAR. The analyses of the Cabibbo-favored D^0 decay to $K^-\pi^+$, and the suppressed decays to $\pi^-\pi^+$ and K^-K^+, proceed as follows: All charged tracks used to reconstruct a channel are required to originate within a fiducial volume of radius 30 mm and length 160 mm centered on the interaction point, and to lie within the region covered by the time-of-flight (TOF) system, $|\cos\theta| \leq 0.76$ (where θ is the polar angle). The two-body decays of the D^0 produce at least one track with a large momentum (~ 1 GeV/c), for which π/K misidentification becomes significant. We therefore employ a technique which separates the signal and misidentification peaks within a single plot by taking advantage of the threshold production of the $D^0\bar{D}^0$ pairs. At threshold, the invariant mass of pairs of tracks arising from real $K^-\pi^+$ decays is insensitive to the interchange of the π and K particle assignments, while a single misidentification results in a narrow reflection peak separated by ± 0.120 GeV/c^2 from the D^0 mass. Hence, for each channel, pairs of oppositely charged tracks are arbitrarily assigned both π and K identities, as long as neither track has a normalized TOF weight[6] exceeding 70% for the alternate assignment. As D^0's produced at the $\psi(3770)$ have a unique momentum ($P_D = 0.276$ GeV/c), we require that all pairs of tracks satisfy $|P_{\text{pair}} - P_D| \leq 0.050$ GeV/c, further reducing combinatorial background. Pairs satisfying all other cuts, but having momenta such that $0.060 \leq |P_{\text{pair}} - P_D| \leq 0.110$ GeV/c, provide a sample representative of the background shape through the signal region.

The signals at 1.864 GeV/c^2 are shown in Fig. 1, along with well-separated reflection peaks arising from particle misidentification. The number of signal and background events is determined by a maximum-likelihood fit. The mass and width obtained from the dominant $K^-\pi^+$ channel are used in the fits for the suppressed channels K^-K^+ and $\pi^-\pi^+$. An additional Gaussian is introduced to account for each reflection peak. The background shape (dashed curve) is derived from the adjacent momentum bands; the magnitude is allowed to vary in the fit. In the regions where both signals and reflections are absent, the background curve so derived is seen to provide an excellent representation of the data. We find 39 ± 12

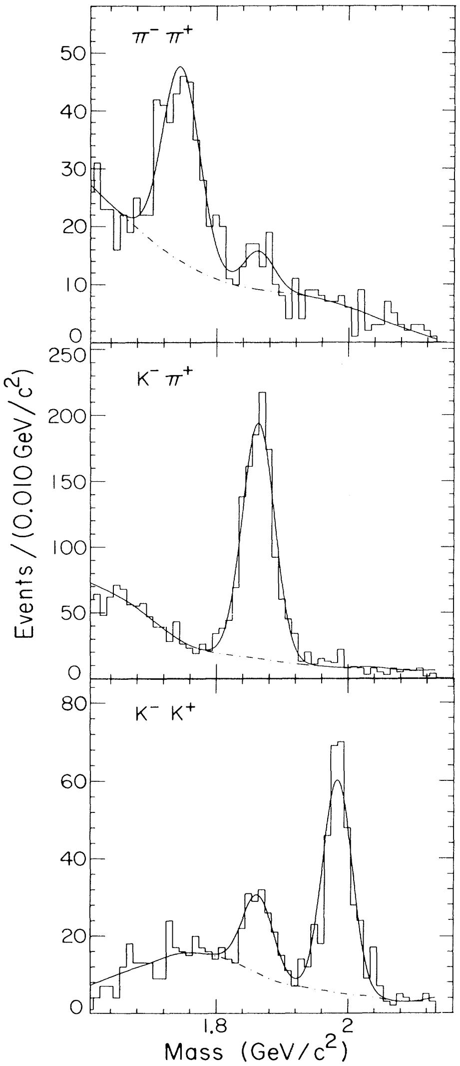

FIG. 1. Invariant mass for K^-K^+, $K^-\pi^+$, and $\pi^-\pi^+$. Here and throughout this paper, we adopt the convention that reference to a particle state also implies reference to its charge conjugate.

$\pi^-\pi^+$, 1091 ± 36 $K^-\pi^+$, and 118 ± 15 K^-K^+ events.

The relative acceptance is determined by a Monte Carlo simulation of $D\bar{D}$ production and decay, and detector response. After corrections we find

$$\frac{\Gamma(D^0 \to K^-K^+)}{\Gamma(D^0 \to K^-\pi^+} = 0.122 \pm 0.018 \pm 0.012,$$

$$\frac{\Gamma(D^0 \to \pi^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+)} = 0.033 \pm 0.010 \pm 0.006,$$

where the errors are statistical and systematic, respectively. By normalizing the suppressed decays to a similar allowed mode, we cancel many systematic uncertainties. The residual error arises almost equally from uncertainties in the background shape, the fitting procedure, and the acceptance correction.

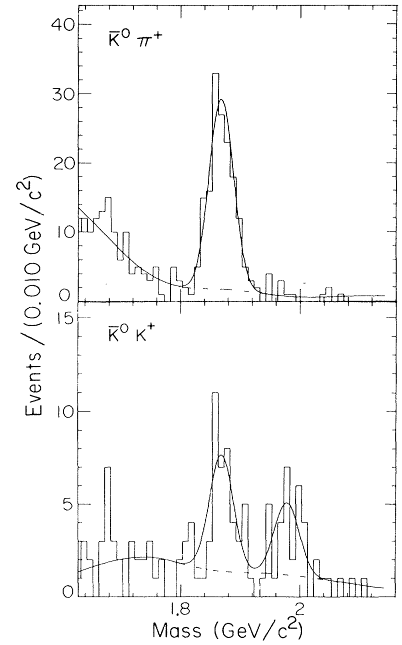

FIG. 2. Invariant mass for $\bar{K}^0K^+$ and $\bar{K}^0\pi^+$.

The same technique is employed to analyze the decays $D^+ \to \bar{K}^0\pi^+$ and $\bar{K}^0K^+$, where the K^0 is identified through the $K_S^0 \to \pi^+\pi^-$ decay. Fits to the resulting mass plots (Fig. 2) yield 141 ± 13 $K_S^0\pi^+$ and 31 ± 8 $K_S^0K^+$ events. Correcting for relative efficiency, we obtain

$$\frac{\Gamma(D^+ \to \bar{K}^0K^+)}{\Gamma(D^+ \to \bar{K}^0\pi^+)} = 0.317 \pm 0.086 \pm 0.048.$$

The analyses of the decays $D^+ \to \pi^-\pi^+\pi^+$ and $K^-K^+\pi^+$ proceed as in the two-body cases. In the $\pi^-\pi^+\pi^+$ analysis, a cut on the mass of each $\pi^+\pi^-$ combination is imposed to eliminate feed-down from the Cabibbo-allowed channel $D^+ \to K_S^0\pi^+$ where $K_S^0 \to \pi^+\pi^-$. Fits to the resulting three-body combinations (Fig. 3) yield 57 ± 21 $\pi^-\pi^+\pi^+$, 1037 ± 36 $K^-\pi^+\pi^+$, and 78 ± 13 $K^-K^+\pi^+$ events. The pseudoscalar-vector components [$\phi\pi^+$ and $\bar{K}^{*0}(892)K^+$] of the $K^-K^+\pi^+$ final state are isolated from the nonresonant component by additional cuts on the K^+K^- mass for the $\phi\pi^+$ decay, and on the $K^-\pi^+$ mass for the $\bar{K}^{*0}K^+$ decays.[7] In the latter, a cut on the decay angular distribution[8] is also made to further reduce overlap with the nonresonant $K^-K^+\pi^+$ component. Figure 3 also shows the $K^-K^+\pi^+$ mass *after* these cuts. There are 22 ± 5 $\phi\pi^+$ events and 19 ± 5 $K^{*0}K^+$ events at the D^+ mass. We estimate by Monte Carlo methods that

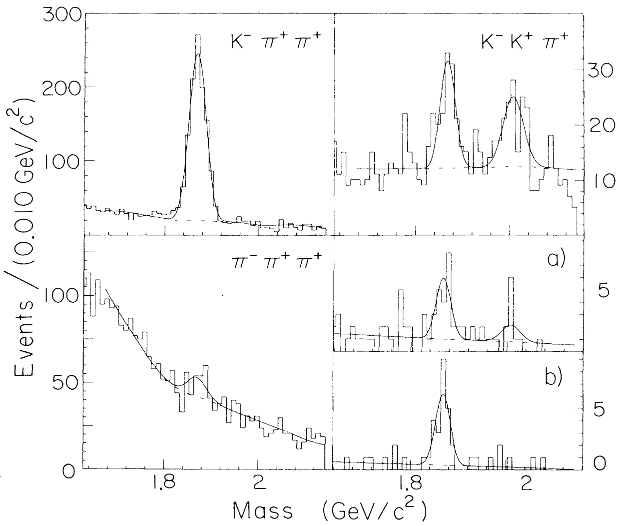

FIG. 3. Invariant mass for $\pi^-\pi^+\pi^+$, $K^-\pi^+\pi^+$, and $K^-K^+\pi^+$. $K^-K^+\pi^+$ events remaining after (a) K^* and (b) ϕ cuts.

1.0 ± 0.4 and 5.0 ± 2.0 events from nonresonant $K^-K^+\pi^+$ contaminate the $\phi\pi^+$ and $\overline{K}^{*0}K^+$ signals, respectively. Correcting for this overlap and the overall detection efficiency we find

$$\frac{\Gamma(D^+ \to \pi^-\pi^+\pi^+)}{\Gamma(D^+ \to K^-\pi^+\pi^+)} = 0.042 \pm 0.016 \pm 0.010,$$

$$\frac{\Gamma(D^+ \to K^-K^+\pi^+)_{\text{nonres.}}}{\Gamma(D^+ \to K^-\pi^+\pi^+)} = 0.059 \pm 0.026 \pm 0.009,$$

$$\frac{\Gamma(D^+ \to \phi\pi^+)}{\Gamma(D^+ \to K^-\pi^+\pi^+)} = 0.084 \pm 0.021 \pm 0.011,$$

$$\frac{\Gamma(D^+ \to \overline{K}^{*0}K^+)}{\Gamma(D^+ \to K^-\pi^+\pi^+)} = 0.048 \pm 0.021 \pm 0.011.$$

The decays $D^+ \to \pi^0\pi^+$, $D^0 \to \pi^-\pi^+\pi^0$, and $D^0 \to \pi^-\pi^+\pi^-\pi^+$ are subject to large combinatorial backgrounds when analyzed by the previous technique. We therefore select events in which one D meson has been identified in a Cabibbo-allowed decay mode (1729 ± 20 D^+D^- and 3762 ± 42 $D^0\overline{D}^0$ events), and evaluate only combinations of the charged tracks and photons belonging to the recoiling D.[9] For the modes $\pi^0\pi^+$ and $\pi^-\pi^+\pi^0$, appropriate combinations are fitted under the two constraints of beam energy and π^0 mass, while for $\pi^-\pi^+\pi^-\pi^+$, only the former constraint is used. To reject background further, a cut on total momentum (± 0.080 GeV/c) is imposed in each event. Background from the Cabibbo-allowed mode $K^-\pi^+\pi^0$ is eliminated by TOF cuts, and that from $\overline{K}^0\pi^0$ and $\overline{K}^0\pi^+\pi^-$, where $K_S^0 \to \pi^+\pi^-$, by cuts on the $\pi^+\pi^-$ mass (0.498 ± 0.030 GeV/c^2). One event of mass 1.869 GeV/c^2, consistent with the decay $D^+ \to \pi^0\pi^+$, is observed in the range 1.8 to 1.9 GeV/c^2, yielding an upper limit (including systematic errors) of 4.2 events at 90% confidence level, or a branching ratio $B(D^+ \to \pi^0\pi^+) \leq 0.53\%$. Using the branching ratio $B(D^+ \to \overline{K}^0\pi^+) = 2.5\%$,[10] we obtain

$$\frac{\Gamma(D^+ \to \pi^0\pi^+)}{\Gamma(D^+ \to \overline{K}^0\pi^+)} < 0.21 \text{ at 90\% confidence level.}$$

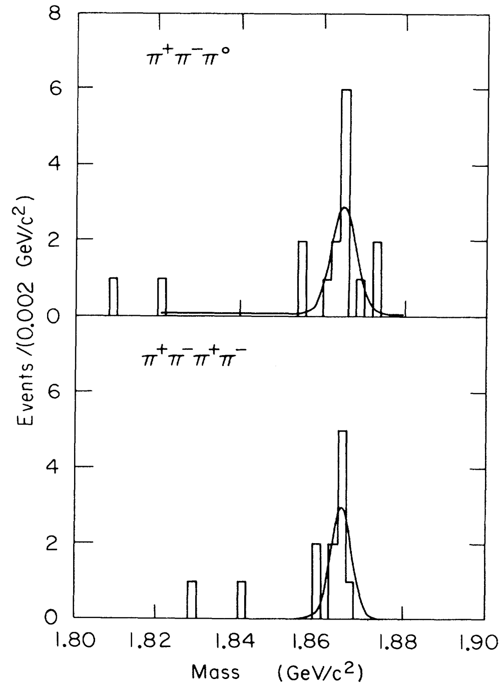

FIG. 4. Mass distribution using the beam energy constraint, for $\pi^-\pi^+\pi^0$ and $\pi^-\pi^+\pi^-\pi^+$.

Fitting to $\pi^-\pi^+\pi^0$ and $\pi^-\pi^+\pi^-\pi^+$ with the expected mass resolution and a flat background (Fig. 4), we find 10^{+4}_{-3} and 9^{+4}_{-3} events, or branching ratios $B(D^0 \to \pi^-\pi^+\pi^0) = (1.1 \pm 0.4 \pm 0.2)\%$ and $B(D^0 \to \pi^-\pi^+\pi^-\pi^+) = (1.5 \pm 0.6 \pm 0.2)\%$. The ten events in the $\pi^-\pi^+\pi^0$ mode are consistent with the decay $D^0 \to \rho^0\pi^0$.

These measurements provide new insights into the mechanism of nonleptonic D decays. Exact SU(3) symmetry predicts the equality of $\Gamma(D^0 \to \pi^-\pi^+)$ and $\Gamma(D^0 \to K^-K^+)$.[11] The inequality previously observed[12] is confirmed here with improved precision. Several distinct effects could contribute to this inequality. The long B-meson lifetime rules out significant contributions from the other quark sectors.[13] Quark-mass effects are likely to be small.[14] Final-state interactions breaking SU(3) symmetry could, however, account for the difference.[14] If the observed inequality is taken to reflect the scale of SU(3)-nonconserving effects, then our observation of the large ratio $\Gamma(D^+ \to \overline{K}^0K^+)/\Gamma(D^+ \to \overline{K}^0\pi^+)$ and the smaller ratio $\Gamma(D^+ \to \pi^0\pi^+)/\Gamma(D^+ \to \overline{K}^0\pi^+)$ suggests that destructive interference between two-body D^+-decay amplitudes may contribute significantly to the difference in D^+ and D^0 lifetimes.[15] Such interference is possible in the amplitudes for both $D^+ \rightarrow \bar{K}^0\pi^+$ and $D^+ \rightarrow \pi^0\pi^+$, but not in that for $D^+ \rightarrow \bar{K}^0K^+$. The magnitudes of the observed ratios could then be attributed to an effective enhancement of the part of the charm-changing weak Hamiltonian that transforms as a 20-plet.[16]

Previous measurements[1,10] have shown that the decay $D^0 \rightarrow \bar{K}^0\pi^0$, which was expected to suffer strong color suppression in the presence of hard-gluon corrections to the weak Hamiltonian,[17] proceeds at a rate comparable to $D^0 \rightarrow K^-\pi^+$. The decay $D^+ \rightarrow \phi\pi^+$, also expected to be color suppressed in this picture,[18] is found to proceed at a rate comparable to other Cabibbo-suppressed D^+ decays. This suggests that color suppression is inoperative in the D^+ system as well, and hence that nonperturbative effects,[19] which could modify the color structure in *both* D^0 and D^+ decays and thereby alter the total widths, may play a significant role.

We gratefully acknowledge the efforts of the SPEAR staff. We also wish to thank A. N. Kamal and M. Peskin for valuable discussions. One of us (N.W.) wishes to thank the Alexander von Humboldt Foundation for support. This work was supported in part by the U. S. National Science Foundation and the U. S. Department of Energy under Contracts No. DE-AC03-76SF00515, No. DE-AC02-76ER01195, No. DE-AC03-81ER40050, and No. DE-AM03-76SF00034.

[1]R. H. Schindler *et al.*, Phys. Rev. D **24**, 78 (1981).

[2]W. Bacino *et al.*, Phys. Rev. Lett. **45**, 329 (1980); R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **54**, 1976 (1985).

[3]E. Di Capua, in *Proceedings of the Twenty Second International Conference on High Energy Physics, Leipzig, East Germany, 1984,* edited by A. Meyer and E. Wieczorek (Akademie der Wissenshaften der DDR, Zeuth, East Germany, 1984), Vol. 1, p. 177.

[4]L.-L. Chau, Phys. Rep. **93**, 1 (1983); R. Rückl, Habilitationsschrift, Universität München, 1983 (unpublished).

[5]D. Bernstein *et al.*, Nucl. Instrum. Methods **226**, 301 (1984).

[6]The weights W_α are calculated as $W_\alpha = \exp[(T_{\text{pred}} - T_{\text{meas}})^2/2\sigma^2]$, where α denotes a π or K, and σ is the TOF time resolution. The normalized weights are defined as $W_\alpha/(W_\pi + W_K)$.

[7]R. Bailey *et al.*, Phys. Lett. **139B**, 320 (1984); S. A. Plaetzer, Ph.D. thesis, University of Illinois, 1985 (unpublished).

[8]The D^+, a pseudoscalar, decays to a pseudoscalar-vector final state in a *p* wave.

[9]For details see R. M. Baltrusaitis *et al.*, Ref. 2.

[10]For a discussion of branching ratios, and their uncertainties, see R. H. Schindler *et al.*, in Ref. 3, Vol. 1, p. 171.

[11]R. L. Kingsley *et al.*, Phys. Rev. D **11**, 1919 (1975); M. B. Einhorn and C. Quigg, Phys. Rev. D **12**, 2015 (1975). The equality of mixing elements $|V_{cd}|$ and $|V_{us}|$ is also assumed.

[12]G. S. Abrams *et al.*, Phys. Rev. Lett. **43**, 481 (1979).

[13]L.-L. Chau and W.-Y. Keung, Phys. Rev. D **29**, 592 (1984), and references therein.

[14]J. F. Donoghue and B. Holstein, Phys. Rev. D **21**, 1334 (1980); D. G. Sutherland, Phys. Lett. **90B**, 173 (1980).

[15]B. Guberina *et al.*, Phys. Lett. **89B**, 111 (1979); B. Stech, University of Heidelberg Report No. HD-THEP-85-8, 1985 (to be published).

[16]I. I. Y. Bigi, Phys. Lett. **90B**, 177 (1980).

[17]J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. **B100**, 313 (1976); N. Cabibbo and L. Maiani, Phys. Lett. **73B**, 418 (1978); D. Fakirov and B. Stech, Nucl. Phys. **B133**, 315 (1978).

[18]R. Rückl, in Ref. 3, Vol. 1, p. 135; see also Stech, Ref. 15.

[19]N. Deshpande, M. Gronau, and D. Sutherland, Phys. Lett. **90B**, 431 (1980); M. Gronau and D. Sutherland, Nucl. Phys. **B183**, 367 (1981).