Measurement of $D_s^{\pm}$ Decays and Cabibbo-Suppressed $D^{\pm}$ Decays

J. C. Anjos,[3] J. A. Appel,[5] A. Bean,[1] S. B. Bracker,[8] T. E. Browder,[1] L. M. Cremaldi,[4] J. R. Elliott,[4] C. O. Escobar,[7] P. Estabrooks,[2] M. C. Gibney,[4] G. F. Hartner,[8] P. E. Karchin,[1],[a] B. R. Kumar,[8] M. J. Losty,[6] G. J. Luste,[8] P. M. Mantsch,[5] J. F. Martin,[8] S. McHugh,[1] S. R. Menary,[8] R. J. Morrison,[1] T. Nash,[5] U. Nauenberg,[4] P. Ong,[8] J. Pinfold,[2] G. Punkar,[1] M. V. Purohit,[5] J. R. Raab,[1],[b] A. F. S. Santoro,[3] J. S. Sidhu,[2],[c] K. Sliwa,[5] M. D. Sokoloff,[5],[d] M. H. G. Souza,[3] W. J. Spalding,[5] M. E. Streetman,[5] A. B. Stundžia,[8] and M. S. Witherell[1]

[1]*University of California, Santa Barbara, Santa Barbara, California, 93106*
[2]*Carleton University, Ottawa, Ontario, Canada K1S 5B6*
[3]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[4]*University of Colorado, Boulder, Colorado, 80309*
[5]*Fermi National Accelerator Laboratory, Batavia, Illinois, 60510*
[6]*National Research Council, Ottawa, Ontario, Canada K1A 0R6*
[7]*Universidade de São Paulo, São Paulo, Brazil*
[8]*University of Toronto, Toronto, Ontario, Canada M5S 1A7*

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We report on a Dalitz-plot analysis of 250 $D^{\pm}$ and 290 $D_s^{\pm}$ decays into $K^+K^-\pi^{\pm}$. We measure the relative rate for each charmed meson decaying into $\phi\pi^{\pm}$, $\bar{K}^{*0}(K^{*0})K^{\pm}$, and nonresonant $K^+K^-\pi^{\pm}$, and determine the $D_s^{\pm}$ mass. In addition, we measure the relative branching ratios for the decays of $D_s^{\pm}$ and $D^{\pm}$ into $\phi\pi^+\pi^-\pi^{\pm}$ and nonresonant $K^+K^-\pi^+\pi^-\pi^{\pm}$.

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Although there has been a systematic study of the hadronic decays of the $D^{\pm}$ and D^0, this has not yet been possible in the case of $D_s^{\pm}$. The D_s was first observed in the decay modes $\phi\pi^{\pm}$,[1] and $\bar{K}^{*0}(K^{*0})K^{\pm}$,[2-4] in which the background is reduced by the selection of the pseudoscalar-vector (PV) final state. We have already published $D_s^{\pm}$ lifetime measurements, using these two modes.[3,5] For the present analysis, which involves the full 10^8-event data sample, we apply additional vertex separation cuts which are not suitable for the lifetime analysis. The resulting sample includes about 250 $D^{\pm}$ and 290 $D_s^{\pm}$ decays into the mode $K^+K^-\pi^{\pm}$ with very little background, even without selection of the resonant components. In this Letter we present the results of a Dalitz-plot analysis of these samples, and we demonstrate the extent to which these decays are dominated by the quasi two-body PV channels. In addition, we give the results of a study of the modes $\phi\pi^+\pi^-\pi^{\pm}$ and nonresonant $K^+K^-\pi^+\pi^-\pi^{\pm}$.

For the study of three-particle states, we choose events satisfying the particle-identification assignment $K^+K^-\pi^+$. (Throughout the paper, the charge-conjugate states are implicitly included.) There is a minimum requirement on the product of Cherenkov probabilities for particle identification. We also require the three charged tracks to form a good vertex, and the line of flight of the reconstructed charm candidate to pass within 75 μm of a reconstructed primary vertex candidate. Candidates which decay at least a distance L downstream of the primary vertex are selected as charm candidates. This distance L is chosen to be 6σ, where σ is the error on the distance between primary and secondary vertices. The value of σ is typically 300 μm for the average D momentum of 60 GeV/c, and increases linearly with momentum.

The above criteria for selecting charm-decay vertices were effectively those used in the lifetime analysis.[3,5] We use two additional cuts in the present analysis to reduce the background further. If any other track in the event passes within 80 μm of the secondary vertex, the event is discarded. We also demand that none of the three tracks from the secondary vertex passes closer to the primary vertex than to the secondary. The two cuts keep about 75% of the D_s^+ events which pass the earlier cuts, but reduce the background by a factor of about 6. The corrected lifetimes after these cuts agree with the measured lifetimes.[3,5]

The $K^+K^-\pi^+$ mass spectra after these cuts are shown in Fig. 1. In both the $\phi\pi^+$ and $\bar{K}^{*0}K^+$ samples there are very clear peaks for the D_s^+ decay and the Cabibbo-suppressed D^+ decay. Figure 1(c) shows the mass spectrum for those events not included in either the $\phi\pi^+$ or $\bar{K}^{*0}K^+$ samples. For this mass plot there is an additional cut $t > 0.2$ ps, where t is the proper time calculated from the minimum distance L. For the first time, we are able to observe the decay of the D_s^+ to nonresonant $K^+K^-\pi^+$, with a significance of about five standard deviations after subtraction of the feedthrough from $K^{*0}K^+$ decays.

The small background allows us to analyze the complete $KK\pi$ Dalitz plot and extract the individual contributions. Figure 2(a) shows the plot for the D^+ mass re-

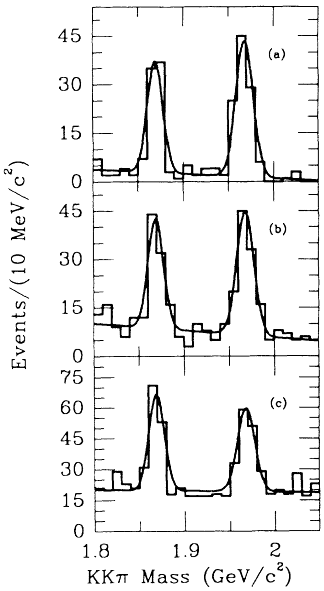

FIG. 1. The $K^+K^-\pi^+$ mass spectra for the (a) $\phi\pi^+$, (b) $\bar{K}^{*0}K^+$, and (c) nonresonant $K^-K^+\pi^+$ final states. All three samples have a cut on vertex separation, as described in the text. There is an additional cut on the decay time of $t > 0.20$ ps in the nonresonant sample. The nonresonant sample also includes some feedthrough from $\bar{K}^{*0}K^+$ events in which the $K^-\pi^+$ mass is outside the accepted $\bar{K}^{*0}$ range. The curve represents a fit with Gaussian peaks for the D^+ and D_s^+ and a straight-line background.

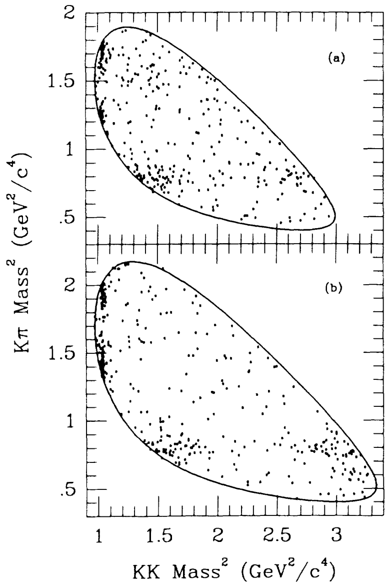

FIG. 2. The Dalitz plots for $K^-K^+\pi^+$ events in the (a) D^+ and (b) D_s^+ regions.

gion, 1.856–1.882 GeV/c^2; Fig. 2(b) shows the plot for the D_s^+ region, 1.954–1.982 GeV/c^2. The $\phi\pi^+$ and $K^{*0}K^+$ bands are evident in each plot.[6] There is also a flat distribution of events in each Dalitz plot, due to a combination of nonresonant $K^+K^-\pi^+$ decays and background.

Because the decay-time distribution of the signal is quite different from that of the background, we are able to make an additional separation of the charm signals from background. We perform a maximum-likelihood fit using the $M^2(KK_\pi)$, $M^2(KK)$, $M^2(K\pi)$, and the decay time t of each event. The charmed meson is described by a Gaussian in mass and an exponential time distribution with lifetime 0.47 ps. The number of events coming from each of the three components, $\phi\pi$, K^*K, and nonresonant $KK\pi$, is allowed to vary, as is the phase of the background amplitude. The normalization and distribution of the background are fixed from the mass regions outside the charm peaks. In addition, in the D_s^+ fit there is a small contribution from misidentified $D^+ \to K^-\pi^+\pi^+$ decays. This misidentification accounts for 5% of the total number of events in the $K^+K^-\pi^+$ sample. The misidentified events are distributed over a large mass region, with very few at the D_s^+ mass. We find 122 ± 12 $\phi\pi^+$, 117 ± 13 $\bar{K}^{*0}K^+$, and 48 ± 13 nonresonant (NR) $K^-K^+\pi^+$ events from the D_s^+ fit. The efficiencies for the three modes are (2.73 ± 0.09)% for $\phi\pi^+$, (2.25 ± 0.09)% for $\bar{K}^{*0}K^+$, and (2.10 ± 0.12)% for nonresonant $K^-K^+\pi^+$. The results of the D^+ fit are 84 ± 10 $\phi\pi^+$, 73 ± 11 $\bar{K}^{*0}K^+$, and 96 ± 13 nonresonant $K^-K^+\pi^+$.

It is convenient to give the branching ratios relative to $D_s^+ \to \phi\pi^+$, which is the mode seen most commonly. There is no measurement yet of the absolute branching ratio, although indirect arguments indicate that $B(D_s^+ \to \phi\pi^+) \approx 4\%$.[1] The relative acceptances are determined by a Monte Carlo simulation. After corrections for acceptance we find the ratios given in Table I.

The results from the D^+ fit can be combined with our measurement of the decay mode $D^+ \to K^-\pi^+\pi^+$ to measure the branching ratios relative to the best measured D^+ mode. The branching ratio used for $D^+ \to K^-\pi^+\pi^+$ is (9.1 ± 1.4)%.[7] The results are shown in Table II. The systematic error is dominated by the error in the probability of identifying the extra kaon.

With this large sample of $D_s^+ \to K^+K^-\pi^+$ events and good mass resolution we are able to measure the D_s^+ mass with high precision. The uncorrected result is $M(D_s^+) = 1967.7\pm0.7$ MeV/c^2. The small systematic

TABLE I. D_s^+ branching ratios (B) relative to $B(D_s^+ \to \phi\pi^+)$.

Decay mode	$B/B(D_s^+ \to \phi\pi^+)$
$D_s^+ \to \bar{K}^{*0}K^+$	$0.87\pm0.13\pm0.05$
$(D_s^+ \to K^-K^+\pi^+)_{NR}$	$0.25\pm0.07\pm0.05$
$D_s^+ \to \phi\pi^+\pi^-\pi^+$	$0.42\pm0.13\pm0.07$
$(D_s^+ \to K^+K^-\pi^+\pi^-\pi^+)_{NR}$	<0.32 (90% C.L.)

TABLE II. D^+ branching ratios (B) relative to $B(D^+ \to K^-\pi^+\pi^+)$ and absolute branching ratios (Ref. 7).

Decay mode	Observed number	$\frac{B}{B(D^+ \to K^-\pi^+\pi^+)}$	Absolute B (%)
$D^+ \to \phi\pi^+$	83.8 ± 10.0	$0.071 \pm 0.008 \pm 0.007$	$0.65 \pm 0.07 \pm 0.12$
$D^+ \to \bar{K}^{*0}K^+$	73.4 ± 10.7	$0.058 \pm 0.009 \pm 0.006$	$0.53 \pm 0.08 \pm 0.10$
$(D^+ \to K^-K^+\pi^+)_{NR}$	94.5 ± 13.4	$0.049 \pm 0.008 \pm 0.006$	$0.45 \pm 0.07 \pm 0.09$
$D^+ \to \phi\pi^+\pi^-\pi^+$	$0.0^{+0.6}_{-0.0}$	< 0.002 (90% C.L.)	< 0.02 (90% C.L.)
$(D^+ \to K^+K^-\pi^+\pi^-\pi^+)_{NR}$	$11.6^{+7.9}_{-6.8}$	< 0.03 (90% C.L.)	< 0.24 (90% C.L.)

offset to the mass scale is determined from the $D^+ \to K^+K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ samples. Since the kinematics of these decays are very similar to $D_s^+ \to K^+K^-\pi^+$, it is possible to calculate reliably the corresponding mass shift for the D_s^+. The result for the D^+ is $M(D^+) = 1868.7 \pm 0.3(\text{stat})$ MeV/c^2, which is somewhat lower than the world average of 1869.3 ± 0.6 MeV/c^2. This corresponds to a shift in the D_s^+ mass of 0.6 ± 0.7 MeV/c^2, resulting in a corrected mass of $M(D_s^+) = 1968.3 \pm 0.7 \pm 0.7$ MeV/c^2. The systematic error is dominated by the absolute uncertainty in the D^+ mass.

We have also looked at the $K^+K^-\pi^+\pi^-\pi^+$ final states, using vertex cuts very similar to those used in the $KK\pi$ analysis. Figure 3(a) shows the five-prong invariant mass with the K^+K^- mass constrained to the ϕ region. There is a clear peak at the D_s^+ mass with a significance of 5.6 standard deviations, but there is no peak at the D^+. Figure 3(b) shows the $K^+K^-\pi^+\pi^-\pi^+$ invariant mass where K^+K^- mass combinations consistent with a ϕ mass are excluded. There is not a clear peak at either the D_s^+ or D^+. Both plots show curves that are the results of fits which allow Gaussian D_s^+ and D^+ peaks, and a background term which is linear in the mass. In the $\phi\pi^+\pi^-\pi^+$ plot there are 19.5 ± 4.7 events in the D_s^+ peak, and 0.0 ± 0.6 at the D^+. The result of the fit for the $K^+K^-\pi^+\pi^-\pi^+$ plot gives 9.5 ± 8.4 events at the D_s^+ and 8.9 ± 7.4 events at the D^+. The efficiencies for obtaining five-body modes are approximately 33% of those for three-body modes. Correcting for efficiency, background under the ϕ peak, and ϕ mesons not included in our cut, we obtain the relative branching ratios given in Tables I and II.

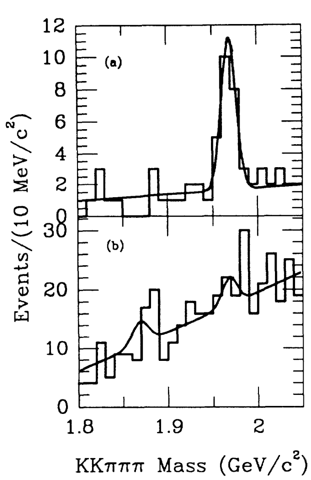

FIG. 3. The $K^+K^-\pi^+\pi^-\pi^+$ mass spectra for the (a) $\phi\pi^+\pi^-\pi^+$ and (b) $(K^+K^-\pi^+\pi^-\pi^+)_{NR}$ final states. The curves show the results of the fits described in the text.

These measurements provide insight into D_s^+ and Cabibbo-suppressed D^+ decays. The decays $D_s^+ \to \phi\pi^+$ and $D^+ \to \bar{K}^{*0}K^+$ are described by the spectator-quark diagram sometimes referred to as color aligned[8]; the decays $D^+ \to \phi\pi^+$ and $D_s^+ \to \bar{K}^{*0}K^+$, on the other hand, proceed via a diagram without automatic color alignment. Our measurement of

$$\frac{\Gamma(D_s^+ \to \bar{K}^{*0}K^+)}{\Gamma(D_s^+ \to \phi\pi^+)} = 0.87 \pm 0.13 \pm 0.05$$

is lower than Albrecht *et al.*'s result of 1.44 ± 0.37.[2] The fact that this ratio is approximately unity confirms that the two spectator diagrams are approximately equal. This is in agreement with the situation in Cabibbo-suppressed D^+ decays, where we measure the ratio

$$\Gamma(D^+ \to \phi\pi^+)/\Gamma(D^+ \to \bar{K}^{*0}K^+) = 1.4 \pm 0.3,$$

and Baltrusaitis *et al.* measures the same ratio to be 1.7 ± 0.9.[9]

The first measurement of the nonresonant $D_s^+ \to K^-K^+\pi^+$ shows that it accounts for only 20% of all $K^-K^+\pi^+$ decays. (One must remember to include the appropriate $\phi \to K^+K^-$ and $\bar{K}^{*0} \to K^-\pi^+$ branching ratios for this calculation.) This is similar to the situation in the decays $D^0 \to K^-\pi^+\pi^0$, $D^+ \to \bar{K}^0\pi^+\pi^0$, and $D^0 \to \bar{K}^0\pi^+\pi^-$, where the PV decays dominate, although the $D^+ \to K^-\pi^+\pi^+$ decay seems to be somewhat anomalous.[7] The ability to observe a rather small decay mode of the D_s without the benefit of resonance-selecting cuts is a measure of the effectiveness of using the vertex separation cuts to reduce background.

Measurements of multibody final states are important in determining whether two-body modes dominate in charmed-meson decay. The dominance of two-body modes is important for models which describe the ratios of lifetimes by summing the predicted decay widths for such modes.[10] Our relative branching ratio for $D_s^+ \rightarrow \phi\pi^+\pi^-\pi^+$ is smaller than the ratio $1.11 \pm 0.37 \pm 0.28$ measured by Albrecht *et al.*[11] It is also smaller than, but consistent with, our previous measurement using a subset of the present sample.[12] The change is due to a better determination of the $D_s^+ \rightarrow \phi\pi^+\pi^-\pi^+$ detection efficiency in addition to the effect of more data. The $\pi^+\pi^-$ mass distribution for events in the $D_s^+ \rightarrow \phi\pi^+\pi^-\pi^+$ peak is not consistent with a phase-space distribution, but consistent with the distribution expected for the $\phi\rho^0\pi^+$ final state. It is impossible to measure the amount of nonresonant $\phi\pi^+\pi^-\pi^+$ with our statistics. We also cannot rule out the possibility that the $\phi\pi^+\pi^-\pi^+$ system is dominated by the quasi two-body decay $D_s^+ \rightarrow \phi a_1(1270)$, $a_1 \rightarrow \rho^0\pi^+$. Although at the central value of the a_1 this decay is not allowed, the tail of the Breit-Wigner form extends well into the kinematically allowed $\rho\pi$ mass region.

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[a]Now at Yale University, New Haven, Connecticut 06520.

[b]Now at CERN, Division EP, CH-1211 Genève, Switzerland.

[c]Deceased.

[d]Now at University of Cincinnati, Cincinnati, Ohio 45221.

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