Direct Measurements of Charmed-*D*-Meson Hadronic Branching Fractions

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A new technique is applied to data collected at the $\psi(3770)$ resonance to derive charmed-*D*-meson branching fractions without relying on the measurement of *D*-production cross sections. Measurements are presented for three decay modes of the D^0 ($K^-\pi^+$, $D^-\pi^-\pi^+\pi^+$, and $K^-\pi^+\pi^0$) and four decay modes of the D^+ ($K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K_S^0\pi^+$, and $K_S^0\pi^+\pi^0$). The resulting branching fractions are significantly larger than previous measurements.

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The exclusive production of $D^0\bar{D}^0$ and D^+D^- pairs at the $\psi(3770)$ resonance provides a unique opportunity to measure charmed-*D*-meson branching fractions directly. Previous measurements at this resonance of *D* hadronic branching fractions[1-3] have relied on a determination of the charm-production cross section (σ_D) to normalize observed *D*-meson production rates. However, the kinematics of $D\bar{D}$ pair production at the $\psi(3770)$ makes it possible to measure *D* branching fractions independent of σ_D. The results obtained by this method differ significantly from earlier results.

The data were collected with the Mark III detector[4] at the SLAC e^+e^- storage ring SPEAR at an average energy of $\sqrt{s}=3.768$ GeV. We assume that events containing charmed *D* mesons arise solely from $D\bar{D}$ production, so that the detection of a single *D* in an event implies that the recoiling system is a monochromatic $\bar{D}$.[5] The data are searched for events containing either one or two reconstructed *D* mesons. For this analysis, three D^0 decay channels ($K^-\pi^+$, $K^-\pi^-\pi^+\pi^+$, and $K^-\pi^+\pi^0$) and four D^+ decay channels ($K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K_S^0\pi^+$, and $K_S^0\pi^+\pi^0$) are considered. By comparison of the number of times a single *D* (or $\bar{D}$) is reconstructed (single tags) with the number of fully reconstructed $D\bar{D}$ events (double tags), the individual *D*-meson branching fractions can be derived independently of σ_D.

Single-tag reconstruction proceeds as follows. Charged particles are required to satisfy $|\cos\theta| < 0.85$ (where θ is the polar angle with respect to the beam) to ensure reliable drift-chamber measurements. A charged particle which enters the time-of-flight (TOF) system ($|\cos\theta| < 0.75$) is identified as either a π or K, according to which predicted time is closer to the measured time. Unidentified tracks are assumed to be pions. Showers with energies greater than 0.050 GeV are used as photon candidates. Neutral kaons are detected through the decay $K_S^0 \to \pi^+\pi^-$, where the $\pi^+\pi^-$ invariant mass is required to lie within 0.0156 GeV/c^2 of the K_S^0 mass. Appropriate combinations of charged tracks and photons are formed for the three D^0 and four D^+ decay modes under study. To improve mass resolution and further reduce backgrounds, the energy of each *D* candidate is constrained to the beam energy (E_b). The small spread in E_b ($\sigma_{E_b}=0.0015$ GeV) and the low *D* momenta (0.245 GeV/*c* for D^+ and 0.285 GeV/*c* for D^0) produce a mass resolution of $\sigma_M \sim 0.003$ GeV/c^2. Modes containing a π^0 are fitted to the two constraints of beam energy and π^0 mass, and fits with $\chi^2 > 6$ are removed. The resulting mass distributions for the single-tag modes are shown in Fig. 1. In each case, a flat background determined from the control region 1.83 to 1.85 GeV/c^2 is subtracted and the number of single tags is counted over a region dependent on the specific decay mode.

Double tags are subject to additional constraints. Events are fitted to the hypothesis

$$e^+e^- \to X\bar{X} \to \text{final state},$$

where $M_X = M_{\bar{X}}$. Energy-momentum conservation for

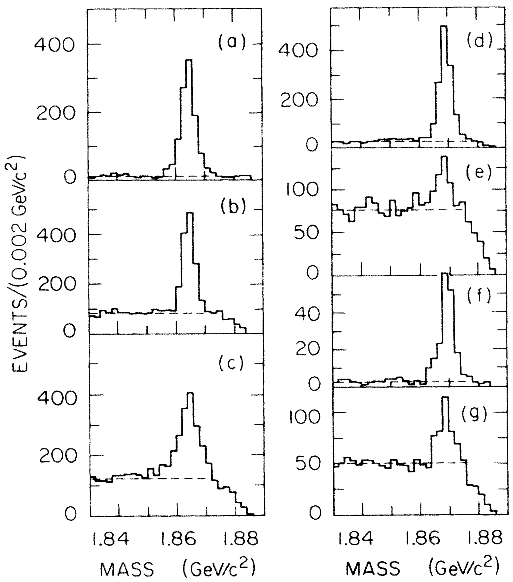

FIG. 1. Beam-constrained mass for single tags: (a) $D^0 \to K^-\pi^+$, (b) $D^0 \to K^-\pi^-\pi^+\pi^+$, (c) $D^0 \to K^-\pi^+\pi^0$, (d) $D^+ \to K^-\pi^+\pi^+$, (e) $D^+ \to K^-\pi^+\pi^+\pi^0$, (f) $D^+ \to K_S^0\pi^+$, (g) $D^+ \to K_S^0\pi^+\pi^0$.

$D\bar{D}$ production provides six constraints (with an additional constraint for each π^0 or K_S^0), all but one of which are used in the kinematic fitting (i.e., M_X is not fixed at M_D). The improved background rejection provided by the constrained fit permits a loosening of the particle-identification cuts, thereby improving detection efficiency. Charged tracks are assigned as either π's or K's (or both), requiring only consistency with the TOF times and the dE/dx pulse-height measurements.[6] When no information is present, or the information is inconclusive, both hypotheses are considered. The resulting distributions of M_X are shown in Fig. 2 for six $D^0\bar{D}^0$ and four D^+D^- decay modes. A constant background is determined from the control region 1.83 to 1.85 GeV/c^2. Events within ± 0.008 GeV/c^2 of the D mass constitute the signal.

To determine the individual branching fractions (B_i) and the number of produced $D\bar{D}$ pairs (N), the corrected number of single tags (S_i) and double tags (D_{ij}) are employed in a χ^2 minimization fit, using the following expressions:

$$S_i = 2NB_i\epsilon_i - \sum_j 2NB_iB_j a_{ij}^i;$$

$$D_{ij} = 2NB_iB_j\epsilon_{ij}, \quad \text{if } i \neq j; \quad D_{ii} = NB_i^2\epsilon_{ii},$$

where ϵ_i is the efficiency for reconstructing a single tag in the ith D decay mode, ϵ_{ij} is the efficiency for reconstructing a double tag for $D\bar{D}$ decay modes i and j, and α_{ij}^i is the efficiency for reconstructing a single tag of mode i while simultaneously reconstructing the entire event as a double tag of modes i and j. The second term[7] in the expression for S_i removes from the

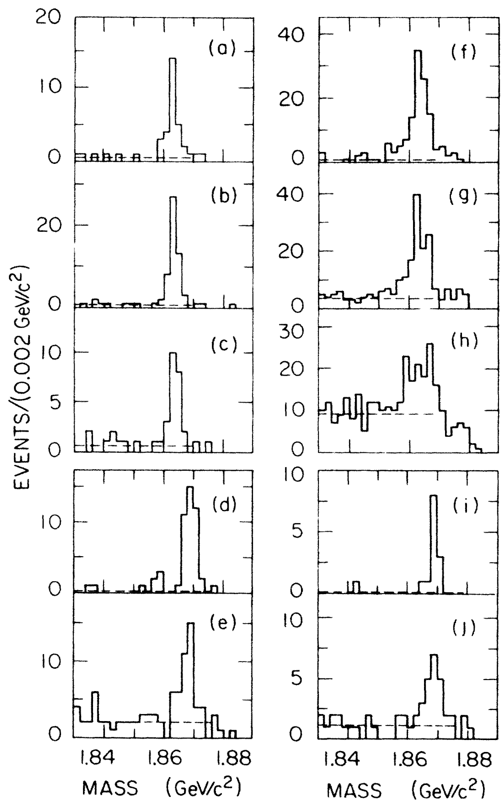

FIG. 2. Fitted mass (M_X) for double tags: (a) $D^0\bar{D}^0 \to K^-\pi^+$ vs $K^+\pi^-$, (b) $D^0\bar{D}^0 \to K^-\pi^+$ vs $K^+\pi^+\pi^-\pi^-$, (c) $D^0\bar{D}^0 \to K^-\pi^-\pi^+\pi^+$ vs $K^+\pi^+\pi^-\pi^-$, (d) $D^+D^- \to K^-\pi^+\pi^+$ vs $K^+\pi^-\pi^-$, (e) $D^+D^- \to K^-\pi^+\pi^+$ vs $K^+\pi^-\pi^-\pi^0$, (f) $D^0\bar{D}^0 \to K^-\pi^+$ vs $K^+\pi^-\pi^0$, (g) $D^0\bar{D}^0 \to K^-\pi^-\pi^+\pi^+$ vs $K^+\pi^-\pi^0$, (h) $D^0\bar{D}^0 \to K^-\pi^+\pi^0$ vs $K^+\pi^-\pi^0$, (i) $D^+D^- \to K^-\pi^+\pi^+$ vs $K_S^0\pi^-$, (j) $D^+D^- \to K^-\pi^+\pi^+$ vs $K_S^0\pi^-\pi^0$.

single-tag sample those tags which also appear in the double-tag sample. This subtraction leaves the two samples independent and eliminates the problem of directly correlated errors. The efficiencies are determined by a detailed Monte Carlo simulation of $D\bar{D}$ production and decay, including the detector response. Fits are performed separately for neutral D's and charged D's, yielding $21\,4000^{+1600}_{-1400} \pm 1400$ produced $D^0\bar{D}^0$ events and $16\,000^{+2100}_{-1700} \pm 800$ produced D^+D^- events (where the first error is statistical and the second systematic). A comparison of the observed numbers of tags with the predictions from the fits is shown in Tables I and II. The fit to neutral D's yields a χ^2 of 4.05 for 5 degrees of freedom while the fit to charged D's yields a χ^2 of 4.79 for 3 degrees of freedom. The ratio of $D^0\bar{D}^0$ to D^+D^- production is not constrained in the fits, but the measured result ($1.34^{+0.17}_{-0.20} \pm 0.11$) agrees well with the ratio (1.36) predicted by Eichten *et al.*[8] using a coupled-channel model. The fitted values for the D branching fractions, summarized in Table III, are significantly larger

TABLE I. Comparison of $D^0\bar{D}^0$ single- and double-tag measurements and fit results. The errors are statistical only, but include the error on the background subtraction. Reference to a state also implies reference to its charge conjugate. The overlaps with double tags have been subtracted from the single tags.

D^0 tags	$K^-\pi^+$	$K^-\pi^+\pi^0$	$K^-\pi^+\pi^-\pi^+$
$K^+\pi^-$	26 ± 6	95 ± 11	50 ± 8
(fit)	29	91	59
$K^+\pi^-\pi^0$		69 ± 17	105 ± 13
(fit)		70	89
$K^+\pi^-\pi^+\pi^-$			22 ± 6
(fit)			23
Single tags	930 ± 37	930 ± 64	992 ± 55
(fit)	916	978	985

than previous determinations. Finally, the measurements of $B(K^-\pi^+)$, $B(\bar{K}^0\pi^+)$, and $B(K^-\pi^+\pi^+)$ can be used to express our previous relative measurements of Cabbibo-angle-suppressed D decays as absolute branching fractions.[9]

The systematic errors on the fitted branching fractions arise from several sources. The uncertainties in charged-particle tracking efficiency and particle identification contribute less than 2% to the uncertainty in final-state efficiencies. The uncertainty in the estimated detection efficiency for π^0's (resulting primarily from the modeling of gaps and support structures in the shower counter) is about 5% for modes containing a single π^0. In addition, backgrounds in specific single-tag modes ($D^0 \to K^-\pi^+\pi^0$, $D^+ \to K_S^0\pi^+\pi^0$, and $D^+ \to K^-\pi^+\pi^+\pi^0$) may not be flat. In these cases, allowances for other background shapes have been included, contributing 5%–16% uncertainty to the efficiencies for these decay modes. The resonance substructure in three-body and four-body final states introduces an additional uncertainty in the detection efficiencies of not more than 15%.[10]

TABLE II. Same as Table I, but for D^+D^- events.

D^+ tags	$K^-\pi^+\pi^+$	$K^-\pi^+\pi^+\pi^0$	$K_S^0\pi^+$	$K_S^0\pi^+\pi^0$
$K^+\pi^-\pi^-$	39 ± 7	35 ± 9	13 ± 4	18 ± 6
(fit)	45	20	12	16
Single tags	1164 ± 42	175 ± 43	161 ± 14	159 ± 32
(fit)	1155	210	162	165

There are several interesting consequences of these larger D branching-fraction measurements. The D^0 and D^+ cross sections at the $\psi(3770)$ can be derived from the number of produced $D\bar{D}$ events together with luminosity measurements. The integrated luminosity as determined from wide-angle Bhabha scattering and $\mu^+\mu^-$ events is 9558 ± 479 nb^{-1}. Using this value, we obtain $\sigma_{D^0} = 4.48^{+0.33}_{-0.29} \pm 0.37$ nb and $\sigma_{D^+} = 3.35^{+0.44}_{-0.36} \pm 0.24$ nb.[11] These are substantially smaller than previous values[12] derived from the direct measurement of $\sigma_{\psi(3770)}$.[13] To further understand this discrepancy, the cross section times branching fractions ($\sigma_D B_i$) for the seven channels studied can be derived from the unsubtracted single tags. These results, along with previous measurements summarized in Table III, show very good agreement between experiments. It is the division by each experiment's value for σ_D which leads to the systematic difference

TABLE III. Comparison of D production cross sections (nanobarns) at the $\psi(3770)$, cross section times branching fractions (nanobarns), and derived branching fractions (percent).

Decay mode	Lead-glass wall[a,b]	Mark II[c]	This experiment
σ_{D^0}	11.5 ± 2.5	8.0 ± 1.0 ± 1.2	$4.48^{+0.33}_{-0.29} \pm 0.37$
$\sigma B(K^-\pi^+)$	0.25 ± 0.05	0.24 ± 0.02	0.248 ± 0.009 ± 0.014
$B(K^-\pi^+)$	2.2 ± 0.6	3.0 ± 0.6	5.6 ± 0.4 ± 0.3
$\sigma B(K^-\pi^-\pi^+\pi^+)$	0.36 ± 0.10	0.68 ± 0.11	0.525 ± 0.026 ± 0.054
$B(K^-\pi^-\pi^+\pi^+)$	3.2 ± 1.1	8.5 ± 2.1	11.8 ± 0.9 ± 1.1
$\sigma B(K^-\pi^+\pi^0)$	1.4 ± 0.6	0.68 ± 0.23	0.759 ± 0.044 ± 0.083
$B(K^-\pi^+\pi^0)$	12 ± 6	8.5 ± 3.2	17.5 ± 1.3 ± 1.3
σ_{D^+}	9.0 ± 2.0	6.0 ± 0.7 ± 1.0	$3.35^{+0.44}_{-0.36} \pm 0.24$
$\sigma B(K^-\pi^+\pi^+)$	0.36 ± 0.06	0.38 ± 0.05	0.388 ± 0.013 ± 0.029
$B(K^-\pi^+\pi^+)$	3.9 ± 1.0	6.3 ± 1.5	11.6 ± 1.4 ± 0.7
$\sigma B(K^-\pi^+\pi^+\pi^0)$			0.177 ± 0.042 ± 0.042
$B(K^-\pi^+\pi^+\pi^0)$			$6.3^{+1.4}_{-1.3} \pm 1.2$
$\sigma B(\bar{K}^0\pi^+)$	0.14 ± 0.05	0.14 ± 0.03	0.135 ± 0.012 ± 0.010
$B(\bar{K}^0\pi^+)$	1.5 ± 0.6	2.3 ± 0.7	4.1 ± 0.6 ± 0.3
$\sigma B(\bar{K}^0\pi^+\pi^0)$		0.78 ± 0.48	0.417 ± 0.081 ± 0.075
$B(\bar{K}^0\pi^+\pi^0)$		12.9 ± 8.4	$12.9^{+2.7}_{-2.6} \pm 2.1$

[a]Reference 1.
[b]Reference 2.
[c]Reference 3.

in branching fractions.[14] This suggests either that the discrepancies in branching fractions lie with the measurements of σ_D, or that the underlying assumption of the previous measurements, namely that the $\psi(3770)$ decays exclusively to $D\bar{D}$, is incorrect. Furthermore, our larger values of the D branching fractions reduce previous determinations of charm-production cross sections and branching fractions of heavy mesons which cascade through D hadronic modes.

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[1]I. Peruzzi *et al.*, Phys. Rev. Lett. **39**, 1301 (1977).

[2]D. L. Scharre *et al.*, Phys. Rev. Lett. **40**, 74 (1978).

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

[4]For a description of the Mark III detector, see D. Bernstein *et al.*, Nucl. Instrum. Methods **226**, 301 (1984).

[5]Throughout this paper, we adopt the convention that reference to a state also implies reference to its charge conjugate. The effects of $D^0\bar{D}^0$ mixing and doubly-Cabibbo-suppressed decays are expected to be negligible and are ignored.

[6]For TOF consistency, the measured time must match the predicted time for a π or K within four standard deviations (σ), where $\sigma \sim 190$ ps. Consistency with the dE/dx measurement implies that the truncated mean of six to twelve ionization measurements is within 3σ (4.5σ) of the predicted value on the low (high) side, where $\sigma \sim 15\%$ of the peak value. For further description of the dE/dx system, see J. Roehrig *et al.*, Nucl. Instrum. Methods **226**, 319 (1984).

[7]For the case $i=j$, the number of decays is NB_i^2, but both the D and the $\bar{D}$ may contribute a single tag to the measurement of S_i. This extra factor of 2 leads to the subtraction of $2NB_i^2\alpha_{ii}^i$ single tags.

[8]E. Eichten *et al.*, Phys. Rev. D **21**, 203 (1980).

[9]With use of our fitted values of $B(K^-\pi^+)$, $B(\bar{K}^0\pi^+)$, and $B(K^-\pi^+\pi^+)$, the results of R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **55**, 150 (1985), become

$$B(D^0 \rightarrow K^+K^-) = (0.68 \pm 0.11 \pm 0.08)\%,$$
$$B(D^0 \rightarrow \pi^+\pi^-) = (0.18 \pm 0.06 \pm 0.04)\%,$$
$$B(D^+ \rightarrow K^+\bar{K}^0) = (1.30 \pm 0.40 \pm 0.22)\%,$$
$$B(D^+ \rightarrow \pi^+\pi^+\pi^-) = (0.49 \pm 0.19 \pm 0.12)\%,$$
$$B(D^+ \rightarrow K^+K^-\pi^+)_{\rm nonres} = (0.68 \pm 0.31 \pm 0.11)\%,$$
$$B(D^+ \rightarrow \phi\pi^+) = (0.97 \pm 0.27 \pm 0.14)\%,$$
$$B(D^+ \rightarrow \bar{K}^{*0}K^+) = (0.56 \pm 0.25 \pm 0.13)\%.$$

[10]The substructure of the three-body decays, taken from R. H. Schindler *et al.*, Stanford Linear Accelerator Center Report No. SLAC-PUB-3799, 1985 (to be published), implies less than 5% uncertainty in the final-state efficiencies. For $K^-\pi^-\pi^+\pi^+$, the results of M. Piccolo *et al.*, Phys. Lett. **70B**, 260 (1977), have been used. Since no measurements for $K^-\pi^+\pi^+\pi^0$ have been reported, we use a phase-space decay with a 15% uncertainty in reconstruction efficiency.

[11]Note that σ_{D^0} is defined to be twice $\sigma_{D^0\bar{D}^0}$ and σ_{D^+} is twice $\sigma_{D^+D^-}$.

[12]Values of σ_{D^0} and σ_{D^+} derived from the measurements of the total hadronic cross section are $\sigma_{D^0} = 11.5 \pm 2.5$ and $\sigma_{D^+} = 9.0 \pm 2.0$ [I. Peruzzi *et al.*, Phys. Rev. Lett. **39**, 1301 (1977)], $\sigma_{D^0} = 8.0 \pm 1.0 \pm 1.2$ and $\sigma_{D^+} = 6.0 \pm 0.7 \pm 1.0$ [R. H. Schindler *et al.*, Phys. Rev. D **21**, 2716 (1980)], and $\sigma_{D^0} = 6.8 \pm 1.2$ and $\sigma_{D^+} = 6.0 \pm 1.1$ [H. Sadrozinski, in *High Energy Physics—1980*, edited by Loyal Durand and Lee G. Pondrom, AIP Conference Proceedings No. 68 (American Institute of Physics, New York, 1981), p. 681.

[13]The direct measurement of $\sigma_\psi(3770)$ leads to predictions for σ_{D^0} and σ_{D^+} by use of the ratio of D^0 to D^+ production predicted by p-wave phase space and the assumption that the $\psi(3770)$ decays exclusively to $D\bar{D}$.

[14]Similar discrepancies have been noted by previous experiments, with lower statistical significance. Rafe H. Schindler, Stanford Linear Accelerator Center Report No. 219, 1979 (unpublished), p. 160; M. Aguilar-Benitez *et al.*, Phys. Lett. **135**, 237 (1984), and **146B**, 266 (1984).