Measurement of the Hadronic Structure of Semileptonic D^0 and D^+ Decays

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Absolute branching fractions for the D_{l3} and D_{l4} decays $D^+ \to \bar{K}^0 e^+ \nu_e$, $D^+ \to \bar{K}^0 \mu^+ \nu_\mu$, $D^+ \to \bar{K}^{*0} e^+ \nu_e$, and $D^0 \to K^{*-} e^+ \nu_e$ are determined using completely reconstructed $D\bar{D}$ events at the $\psi(3770)$. Reconstructed $D^0 \to K^- e^+ \nu_e$ decays are used to determine the pole mass of the $f_+(q^2)$ form factor. Resonant K^* production dominates the process $D \to K\pi e\nu$; the K^* polarization is measured. Limits on several Cabibbo-suppressed channels are evaluated. A global fit imposing isospin symmetry is performed to the measured exclusive and inclusive semileptonic D^0 and D^+ branching fractions to obtain an improved set of branching fractions.

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Semileptonic decays of heavy mesons are the simplest to understand following pure leptonic decays;[1] there are no interfering diagrams of final-state interactions. While experiments measuring D_{l3} decays[2,3] are largely in agreement with theory, recent measurements[4] of D_{l4} decays have yielded results not expected from theory for the magnitude of the branching fractions, the polarization of the vector meson, and the magnitude of the vector and axial-vector form factors, V, A_1, and A_2. In a previous publication[2] we analyzed the rates of a restricted set of Cabibbo-allowed and -forbidden D_{l3} decays to establish both their absolute branching fractions and the ratio of the Cabibbo-Kobayashi-Maskawa parameters V_{cd} and V_{cs}. We present herein a more complete analysis of absolute branching fractions and the dynamics of D_{e3}, $D_{\mu 3}$, and D_{e4} decays of charmed D^0 and D^+ mesons. By combining these and other results within the framework of the spectator picture, we derive new insights into the discrepancies reported for D_{l4} decays.

The data reported consist of 9.56 pb^{-1} collected with the Mark III detector[5] near the peak of the $\psi(3770)$. We search for a semileptonic decay candidate in the recoiling system of reconstructed hadronic D decays, denoted tags [Figs. 1(a) and 1(b)], following the method of Ref. 2. A signal region from 1.854 to 1.874 (1.858 to 1.878) GeV/c^2 is defined for D^0 (D^+) tags,[6] while events in the sideband from 1.830 to 1.850 (1.834 to 1.854) GeV/c^2 are used to evaluate the background under the peak. The number of signal events with D^0 (D^+) tags is $3675 \pm 54 \pm 195$ ($1776 \pm 27 \pm 89$).[2]

A semileptonic decay candidate recoiling against the tag is required to have a lepton with charge opposite to the charm of the tag.[7] Electrons are identified by time of flight (TOF) and electromagnetic calorimetry. Typically, 80% of electrons and 5% of charged pions within the acceptance for particle identification ($|\cos\theta| \leq 0.76$) are called electrons. A track is called a muon if it fails

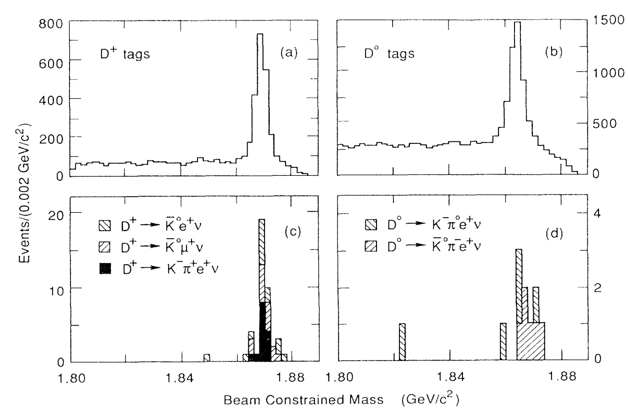

FIG. 1. Beam-constrained mass of tagging meson for (a) D^+ tags, (b) D^0 tags, (c) D^- semileptonic decays, and (d) $\bar{D}^0$ leptonic decays.

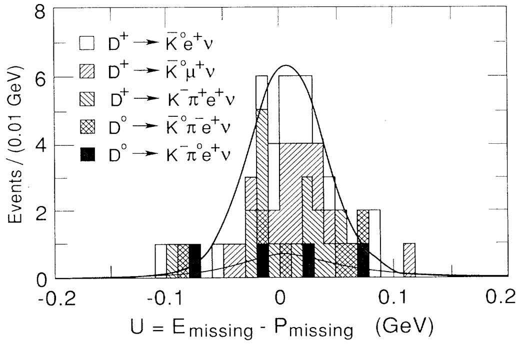

FIG. 2. The U distribution for semileptonic decays. The heavy and light curves are Monte Carlo predictions for the all-charged channels and the $D^0 \to K^-\pi^0 e^+\nu_e$ channel, respectively.

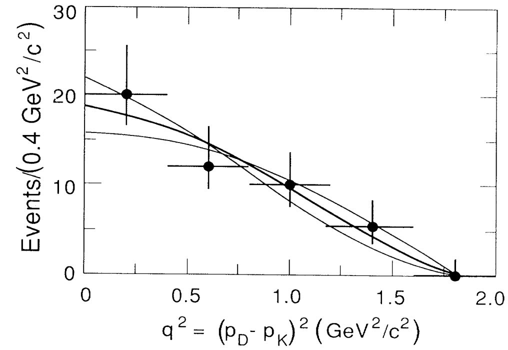

FIG. 3. The q^2 spectrum of $D^0 \to K^- e^+\nu_e$ events. The heavy curve is for $M_{\rm pole} = 1.8$ GeV/c^2; the light curves correspond to $\pm 1\sigma$ errors.

the electron-identification criteria and TOF rejects the kaon hypothesis. Typically, 85% of fiducial muons are so identified. For those final states with a charged kaon, TOF identification (ID) is required. Neutral kaons are reconstructed through the decay $K_s^0 \to \pi^+\pi^-$. Neutral-pion candidates are formed from two isolated showers constrained to the π^0 mass.

Each semileptonic mode has a potential hadronic background caused by the misidentification of a charged pion as a lepton, e.g., $D^+ \to K^-\pi^+\pi^+$ as $D^+ \to K^-\pi^+ e^+\nu_e$. These events can be suppressed by requiring the invariant mass of the visible particles to be less than 1.7 GeV/c^2. Decays with π^0's such as $D^+ \to \bar{K}^0\pi^+\pi^0$ and $D^+ \to \bar{K}^0\pi^0 e^+\nu_e$ mimicking $D^+ \to \bar{K}^0 e^+\nu_e$ are eliminated by rejecting events with extra photons.[2]

For additional rejection of events with undetected π^0's and K^0's, we require $|U| < 0.1$ GeV, where $U \equiv E_{\rm miss} - |\mathbf{p}_{\rm miss}|$.[8] To distinguish between the $D^+ \to K^-\pi^+ e^+\nu_e$ and $D^+ \to \bar{K}^0 e^+\nu_e \to \pi^-\pi^+ e^+\nu_e$ assignments, we retain an event only if the value of U calculated using our particle-identification assignments is smaller than that calculated by interchanging the pion and kaon assignments. A candidate $D^0 \to K^-\pi^0 e^+\nu_e$ event is retained if its U value is smaller than that obtained by ignoring the π^0. The U distributions are shown in Fig. 2.

Table I summarizes signals, backgrounds, reconstruction efficiencies, and resulting branching fractions. The mass distributions for events satisfying the requirements described above are shown in Figs. 1(c) and 1(d). The number of sideband events ($N_{\rm side}$) is subtracted, and a Monte Carlo simulation incorporating a complete model of D decays[2,9,10] is used to evaluate the number of background events ($N_{\rm bg}$) expected to occur with a correct tag. A small probability (1%–4%) remains for reconstructing a semimuonic decay as the corresponding semielectronic decay and vice versa. A correction is applied assuming lepton universality. Sources of systematic errors (added in quadrature) are the simulation of backgrounds (12%–17%), counting tags (5%), electron ID (2%), μ ID (2%), simulation of the photon veto (5%), visual scan (2%), track reconstruction (2%), kaon TOF ID (5%), π^0 finding (5%), K^0 finding (5%), and K^* po-

TABLE I. D^0, D^+ semileptonic branching fractions. Limits are given at the 90% confidence level.

Channel	$N_{\rm signal}$	$N_{\rm side}$	$N_{\rm bg}$	$\epsilon_{Xl\nu}$	B (%)
$D^0 \to K^- e^+\nu_e$ [a]	55	1	0.5	0.365	$3.4 \pm 0.5 \pm 0.4$
$D^0 \to \pi^- e^+\nu_e$ [a]	7	0	0.5	0.384	$0.39^{+0.23}_{-0.11} \pm 0.04$
$D^0 \to \bar{K}^0\pi^- e^+\nu_e$	6	0	0.23	0.132	$2.8^{+1.7}_{-0.8} \pm 0.3$
$D^0 \to K^-\pi^0 e^+\nu_e$	4	0	≤ 0.3	0.054	$1.6^{+1.3}_{-0.5} \pm 0.2$
$D^+ \to \bar{K}^0 e^+\nu_e$	13	0	0.08	0.300	$6.0^{+2.2}_{-1.3} \pm 0.7$
$D^+ \to \bar{K}^0\mu^+\nu_\mu$	14	1	0.77	0.230	$7.0^{+2.8}_{-1.6} \pm 1.2$
$D^+ \to K^-\pi^+ e^+\nu_e$	14	0	0.19	0.177	$3.5^{+1.2}_{-0.7} \pm 0.4$
$D^+ \to \rho^0 e^+\nu_e$	0	0	···	0.317	< 0.37
$D^+ \to \phi e^+\nu_e$	0	0	···	0.112	< 2.09
$D^+ \to \phi\mu^+\nu_\mu$	0	1	···	0.060	< 3.72

[a]Reference 2.

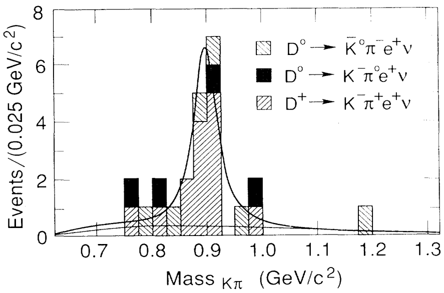

FIG. 4. The $K\pi$ mass of D_{e4} events. The fit (heavy curve) and its nonresonant component (light curve) are described in the text.

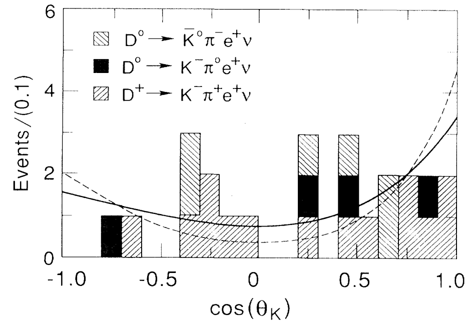

FIG. 5. The $\cos\theta_K$ distribution for D_{e4} events. Also shown are our fit (solid curve) and the prediction using $\Gamma_L/\Gamma_T = 1.8$ from E691 (dashed curve) (Ref. 4).

larization (0%–5%). The branching fractions $B(D^+ \to \bar{K}^0 e^+ \nu_e)$ and $B(D^+ \to \bar{K}^0 \mu^+ \nu_\mu)$ are combined yielding $B(D^+ \to \bar{K}^0 e^+ \nu_e) = (6.5^{+1.6}_{-1.1} \pm 0.7)\%$. Combining the branching-fractions limits for $D^+ \to \phi e^+ \nu_e$ and $D^+ \to \phi \mu^+ \nu_\mu$ yields $B(D^+ \to \phi e^+ \nu_e) < 1.34\%$ at the 90% confidence level.

The dynamics of D_{l3} decays is explored with our previous $D^0 \to K^- e^+ \nu_e$ sample.[2] The differential decay rate $d\Gamma(D \to Kev)/dq^2$ depends only on $q^2 \equiv (P_D - P_K)^2$ and is proportional to $|f_+(q^2)|^2 p_K^3$. The observed q^2 spectrum (Fig. 3) is fitted using the single-pole parametrization $f_+(q^2) = f_+(0) M_{\text{pole}}^2/(M_{\text{pole}}^2 - q^2)$. We obtain $M_{\text{pole}} = 1.8^{+0.5}_{-0.2}{}^{+0.3}_{-0.2}$ GeV/c^2 in agreement with E691 (Ref. 3) and the mass of the lowest-lying $J^P = 1^-$ $(c\bar{s})$ state D_s^*. The estimated background is 1.5 events; the dominant systematic error, the unknown background shape, is taken as the largest variation of the result when any two events are removed.

In the $D \to K\pi e\nu$ channel, $D \to K^* e\nu$ is expected to dominate.[11] The $K\pi$ invariant-mass distribution of the D_{l4} events is shown in Fig. 4. A fit by the sum of a Breit-Wigner shape and nonresonant s-wave shapes convoluted with detector resolution yields a resonant fraction of $0.79^{+0.15}_{-0.17}{}^{+0.09}_{-0.03}$ (Ref. 12) which is consistent with the K^* domination found by E691.[4]

The K^* polarization is analyzed using the helicity-angle distribution of the kaon in the K^* rest frame, θ_K. The $\cos\theta_K$ distribution of Fig. 5 is fitted by the form

$$dN/d(\cos\theta_K) \propto [1 + (2\Gamma_L/\Gamma_T - 1)\cos^2\theta_K] \times \text{(efficiency)}$$

to give $\Gamma_L/\Gamma_T = 0.5^{+1.0}_{-0.1}{}^{+0.1}_{-0.2}$.[12] Our measurement of Γ_L/Γ_T, although statistically weak, is smaller than that of E691 (Ref. 4) and is consistent with theoretical expectations.[11]

Our branching-fraction measurements can be improved with theoretical input from the spectator model of semileptonic decay. Within the spectator model,

$$\Gamma(D^+ \to \bar{K}^0 e^+ \nu_e) = \Gamma(D^0 \to K^- e^+ \nu_e),$$

$$\Gamma(D^+ \to [\bar{K}\pi]^0 e^+ \nu_e) = \Gamma(D^0 \to [\bar{K}\pi]^- e^+ \nu_e),$$

and

$$\Gamma(D^+ \to \pi^0 e^+ \nu_e) = \tfrac{1}{2}\Gamma(D^0 \to \pi^- e^+ \nu_e),$$

where $[\bar{K}\pi]^0$ ($[\bar{K}\pi]^-$) represents all $\bar{K}\pi$ states with net charge 0 (-1). The fits of Table II incorporate the

TABLE II. Fits to semileptonic branching fractions within a spectator-model framework.

Quantity	Measurement	Fit 1	Fit 2
$B(D^0 \to \pi^- e^+ \nu_e)$	$(0.39^{+0.23}_{-0.11} \pm 0.04)\%$ [a]	$(0.4 \pm 0.2)\%$	$(0.4^{+0.2}_{-0.1})\%$
$B(D^0 \to K^- e^+ \nu_e)$	$(3.4 \pm 0.5 \pm 0.4)\%$ [a]	$(3.1 \pm 0.4)\%$	$(3.0 \pm 0.5)\%$
$B(D^0 \to [\bar{K}\pi]^- e^+ \nu_e)$	$(4.4^{+1.9}_{-1.0} \pm 0.6)\%$	$(3.0 \pm 0.5)\%$	$(2.8 \pm 0.7)\%$
$B(D^0 \to Y^- e^+ \nu_e)$	$\cdots$	0%	$(0.7 \pm 1.1)\%$
$B(D^0 \to e^+ X)$	$(7.5 \pm 1.1 \pm 0.4)\%$ [b]	$(6.9 \pm 0.6)\%$	$(7.2 \pm 0.6)\%$
$B(D^+ \to \pi^0 e^+ \nu_e)$	$\cdots$	$(0.6^{+0.3}_{-0.2})\%$	$(0.5^{+0.3}_{-0.2})\%$
$B(D^+ \to \bar{K}^0 e^+ \nu_e)$	$(6.5^{+1.6}_{-1.1} \pm 0.7)\%$	$(8.0 \pm 1.1)\%$	$(7.6 \pm 1.2)\%$
$B(D^+ \to [\bar{K}\pi]^0 e^+ \nu_e)$	$(5.3^{+1.9}_{-1.1} \pm 0.6)\%$	$(7.7 \pm 1.3)\%$	$(7.0 \pm 1.7)\%$
$B(D^+ \to \bar{Y}^0 e^+ \nu_e)$	$\cdots$	0%	$(1.8 \pm 2.7)\%$
$B(D^+ \to e^+ X)$	$(17.0 \pm 1.9 \pm 0.7)\%$ [b]	$(16.7 \pm 1.3)\%$	$(17.4 \pm 1.7)\%$
τ_{D^+}/τ_{D^0}	$2.58 \pm 0.09 \pm 0.08$ [c]	2.54 ± 0.11	2.54 ± 0.12
χ^2	$\cdots$	4.0 for 4 DOF	3.6 for 3 DOF

[a]Reference 2.
[b]Reference 14.
[c]Reference 17.

measurement $\tau_{D^+}/\tau_{D^0}=2.58\pm0.09\pm0.08$ (Ref. 13) to impose the spectator-model relations on the data. Contributions from unmeasured Cabibbo-suppressed decays are small and are fixed relative to $B(D^0\to\pi^-e^+\nu_e)$ (Ref. 2) according to Ref. 14; they are also consistent with our measured limits. Fit 1 requires the sum of D_{e3} and D_{l4} channels to equal the inclusive measurements.[10] Fit 2 relaxes this requirement, allowing for an unexpected spectator channel $D\to Ye\nu$, but finds $B(D\to Ye\nu)$ to be consistent with zero. From fit 1 we extract $\Gamma(D\to K\pi e\nu)/\Gamma(D\to Ke\nu)=1.0^{+0.3}_{-0.2}$ to be compared with the E691 value of[4,15]

$$\Gamma(D\to K\pi e\nu)/\Gamma(D\to Ke\nu)=0.50\pm0.09\pm0.07\,.$$

Our data can be compared with theoretical approaches based on the quark model, QCD sum rules, and lattice gauge theory which predict semileptonic-form-factor values.[11] In the case of D_{l3} decays, the $B(D^0\to K^-e^+\nu_e)$ value yields $|f_+(0)|=|V_{cs}|(0.72\pm0.05\pm0.04)$ in agreement with the predictions which range from 0.69 to 0.77. The ratio $\Gamma(D\to K\pi e\nu)/\Gamma(D\to Ke\nu)=1.0^{+0.3}_{-0.2}$ from fit 1 is consistent with the predictions for $\Gamma(D\to K^*e\nu)/\Gamma(D\to Ke\nu)$ which range from 0.9 to 1.3. Finally, $\Gamma_L/\Gamma_T=0.5^{+1.0}_{-0.1}{}^{+0.1}_{-0.2}$ is consistent with the predictions which range from 0.9 to 1.2.

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[1] J. Adler *et al.*, Phys. Rev. Lett. **60**, 1375 (1988).

[2] J. Adler *et al.*, Phys. Rev. Lett. **62**, 1821 (1989).

[3] E691 finds $B(D^0\to K^-e^+\nu_e)=(3.8\pm0.5\pm0.6)\%$ and $M_{\rm pole}=2.1^{+0.3}_{-0.2}$ GeV/c^2; J. C. Anjos *et al.*, Phys. Rev. Lett. **62**, 1587 (1989).

[4] E691 finds $B(D^+\to\bar K^{*0}e^+\nu_e)=(4.4\pm0.4\pm0.8)\%$, $B(D^+\to(K^-\pi^+)_{\rm nonres}e^+\nu_e)=(0.3\pm0.2\pm0.2)\%$, $\Gamma_L/\Gamma_T=1.8^{+0.6}_{-0.4}\pm0.3$, and $B(D\to\bar K^*e\nu_e)/B(D\to\bar K\pi e\nu_e)=0.91\pm0.06\pm0.06$; the total D_{l4} rate, correcting for unobserved $D\to\bar K^0\pi^0e\nu_e$ decays, is calculated using

$$B(D\to\bar K\pi e\nu_e)=B(D^+\to\bar K^{*0}e^+\nu_e)+1.5B(D^+\to(K^-\pi^+)_{\rm nonres}e^+\nu_e);$$

J. C. Anjos *et al.*, Phys. Rev. Lett. **62**, 722 (1989); J. C. Anjos *et al.*, Phys. Rev. Lett. **65**, 2630 (1990).

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

[6] Reference to a state also implies reference to its charge conjugate.

[7] A $K^0\pi^+\pi^-$ tag on a $\bar K^0\pi^+\pi^-$ tag cannot be distinguished without information from the recoiling system; hence both lepton signs are accepted.

[8] For $D^+\to\bar K^0\mu^+\nu_\mu$, we require that $|U|<0.05$ GeV, the transverse component of $\mathbf{p}_{\rm miss}$ be >0.2 GeV/c, and no isolated shower have energy >0.05 GeV.

[9] J. Adler *et al.*, Phys. Rev. Lett. **60**, 89 (1988); J. Adler *et al.*, Phys. Lett. B **196**, 107 (1987); R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **56**, 2136 (1986); R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **55**, 150 (1985).

[10] R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **54**, 1976 (1986).

[11] F. J. Gilman and R. L. Singleton, Jr., Phys. Rev. D **41**, 142 (1990), and references contained therein; C. Bernard *et al.*, in *Proceedings of the Symposium on Lattice Field Theory, Batavia, Illinois* (Fermilab, Batavia, 1988), p. 186; Brookhaven Report No. BNL-43521, 1990 (unpublished); J. M. Cline *et al.*, Phys. Rev. D **40**, 793 (1989); M. Crisafulli *et al.*, Phys. Lett. B **223**, 90 (1989); C. A. Dominguez and N. Paver, Phys. Lett. B **207**, 499 (1988).

[12] The dominant systematic error, the unknown background shape, is taken as the largest variation when any one event is removed. The total estimated D_{l4} background is 0.5 event.

[13] J. C. Anjos *et al.*, Phys. Rev. D **37**, 2391 (1988).

[14] Cline *et al.* (Ref. 11) predict $R_\eta=0.11$, $R_{\eta'}=0.03$, and $R_\rho=0.36$, where $R_X\equiv\Gamma(D^+\to Xe^+\nu_e)/\Gamma(D^0\to\pi^-e^+\nu_e)$.

[15] Including E691 branching-fraction measurements of Refs. 3 and 4 in fit 1 increases the χ^2 to 6.8 for 4 degrees of freedom.