

Absolute Branching Fraction Measurements of Exclusive D^0 Semileptonic Decays

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With the first data sample collected by the CLEO-c detector at the $\psi(3770)$ resonance we have studied four exclusive semileptonic decays of the D^0 meson. Our results include the first observation and absolute branching fraction measurement for $D^0 \rightarrow \rho^- e^+ \nu_e$ and improved measurements of the absolute branching fractions for D^0 decays to $K^- e^+ \nu_e$, $\pi^- e^+ \nu_e$, and $K^{*-} e^+ \nu_e$.

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The weak-current couplings of quarks within the standard model are described by the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1], which must be determined experimentally. Because of their simplicity,

semileptonic decays of hadrons provide powerful tools for probing the CKM matrix. Interpreting experimental measurements of semileptonic decay rates requires precise knowledge of form factors that are not easily calculated in

quantum chromodynamics because of nonperturbative effects. Form factor uncertainties are presently the main limitation in extracting $|V_{ub}|$ and $|V_{cb}|$ from semileptonic B decays [2].

Heavy quark effective theory relates form factors in charm decays to those in bottom decays, and lattice gauge techniques calculate form factors in both charm and bottom decays. Precision measurements of semileptonic charm decay rates and form factors are a principal goal of the CLEO-c program at the Cornell Electron Storage Ring (CESR) [3]. In this Letter, we report first results on semileptonic D^0 decays from CLEO-c: improved measurements of the branching fractions for $D^0 \rightarrow K^- e^+ \nu_e$, $\pi^- e^+ \nu_e$, and $K^{*-} e^+ \nu_e$, and the first observation and branching fraction measurement for the decay $D^0 \rightarrow \rho^- e^+ \nu_e$. (Charge-conjugate modes are implied throughout this Letter.) The data sample used for these measurements consists of an integrated luminosity of 55.8 pb^{-1} at the $\psi(3770)$ resonance, and includes about 0.20×10^6 $D^0 \bar{D}^0$ events [4]. The same data and analysis techniques are used for the branching fraction measurements of D^+ semileptonic decays in Ref. [5].

The technique for this analysis, which was first applied by the Mark III Collaboration [6] at SPEAR, relies on the purity and kinematics of $D\bar{D}$ events produced at the $\psi(3770)$. We select events by reconstructing a \bar{D}^0 meson in one of eight hadronic final states: $K^+ \pi^-$, $K^+ \pi^- \pi^0$, $K^+ \pi^- \pi^0 \pi^0$, $K^+ \pi^- \pi^+ \pi^-$, $K_S^0 \pi^0$, $K_S^0 \pi^+ \pi^-$, $K_S^0 \pi^+ \pi^- \pi^0$, and $K^- K^+$, representing about 46% [4] of all \bar{D}^0 decays. Within these tagged events, D^0 semileptonic decays are reconstructed in the exclusive final states: $K^- e^+ \nu_e$, $\pi^- e^+ \nu_e$, $K^{*-} e^+ \nu_e$, and $\rho^- e^+ \nu_e$, where $K^{*-} \rightarrow K^- \pi^0$ or $K_S^0 \pi^-$, and $\rho^- \rightarrow \pi^- \pi^0$. Separation between signal and background from misidentified or missing particles is achieved with the kinematic variable $U \equiv E_{\text{miss}} - c|\vec{p}_{\text{miss}}|$, where E_{miss} and \vec{p}_{miss} are the missing energy and momentum of the D meson decaying semileptonically. The efficiency-corrected ratio of tagged events with semileptonic decays to the total number of tags gives the absolute branching fraction for the exclusive semileptonic decay mode. This branching fraction is independent of the luminosity of the data and benefits from the cancellation of many systematic uncertainties.

The efficient reconstruction of tag events and the clean selection of semileptonic decays relies on the power of the CLEO-c detector, most components of which were developed for and used in B meson studies in the CLEO II and CLEO III experiments [7]. The tracking system covers a solid angle of 93% of 4π with a six-layer low-mass stereo wire drift chamber surrounded by a 47-layer cylindrical (main) drift chamber. The main drift chamber provides specific-ionization (dE/dx) measurements that discriminate between charged pions and kaons. Additional hadron identification is provided by a Ring-Imaging Cherenkov (RICH) detector covering about 80% of 4π . Identification

of positrons and detection of neutral pions rely on an electromagnetic calorimeter consisting of 7800 cesium iodide crystals and covering 93% of 4π .

Details of the criteria for selecting tracks, π^0 and K_S^0 candidates, and hadronic tags are provided in Ref. [4]. The tag selection is based on two variables: $\Delta E \equiv E_D - E_{\text{beam}}$, the difference between the energy (E_D) of the fully reconstructed \bar{D}^0 candidate and the beam energy (E_{beam}), and $M_{\text{bc}} \equiv \sqrt{E_{\text{beam}}^2/c^4 - |\vec{p}_D|^2/c^2}$, the beam-constrained mass of the \bar{D}^0 candidate, where \vec{p}_D is the measured momentum of the \bar{D}^0 candidate. In the case of multiple candidates, ΔE is used to select one \bar{D}^0 candidate for each tag mode, and we fit the beam-constrained mass distributions to obtain the tag yields. The signal component in these fits consists of a Gaussian and a bifurcated Gaussian to account for radiative and other effects. The background component is represented by an ARGUS function [8]. The yields of tags in all decay modes are given in Table I. The total number of tags in our data sample is approximately 60 000.

The requirement of a fully reconstructed \bar{D}^0 meson tag greatly suppresses background. After a tag is identified, we search for a positron and a set of hadrons recoiling against the tag. [Only positrons are used because the CLEO-c muon identification system has poor acceptance in the momentum range characteristic of semileptonic D decays at the $\psi(3770)$.] Positron candidates are selected based on a likelihood ratio constructed from three inputs: the ratio of the energy deposited in the calorimeter to the measured momentum (E/p), dE/dx , and RICH information. Positron candidates are required to have momentum of at least 200 MeV/ c and to satisfy the fiducial requirement $|\cos\theta| < 0.90$, where θ is the angle between the positron direction and the beam axis. The minimum momentum is chosen because of backgrounds from low-momentum pions. More than 80% of the positrons from D^0 semileptonic decays at the $\psi(3770)$ resonance satisfy these requirements. The efficiency for positron identification has been measured primarily from radiative Bhabha events. For the criteria used in this analysis, it rises from $\sim 50\%$

TABLE I. The tag yields for the eight \bar{D}^0 decay modes with statistical uncertainties.

Tag mode	Tag yield
$\bar{D}^0 \rightarrow K^+ \pi^-$	$10\,223 \pm 109$
$\bar{D}^0 \rightarrow K^+ \pi^- \pi^0$	$18\,574 \pm 173$
$\bar{D}^0 \rightarrow K^+ \pi^- \pi^0 \pi^0$	4813 ± 229
$\bar{D}^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$	$14\,767 \pm 145$
$\bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^-$	4879 ± 99
$\bar{D}^0 \rightarrow K_S^0 \pi^+ \pi^- \pi^0$	4299 ± 195
$\bar{D}^0 \rightarrow K_S^0 \pi^0$	1585 ± 49
$\bar{D}^0 \rightarrow K^- K^+$	901 ± 32
All Tags	$60\,041 \pm 408$

at 200 MeV/c to 95% just above 300 MeV/c and then is roughly constant. The rates for misidentifying charged pions and kaons as positrons have been determined with exclusive hadronic decays of K_S^0 and D mesons in CLEO-c data. Averaged over the full momentum range, the pion and kaon misidentification rates are approximately 0.1%. The energy lost by positrons to bremsstrahlung photons is recovered by adding showers that are within 5° of the positron and are not matched to other particles.

To select the hadronic daughters of a semileptonic D^0 decay, charged pions and kaons with momenta greater than 50 MeV/c are identified with criteria based on dE/dx and RICH information. Charged pion and kaon candidates must have dE/dx measurements within 3 standard deviations (3σ) of the expected values. For tracks with momenta greater than 700 MeV/c, RICH information, if available, is combined with dE/dx . The efficiencies ($\sim 95\%$ or higher) and misidentification rates (no more than a few per cent per track) are determined with charged pion and kaon samples from fully reconstructed decays of D^0 and D^+ in CLEO-c data.

We form π^0 candidates with pairs of photons, each with an energy of at least 30 MeV and a shower shape consistent with that expected for a photon. The invariant mass of the photon pair must be within 3σ ($\sigma \sim 6$ MeV/ c^2) of the known π^0 mass. After selection, a mass constraint is imposed when π^0 candidates are used in reconstructing other states. We reconstruct pairs of oppositely charged tracks from a common vertex to form a K_S^0 candidate within 12 MeV/ c^2 ($\sim 4.5\sigma$) of the K_S^0 mass.

The K^- and π^0 , or K_S^0 and π^- , candidates are combined to form K^{*-} candidates. We require the invariant masses of the K^{*-} candidates to be within 100 MeV/ c^2 of the mean K^{*-} mass. Likewise, π^- and π^0 candidates are combined to form ρ^- candidates within 150 MeV/ c^2 of the mean ρ^- mass.

A tag and the semileptonic decay are then combined. If there are no tracks other than the daughters of the tag and the semileptonic candidate in events, we compute U , which should peak at zero for a correctly reconstructed semileptonic decay. To improve the U resolution, we constrain the magnitude of the momentum of the D^0 candidate decaying semileptonically to be $\sqrt{E_{\text{beam}}^2/c^2 - c^2 m_{D^0}^2}$, with its direction opposite to that of the tag \bar{D}^0 ($\hat{\mathbf{p}}_{\bar{D}^0}$) in the $\psi(3770)$ rest frame, where $\vec{\mathbf{p}}_{\bar{D}^0} = -\vec{\mathbf{p}}_{D^0}$. The distribution of U is approximately Gaussian with $\sigma \sim 10$ MeV, varying mode by mode, and somewhat larger for modes with neutral pions. In events with multiple K^{*-} ($K^- \pi^0$) or ρ^- we choose the combination with invariant masses closest to the nominal resonance and π^0 masses. This occurs in only a few percent of all events and has been shown to introduce no significant bias into our measurements. The U distributions for $D^0 \rightarrow K^- e^+ \nu_e$, $\pi^- e^+ \nu_e$, $K^{*-} e^+ \nu_e$, and $\rho^- e^+ \nu_e$, summed over tag modes, are shown in Fig. 1.

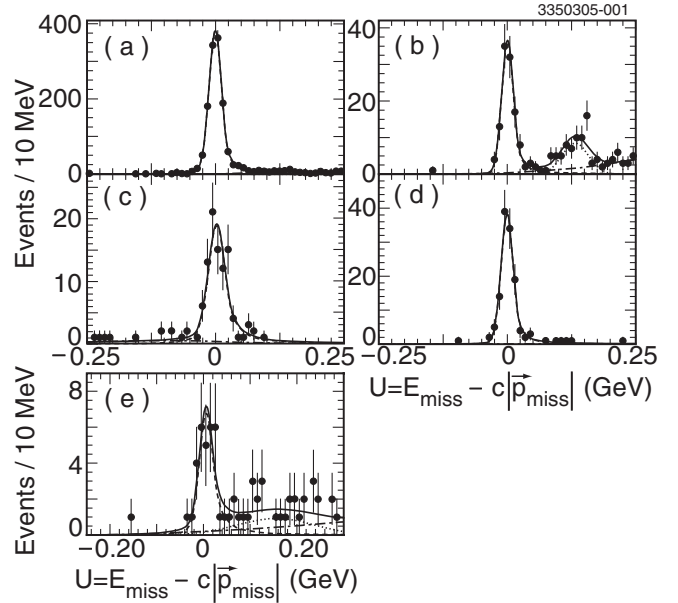


FIG. 1. Fits to $U = E_{\text{miss}} - c|\vec{p}_{\text{miss}}|$ distributions for (a) $D^0 \rightarrow K^- e^+ \nu_e$, (b) $\pi^- e^+ \nu_e$, (c) $K^{*-}(K^- \pi^0) e^+ \nu_e$, (d) $K^{*-}(K_S^0 \pi^-) e^+ \nu_e$, and (e) $\rho^- e^+ \nu_e$, with the \bar{D}^0 meson fully reconstructed. The solid line represents the total fit to the data, which includes the signal (dashed line), peaking background (dotted line), and nonpeaking background (dot-dashed line).

The signal yields are determined by fitting the U distributions. The signal is represented with a Gaussian and a Crystal Ball [9] function to accommodate the tails due to radiative effects. The tails of the signal function are fixed to the prediction of a GEANT-based [10] Monte Carlo (MC) simulation. The background function is determined from a MC simulation for each mode. The backgrounds are small and arise mostly from misreconstructed semileptonic decays with correctly reconstructed tags. The background shape parameters are fixed, while the background normalizations are allowed to float in all fits to the data.

The background level for the decay $D^0 \rightarrow K^- e^+ \nu_e$ ($D^0 \rightarrow K^{*-} e^+ \nu_e$) is small. For $D^0 \rightarrow K^- e^+ \nu_e$, there is background from $D^0 \rightarrow K^{*-}(K^- \pi^0) e^+ \nu_e$ with an undetected π^0 , but it is well separated from the signal because of the missing π^0 . For the decay $D^0 \rightarrow \pi^- e^+ \nu_e$ ($D^0 \rightarrow \rho^- e^+ \nu_e$), the background peaks at positive U (well above the signal peak) and is primarily from $D^0 \rightarrow K^- e^+ \nu_e$ [$D^0 \rightarrow K^{*-}(K^- \pi^0) e^+ \nu_e$] where a kaon is misidentified as a pion. For $D^0 \rightarrow K^{*-}(K^- \pi^0) e^+ \nu_e$, there is considerable background from $D^0 \rightarrow K^- e^+ \nu_e$ when a K^- is combined with a random π^0 candidate, which is well below the signal peak. The signal yield for $D^0 \rightarrow K^- e^+ \nu_e$ is determined by separately fitting subsamples for each tag mode. The results for all tag modes are found to be consistent. For the other modes, the yields are obtained with all tag modes combined due to limited statistics. The fits to the data are shown in Fig. 1, and the yields are given in Table II. The

TABLE II. Signal efficiencies, yields with statistical uncertainties, and branching fractions with both statistical and systematic uncertainties for $D^0 \rightarrow K^- e^+ \nu_e$, $\pi^- e^+ \nu_e$, $K^{*-} e^+ \nu_e$, and $\rho^- e^+ \nu_e$, as well as PDG branching fractions with total uncertainties [11] and BES branching fractions with statistical and systematic uncertainties [12]. For $D^0 \rightarrow K^{*-} e^+ \nu_e$, the efficiencies do not include subsidiary decay branching fractions. The branching fractions for $D^0 \rightarrow K^{*-} e^+ \nu_e$ are reduced by 2.4% (see the text).

Decay mode	$\epsilon(\%)$	Yield	$\mathcal{B}(\%)$	$\mathcal{B}(\%)$ (PDG)	$\mathcal{B}(\%)$ (BES)
$D^0 \rightarrow K^- e^+ \nu_e$	63.58 ± 0.50	1311.0 ± 36.6	$3.44 \pm 0.10 \pm 0.10$	3.58 ± 0.18	$3.82 \pm 0.40 \pm 0.27$
$D^0 \rightarrow \pi^- e^+ \nu_e$	74.18 ± 0.52	116.8 ± 11.2	$0.262 \pm 0.025 \pm 0.008$	0.36 ± 0.06	$0.33 \pm 0.13 \pm 0.03$
$D^0 \rightarrow K^{*-} (K^- \pi^0) e^+ \nu_e$	22.02 ± 0.32	94.1 ± 10.4	$2.11 \pm 0.23 \pm 0.10$		
$D^0 \rightarrow K^{*-} (K_S^0 \pi^-) e^+ \nu_e$	40.43 ± 0.42	125.2 ± 11.6	$2.19 \pm 0.20 \pm 0.11$		
$D^0 \rightarrow K^{*-} e^+ \nu_e$			$2.16 \pm 0.15 \pm 0.08$	2.15 ± 0.35	
$D^0 \rightarrow \rho^- e^+ \nu_e$	26.97 ± 0.35	31.1 ± 6.3	$0.194 \pm 0.039 \pm 0.013$		

31.1 ± 6.3 $D^0 \rightarrow \rho^- e^+ \nu_e$ events provide the first observation of this decay.

The absolute branching fraction for any D^0 semileptonic decay mode is given by $\mathcal{B} = N_{\text{signal}}/\epsilon N_{\text{tag}}$, where N_{signal} is the number of $D^0 \bar{D}^0$ events with the tag \bar{D}^0 fully reconstructed and the D^0 reconstructed in that semileptonic mode, N_{tag} is the number of \bar{D}^0 tags, and ϵ is the effective efficiency for detecting the semileptonic decay in an event with an identified tag. Note that $\epsilon = \epsilon_{\text{signal}}/\epsilon_{\text{tag}}$ is the ratio of the separate efficiencies for tag events with semileptonic decays and tag events in general. It is determined with a MC sample that includes relative populations of the eight tag modes that are consistent with the data. The cancellation of systematic uncertainties due to common effects in the numerator and denominator is clear.

We consider the following sources of systematic uncertainty and give our estimates of their magnitudes in parentheses. The uncertainties in the efficiencies for finding tracks (0.7%) and for reconstructing π^0 (2.0%) and K_S^0 (3.0%) are estimated with missing-mass techniques [4] applied to CLEO-c data and MC simulations. The uncertainty in the positron-identification efficiency (1.0%) is taken from detailed comparisons of the detector response to positrons of radiative Bhabhas in data and MC simulations. The effect of event complexity was incorporated by studying positrons both in isolation and embedded in hadronic events. The positron-identification efficiency depends on final-state radiation (FSR) and on bremsstrahlung in the material of the CLEO-c detector, the effects of both of which are included in the MC simulations. To assess the systematic uncertainty from these sources (0.6% combined), we vary the amount of FSR [simulated by PHOTOS [13]] and radiation in detector material, and we carry out the analyses with and without the recovery of radiated photons near positrons. Uncertainties in the charged pion and kaon identification efficiencies (0.3% per pion and 1.3% per kaon) are estimated by detailed comparisons of the detector response to tracks from hadronic D -meson decays in data and MC simulations. There is an uncertainty in the number of \bar{D}^0 tags (0.7%), which is estimated by using alternative signal functions in the M_{bc} fits and by varying the end point (beam energy) of the

ARGUS function parametrizing the background. The uncertainty in modeling the background shapes in the U fits (mode dependent: from 1.0% to 5.0%) has contributions from the simulation of the positron and hadron misidentification rates, as well as the input branching fractions. The uncertainty associated with the requirement of no extra tracks in a candidate event (0.5%) is estimated using fully reconstructed $D^0 \bar{D}^0$ events in the data and MC simulations. The uncertainty in the semileptonic reconstruction efficiencies due to imperfect knowledge of the semileptonic form factors is small because of the uniform acceptance of the CLEO-c detector. It is estimated by varying the form factors in the MC simulations within their uncertainties (1.0%) for all modes except $D^0 \rightarrow \rho^- e^+ \nu_e$, for which a conservative uncertainty (3.0%) is used in the absence of experimental information on the form factors in Cabibbo-suppressed pseudoscalar-to-vector transitions. The uncertainty associated with the simulation of initial state radiation ($e^+ e^- \rightarrow D \bar{D} \gamma$) is found to be negligible. Finally, there is systematic uncertainty due to limited MC statistics (0.7% to 1.5%, depending on mode).

A nonresonant component is likely to contribute background in semileptonic decays to vector mesons. Based on evidence from the FOCUS experiment of a nonresonant component consistent with an S -wave interfering with $D \rightarrow K^* \ell \nu_l$ [14], its contribution is estimated to be 2.4% in this analysis and subtracted when calculating the branching fractions for $D^0 \rightarrow K^{*-} e^+ \nu_e$. Systematic uncertainty associated with the subtraction (1.0%) is due to imperfect knowledge of the amplitude and phase of the nonresonant component. Interference with the S -wave amplitude alters the angular correlations among the decay products and introduces a systematic uncertainty (1.5%) in the reconstruction efficiency for $D^0 \rightarrow K^{*-} (K^- \pi^0) e^+ \nu_e$. A relativistic Breit-Wigner resonance with a Blatt-Weisskopf form factor is used to simulate wide resonances in MC calculations. A systematic uncertainty associated with the K^* line shape (1.2%) is estimated using $D^+ \rightarrow \bar{K}^{*0} (K^- \pi^+) e^+ \nu_e$, which has a much larger yield [5]. For $D^0 \rightarrow \rho^- e^+ \nu_e$, there are insufficient data to constrain the nonresonant background or the resonance line shape. Systematic uncertainties from these two sources are

TABLE III. Ratios of branching fractions for exclusive D^0 semileptonic decays, from this analysis, the PDG [11], CLEO III [15], and FOCUS [16]. Uncertainties in the CLEO and FOCUS measurements are statistical and systematic, respectively.

	$\frac{\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu_e)}{\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e)}$	$\frac{\mathcal{B}(D^0 \rightarrow \rho^- e^+ \nu_e)}{\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e)}$	$\frac{\mathcal{B}(D^0 \rightarrow \pi^- \mu^+ \nu_\mu)}{\mathcal{B}(D^0 \rightarrow K^- \mu^+ \nu_\mu)}$
This measurement	$(7.6 \pm 0.8 \pm 0.2)\%$	$(9.0 \pm 1.9 \pm 0.6)\%$	
PDG [11]	$(10.1 \pm 1.8)\%$		
CLEO III [15]	$(8.2 \pm 0.6 \pm 0.5)\%$		
FOCUS [16]			$(7.4 \pm 0.8 \pm 0.7)\%$

expected to be much smaller than the current statistical uncertainty for this mode, and they are neglected.

The estimated systematic uncertainties are added in quadrature to obtain the total systematic uncertainties in the branching fractions (Table II): 2.8%, 2.9%, 4.9%, 5.1%, and 6.6% for $D^0 \rightarrow K^- e^+ \nu_e$, $D^0 \rightarrow \pi^- e^+ \nu_e$, $D^0 \rightarrow K^{*-}(K^- \pi^0) e^+ \nu_e$, $D^0 \rightarrow K^{*-}(K_S^0 \pi^-) e^+ \nu_e$, and $D^0 \rightarrow \rho^- e^+ \nu_e$, respectively. Most of the estimates of systematic uncertainties are limited by data statistics and will be reduced with a larger data sample.

In summary, we have presented absolute branching fraction measurements of D^0 semileptonic decays with the first 55.8 pb^{-1} of data collected with the CLEO-c detector at the $\psi(3770)$. Our branching fractions for D^0 decays to $K^- e^+ \nu_e$, $\pi^- e^+ \nu_e$, $K^{*-} e^+ \nu_e$, and $\rho^- e^+ \nu_e$ are given in Tables II and III along with current world-average values compiled by the Particle Data Group [11]. Recent CLEO III [15], BES [12], and FOCUS [16] measurements, which are not included in Ref. [11], are also listed. The measurement of $D^0 \rightarrow \rho^- e^+ \nu_e$ is the first observation of this mode. The absolute branching fraction measurements of other modes are more precise than and consistent with current world averages. Corresponding results for D^+ semileptonic decays and more extensive interpretation are presented in a companion Letter [5].

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