Absolute Branching Fraction Measurements of Exclusive D^+ Semileptonic Decays

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Using data collected at the $\psi(3770)$ resonance with the CLEO-c detector at the Cornell e^+e^- storage ring, we present improved measurements of the absolute branching fractions of D^+ decays to $\bar{K}^0 e^+ \nu_e$, $\pi^0 e^+ \nu_e$, $\bar{K}^{*0} e^+ \nu_e$, and $\rho^0 e^+ \nu_e$, and the first observation and absolute branching fraction measurement of $D^+ \to \omega e^+ \nu_e$. We also report the most precise tests to date of isospin invariance in semileptonic D^0 and D^+ decays.

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The quark mixing parameters are fundamental constants of the standard model of particle physics. They determine the nine weak-current quark coupling elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1]. The extraction of the quark couplings is difficult because quarks are bound inside hadrons by the strong interaction. Semileptonic decays are the preferred way to determine the CKM matrix elements as the strong interaction binding effects are confined to the hadronic current. They are parametrized by form factors that are calculable, for example, by lattice quantum chromodynamics (LQCD) and QCD sum rules. Nevertheless, form factor uncertainties dominate the precision with which the CKM matrix elements can be determined [2]. In charm quark decays, however, couplings V_{cs} and V_{cd} are tightly constrained by the unitarity of the CKM matrix. Therefore, measurements of charm semileptonic decay rates and form factors rigorously test theoretical predictions.

We report herein measurements with the first CLEO-c data [3] of the absolute branching fractions of D^+ decays to $\bar{K}^0 e^+ \nu_e$, $\pi^0 e^+ \nu_e$, $\bar{K}^{*0} e^+ \nu_e$, and $\rho^0 e^+ \nu_e$, and the first observation and absolute branching fraction measurement of $D^+ \to \omega e^+ \nu_e$. (Throughout this Letter charge-conjugate modes are implied.) We combine these results with the measurements of D^0 semileptonic branching fractions reported in Ref. [4], which use the same data and analysis technique, and test isospin invariance of the hadronic current in semileptonic decays.

The data were collected by the CLEO-c detector at the $\psi(3770)$ resonance, about 40 MeV above the $D\bar{D}$ pair production threshold. A description of the CLEO-c detector is provided in Ref. [4] and references therein. The data sample consists of an integrated luminosity of 55.8 pb^{-1} and includes about 0.16×10^6 D^+D^- events.

The technique for these measurements was first applied by the Mark III Collaboration [5] at SPEAR. Candidate events are selected by reconstructing a D^-, called a tag, in the following six hadronic final states: $K_S^0\pi^-$, $K^+\pi^-\pi^-$, $K_S^0\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^0$, $K_S^0\pi^-\pi^-\pi^+$, and $K^-K^+\pi^-$, constituting approximately 28% [6] of all D^- decays. The absolute branching fractions of D^+ semileptonic decays are then measured by their reconstruction in the system recoiling from the tag. Tagging a D^- meson in a $\psi(3770)$ decay provides a D^+ with known four-momentum, allowing a semileptonic decay to be reconstructed with no kinematic ambiguity, even though the neutrino is undetected.

Tagged events are selected based on two variables: $\Delta E \equiv E_D - E_{\text{beam}}$, the difference between the energy of the D^- tag candidate (E_D) and the beam energy (E_{beam}), and the beam-constrained mass $M_{\text{bc}} \equiv \sqrt{E_{\text{beam}}^2/c^4 - |\vec{p}_D|^2/c^2}$, where $\vec{p}_D$ is the measured momentum of the D^- candidate. Selection criteria for tracks, π^0 and K_S^0 candidates for tags are described in Ref. [6]. If multiple candidates are present in the same tag mode, one candidate per tag charge is chosen using ΔE. The yields of the six tag modes are obtained from fits to the M_{bc} distributions. The data sample comprises approximately 32 000 charged tags (Table I).

TABLE I. Tag yields of the six D^- hadronic modes with statistical uncertainties.

Tag mode	Yield
$D^- \to K_S^0\pi^-$	2243 ± 51
$D^- \to K^+\pi^-\pi^-$	$15\,174 \pm 128$
$D^- \to K_S^0\pi^-\pi^0$	5188 ± 100
$D^- \to K^+\pi^-\pi^-\pi^0$	4734 ± 91
$D^- \to K_S^0\pi^-\pi^-\pi^+$	3281 ± 94
$D^- \to K^-K^+\pi^-$	1302 ± 44
All Tags	$31\,922 \pm 219$

After a tag is identified, we search for a positron and a set of hadrons recoiling against the tag. [Muons are not used as D semileptonic decays at the $\psi(3770)$ produce low momentum leptons for which the CLEO-c muon identification is not efficient.] Positron candidates, selected with criteria described in Ref. [4], are required to have momentum of at least 200 MeV$/c$ and to satisfy $|\cos\theta| < 0.90$, where θ is the angle between the positron direction and the beam axis. The efficiency for positron identification rises from about 50% at 200 MeV$/c$ to 95% just above 300 MeV$/c$ and is roughly constant thereafter. The rates for misidentifying charged pions and kaons as positrons averaged over the momentum range are approximately 0.1%. The energy lost by positrons to bremsstrahlung photons is recovered by the procedure described in Ref. [4].

Hadronic tracks must have momenta above 50 MeV$/c$ and $|\cos\theta| < 0.93$. Identification of hadrons is based on measurements of specific ionization (dE/dx) in the main drift chamber and information from the Ring-Imaging Cherenkov Detector (RICH). Pion and kaon candidates are required to have dE/dx measurements within 3 standard deviations (3.0σ) of the expected value. For tracks with momenta greater than 700 MeV$/c$, RICH information, if available, is combined with dE/dx. The efficiencies (95% or higher) and misidentification rates (a few percent) are determined with charged pion and kaon samples from hadronic D decays.

We form π^0 candidates from pairs of photons, each having an energy of at least 30 MeV, and require that the invariant mass of the pair be within 3.0σ ($\sigma \sim 6$ MeV$/c^2$) of the known π^0 mass. A mass constraint is imposed when π^0 candidates are used in further reconstruction. The K_S^0 candidates are formed from pairs of oppositely charged and vertex-constrained tracks having an invariant mass within 12 MeV$/c^2$ ($\sim 4.5\sigma$) of the known K_S^0 mass. We form a $\bar{K}^{*0}$ (ρ^0) candidate from K^- and π^+ (π^- and π^+) candidates and require an invariant mass within 100 MeV$/c^2$ (150 MeV$/c^2$) of its mean value. The reconstruction of $\omega \to \pi^+\pi^-\pi^0$ candidates is achieved by combining three pions, requiring an invariant mass within 20 MeV$/c^2$ of the known mass, and demanding that the charged pions do not satisfy interpretation as a K_S^0.

The tag and the semileptonic decay are then combined, if the event includes no tracks other than those of the tag and the semileptonic candidate. Semileptonic decays are identified using the variable $U \equiv E_{\rm miss} - c|\vec{p}_{\rm miss}|$, where $E_{\rm miss}$ and $\vec{p}_{\rm miss}$ are the missing energy and momentum of the D meson decaying semileptonically. If the decay products of the semileptonic decay have been correctly identified, U is expected to be zero, since only a neutrino is undetected. The resolution in U is improved using constraints described in Ref. [4]. Because of the finite resolution of the detector, the distribution in U is approximately Gaussian, centered at $U = 0$ with $\sigma \sim 10$ MeV. (The width varies by mode and is larger for modes with neutral pions.) Multiple candidates appear in a few percent of events in the reconstruction of semileptonic modes with a π^0 meson, and less often in other modes. To remove multiple candidates in each semileptonic mode, one combination is chosen per tag mode, based on the proximity of the invariant masses of the K_S^0, $\bar{K}^{*0}$, ρ^0, π^0, or ω candidates to their expected masses. This procedure has been shown to introduce no significant bias into our measurements.

The yield for each semileptonic mode is determined from a fit to its U distribution, as shown in Fig. 1 with all tag modes combined. In each case the signal is represented by a Gaussian and a Crystal Ball function [7] to account for initial and final state radiation (FSR). The parameters describing the tails of the signal function are fixed with a GEANT-based Monte Carlo (MC) simulation [8]. The background functions are determined by a MC simulation that incorporates all available data on D meson decays. The backgrounds are small and arise mostly from misreconstructed semileptonic decays with correctly reconstructed tags [9]. The background shape parameters are fixed, while the background normalizations are allowed to float in all fits to the data.

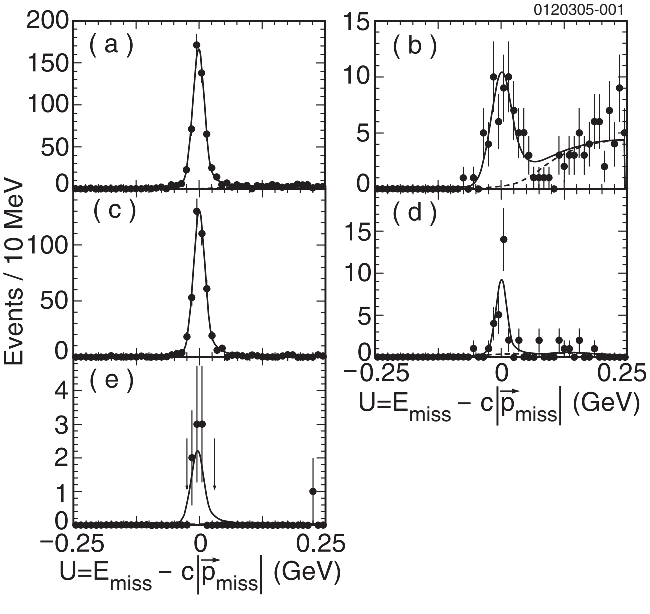

FIG. 1. Fits (solid line) to the U distributions in data (dots with error bars) for the five D^+ semileptonic modes: (a) $D^+ \to \bar{K}^0 e^+ \nu_e$, (b) $D^+ \to \pi^0 e^+ \nu_e$, (c) $D^+ \to \bar{K}^{*0} e^+ \nu_e$, (d) $D^+ \to \rho^0 e^+ \nu_e$, and (e) $D^+ \to \omega e^+ \nu_e$. The background contribution is the dashed line only visible in (b) and (d). The arrows show the signal region for $D^+ \to \omega e^+ \nu_e$.

The mode $D^+ \to \omega e^+ \nu_e$ has never previously been observed. There are 8 events consistent with $D^+ \to \omega e^+ \nu_e$ in Fig. 1(e). The background in the signal region ([−25; +30] MeV in U) is estimated to be 0.4 ± 0.2 events. The probability for the background of 0.6 events to fluctuate to 8 or more events is 2.4×10^{-7}, which corresponds to significance exceeding 5.0σ. Therefore, this is the first observation of $D^+ \to \omega e^+ \nu_e$.

The absolute branching fractions in Table II are determined using $\mathcal{B} = N_{\rm signal}/\epsilon N_{\rm tag}$, where $N_{\rm signal}$ is the number of fully reconstructed D^+D^- events obtained by fitting the U distribution, $N_{\rm tag}$ is the number of events with a reconstructed tag, and ϵ is the effective efficiency for detecting the semileptonic decay in an event with an identified tag. A MC simulation where the relative population of tag yields across tag modes approximates that in the data is used to determine the efficiency.

We have considered the following sources of systematic uncertainty and give our estimates of their magnitudes in parentheses. The uncertainties associated with the efficiency for finding a track (0.7%), π^0 (2.0% for $D^+ \to \omega e^+ \nu_e$ and 4.3% for $D^+ \to \pi^0 e^+ \nu_e$), and K_S^0 (3.0%) are estimated using missing mass techniques with the data [6]. Details on the uncertainties associated with positron identification efficiency (1.0%) are provided in Ref. [4]. Uncertainties in the charged pion and kaon identification efficiencies (0.3% per pion and 1.3% per kaon) are estimated using hadronic D meson decays. The uncertainty in the number of tags (1.1%) is estimated by using alternative signal functions in the fits to the $M_{\rm bc}$ distributions and by varying the end point of the background function [11]. The uncertainty in modeling the background shapes in the fits to the U distributions (0.4% to 3.3% by mode) has contributions from the uncertainties in the simulation of the positron and hadron fake rates as well as the input branching fractions in the MC simulation. The uncertainty associated with the requirement that there be no additional tracks in tagged semileptonic events (0.3%) is estimated by comparing fully reconstructed $D\bar{D}$ events in data and MC simulation. The uncertainty in the semileptonic reconstruction efficiencies due to imperfect knowledge of the semileptonic form factors is estimated by varying the form factors in the MC simulation within their uncertainties (1.0%) for all modes except $D^+ \to \rho^0 e^+ \nu_e$ and $D^+ \to \omega e^+ \nu_e$; for these a conservative uncertainty (3.0%) is taken, as no experimental information on the form factors in Cabibbo-suppressed pseudoscalar-to-vector transitions exists. The uncertainty associated with the simulation of FSR and bremsstrahlung

TABLE II. Signal efficiencies, yields, and branching fractions in this work and a comparison to the PDG [10]. The first uncertainty is statistical and the second systematic in the fourth column, and statistical or total in the other columns. The efficiencies do not include subsidiary branching fractions. The $D^+ \to \bar{K}^{*0} e^+ \nu_e$ yield is reduced by 2.4% in the calculation of the branching fraction (see the text for details).

Decay mode	ϵ (%)	Yield	$\mathcal{B}$ (%)	$\mathcal{B}$ (%) (PDG)
$D^+ \to \bar{K}^0 e^+ \nu_e$	57.1 ± 0.4	545 ± 24	$8.71 \pm 0.38 \pm 0.37$	6.7 ± 0.9
$D^+ \to \pi^0 e^+ \nu_e$	45.2 ± 1.0	63.0 ± 8.5	$0.44 \pm 0.06 \pm 0.03$	0.31 ± 0.15
$D^+ \to \bar{K}^{*0} e^+ \nu_e$	34.8 ± 0.3	422 ± 21	$5.56 \pm 0.27 \pm 0.23$	5.5 ± 0.7
$D^+ \to \rho^0 e^+ \nu_e$	40.0 ± 1.1	27.4 ± 5.7	$0.21 \pm 0.04 \pm 0.01$	0.25 ± 0.10
$D^+ \to \omega e^+ \nu_e$	16.4 ± 0.6	$7.6^{+3.3}_{-2.7}$	$0.16^{+0.07}_{-0.06} \pm 0.01$	

radiation in the detector material (0.6%) is estimated by varying the amount of FSR modeled by the PHOTOS algorithm [12] and by repeating the analysis with and without recovery of photons radiated by the positron. The uncertainty associated with the simulation of initial state radiation ($e^+e^- \to D\bar{D}\gamma$) is negligible. There is a systematic uncertainty due to finite MC statistics (0.7% to 4.0% by mode).

Nonresonant semileptonic decays $D^+ \to K^- \pi^+ e^+ \nu_e$ are background to $D^+ \to \bar{K}^{*0} e^+ \nu_e$. There is evidence from the FOCUS experiment for a nonresonant component consistent with an S-wave amplitude interfering with $D^+ \to \bar{K}^{*0} e^+ \nu_e$ [13]. Its contribution, estimated to be 2.4% in this analysis, is subtracted in the calculation of the branching fraction of $D^+ \to \bar{K}^{*0} e^+ \nu_e$ [14]. Systematic uncertainties associated with the subtraction are due to imperfect knowledge of the amplitude and phase of the nonresonant component (1.0%), and its effect on the reconstruction efficiency (1.5%) [15]. The line shapes for semileptonic modes with wide resonances are simulated using a relativistic Breit-Wigner resonance with a Blatt-Weisskopf form factor. A systematic uncertainty associated with the $\bar{K}^{*0}$ line shape (1.2%) is assigned by comparing the $(K^-\pi^+)$ invariant mass distribution in the data to alternative line shapes and the nonresonant contribution. For $D^+ \to \rho^0 e^+ \nu_e$, there is insufficient data to constrain the nonresonant background or the resonance line shape. The systematic uncertainties from these two sources are expected to be much smaller than the current statistical uncertainty for this mode, and are neglected.

These estimates of systematic uncertainty are added in quadrature to obtain the total systematic uncertainty (Table II): 4.2%, 5.6%, 4.1%, 6.2%, and 7.8% for $D^+ \to \bar{K}^0 e^+ \nu_e$, $D^+ \to \pi^0 e^+ \nu_e$, $D^+ \to \bar{K}^{*0} e^+ \nu_e$, $D^+ \to \rho^0 e^+ \nu_e$, and $D^+ \to \omega e^+ \nu_e$, respectively.

We now discuss the results presented in this Letter and the D^0 semileptonic study in Ref. [4]. The measured equality [10] of the inclusive semileptonic widths of D^0 and D^+ mesons demonstrates that the source of the lifetime difference between them is attributable to differences in the hadronic widths. The widths of the isospin conjugate exclusive semileptonic decay modes of the D^0 and D^+ are related by isospin invariance of the hadronic current. The results obtained here and in Ref. [4] allow the most precise tests so far.

The ratio $\frac{\Gamma(D^0 \to K^- e^+ \nu_e)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu_e)}$ is expected to be unity. The world average value is 1.35 ± 0.19 [10]. Using our results and the lifetimes of the D^0 and D^+ [10], we obtain: $\frac{\Gamma(D^0 \to K^- e^+ \nu_e)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu_e)} = 1.00 \pm 0.05(\text{stat}) \pm 0.04(\text{syst})$. The result is consistent with unity and with two recent less precise results: a measurement from BES II using the same technique [16] and an indirect measurement from FOCUS [17,18]. Ratios of isospin conjugate decay widths for other semileptonic decay modes are given in Table III.

As the data are consistent with isospin invariance, the precision of each branching fraction can be improved by averaging the D^0 and D^+ results for isospin conjugate pairs. The isospin-averaged semileptonic decay widths, with correlations among systematic uncertainties taken into account, are given in Table IV.

The ratio of decay widths for $D \to \pi e^+ \nu$ and $D \to K e^+ \nu$ provides a test of the LQCD charm semileptonic rate ratio prediction [19]. Using the isospin-averaged results in Table IV, we find $\frac{\Gamma(D^0 \to \pi^- e^+ \nu)}{\Gamma(D \to K e^+ \nu)} = [8.1 \pm 0.7(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-2}$, consistent with LQCD and two recent measurements [20,21]. Furthermore, the ratio $\frac{\Gamma(D \to K^* e^+ \nu)}{\Gamma(D \to K e^+ \nu)}$ is predicted to be in the range 0.5 to 1.1 [for a compilation see Ref. [17]]. Using the isospin averages in Table IV, we find $\frac{\Gamma(D \to K^* e^+ \nu)}{\Gamma(D \to K e^+ \nu)} = 0.63 \pm 0.03(\text{stat}) \pm 0.02(\text{syst})$.

Finally, summing all CLEO-c exclusive semileptonic branching fractions gives $\sum \mathcal{B}(D^0_{\text{excl}}) = [6.1 \pm 0.2(\text{stat}) \pm 0.2(\text{syst})]\%$ and $\sum \mathcal{B}(D^+_{\text{excl}}) = [15.1 \pm 0.5(\text{stat}) \pm 0.5(\text{syst})]\%$. These are consistent with the world average

TABLE III. Ratios of semileptonic decay widths of D^0 and D^+ mesons. The uncertainties are statistical and systematic. In each case the ratio is expected to be unity.

Ratio	Measured value
$\Gamma(D^0 \to K^- e^+ \nu)/\Gamma(D^+ \to \bar{K}^0 e^+ \nu)$	$1.00 \pm 0.05 \pm 0.04$
$\Gamma(D^0 \to \pi^- e^+ \nu)/[2 \cdot \Gamma(D^+ \to \pi^0 e^+ \nu)]$	$0.75^{+0.14}_{-0.11} \pm 0.04$
$\Gamma(D^0 \to K^{*-} e^+ \nu)/\Gamma(D^+ \to \bar{K}^{*0} e^+ \nu)$	$0.98 \pm 0.08 \pm 0.04$
$\Gamma(D^0 \to \rho^- e^+ \nu)/[2 \cdot \Gamma(D^+ \to \rho^0 e^+ \nu)]$	$1.2^{+0.4}_{-0.3} \pm 0.1$

TABLE IV. Isospin-averaged semileptonic decay widths with statistical and systematic uncertainties. For Cabibbo-suppressed modes, the isospin average is calculated for the D^0 using $\Gamma(D^0) = 2 \cdot \Gamma(D^+)$.

Decay mode	Γ $(10^{-2} \cdot \mathrm{ps}^{-1})$
$D \to K e^+ \nu_e$	$8.38 \pm 0.20 \pm 0.23$
$D^0 \to \pi^- e^+ \nu_e$	$0.68 \pm 0.05 \pm 0.02$
$D \to K^* e^+ \nu_e$	$5.32 \pm 0.21 \pm 0.20$
$D^0 \to \rho^- e^+ \nu_e$	$0.43 \pm 0.06 \pm 0.02$

inclusive semileptonic branching fractions: $\mathcal{B}(D^0 \to e^+ X) = (6.9 \pm 0.3)\%$ and $\mathcal{B}(D^+ \to e^+ X) = (17.2 \pm 1.9)\%$ [10], excluding the possibility of additional semileptonic modes of the D^0 and D^+ with large branching fractions.

In summary, we have presented the most precise measurements to date of the absolute branching fractions of D^+ decays to $\bar{K}^0 e^+ \nu_e$, $\pi^0 e^+ \nu_e$, $\bar{K}^{*0} e^+ \nu_e$, and $\rho^0 e^+ \nu_e$, and the first observation and absolute branching fraction measurement of $D^+ \to \omega e^+ \nu_e$. We have combined these with measurements in Ref. [4], which use the same data and analysis technique, to demonstrate that charm exclusive semileptonic decays are consistent with isospin invariance and to test other theoretical predictions. A comparison of the world average inclusive semileptonic branching fractions to the sum of the semileptonic branching fractions in this work excludes the possibility of additional semileptonic modes with large branching fractions.

The precision achieved in this analysis is consistent with the expected performance of CLEO-c. CESR is currently running to collect a much larger $\psi(3770)$ data sample. It is expected that this sample will result in greatly improved measurements of D^0 and D^+ semileptonic branching fractions, measurements of the decay form factors, which are stringent tests of LQCD, and the CKM matrix elements V_{cs} and V_{cd} [3].

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