D Semileptonic Decays at CLEO-c

Semileptonic decays are the preferred way to determine the CKM matrix elements as the strong interaction binding effects in these decays are confined to the hadronic current. They are parameterized 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. 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.

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)[1]. We review herein measurements with the first CLEO-c data of the absolute branching fractions of D^0 decays to $K^-e^+\nu_e$, $\pi^-e^+\nu_e$, $K^{*-}e^+\nu_e$ and $\rho^-e^+\nu_e$, as well as of D^+ decays to $\bar{K}^0e^+\nu_e$, $\pi^0e^+\nu_e$, $\bar{K}^{*0}e^+\nu_e$ and $\rho^0e^+\nu_e$, including the first observations and absolute branching fraction measurements of $D^0 \to \rho^-e^+\nu_e$ and $D^+ \to \omega e^+\nu_e$ [2, 3], and compare them to recent measurements from other experiments and theoretical predictions. We also review the prospects for measuring semileptonic form factors and the CKM matrix elements V_{cs} and V_{cd} with the full CLEO-c data set.

The data for this analysis 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. [2] and references therein. The data sample consists of an integrated luminosity of 55.8 pb^{-1} and includes about 160,000 D^+D^- and 200,000 $D^0\bar{D}^0$ events.

The technique for these measurements was first applied by the Mark III collaboration [4] at SPEAR. Candidate events are selected by reconstructing a $\bar{D}^0$ (D^-), called a tag, in a hadronic final state. The absolute branching fractions of D^0 (D^+) semileptonic decays are then measured by their reconstruction in the system recoiling from the tag. Tagging a $\bar{D}^0$ (D^-) meson in a $\psi(3770)$ decay provides a D^0 (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 [5]. If multiple candidates are present in the same tag mode, one candidate per $\bar{D}^0$ or D^- is chosen using ΔE, and the yields in each tag modes are obtained from fits to the M_{bc} distributions. The data sample comprises approximately 60,000 (32,000) neutral (charged) tags, reconstructed in eight neutral (six charged) D meson hadronic final states [2, 3], respectively.

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.) 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, while the positron fake rate from charged pions and kaons is approximately 0.1% [2]. 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. The K^0_S 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^0_S mass. We form $\bar{K}^{*-}/\rho^-/\bar{K}^{*0}/\rho^0$ candidates from (K^- and π^0) or (K^0_S and π^-) / (π^- and π^0) / (K^- and π^+) / (π^- and π^+) combinations and require an invariant mass within 100 MeV/c^2 and 150 MeV/c^2 for the K^* and ρ from the expected mean values. 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^0_S.

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 $U \equiv E_{\text{miss}} - |\vec{p}_{\text{miss}}|c$, where E_{miss} and $\vec{p}_{\text{miss}}$ 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 U distribution has $\sigma \sim 10$ MeV. (The width varies by mode and is larger for modes with π^0 mesons.) 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^0_S, $\bar{K}^*$, ρ, π^0, or ω candidates to their expected masses.

The yield for each semileptonic mode is determined from a fit to its U distribution. The backgrounds are generally small and arise mostly from misreconstructed semileptonic decays with correctly reconstructed tags. The absolute branching fractions in Table I are determined using $\mathcal{B} = N_{\text{signal}}/\epsilon N_{\text{tag}}$, where N_{signal} is the number of fully reconstructed $D\bar{D}$ events obtained by fitting the U distribution, N_{tag} is the number of events with a reconstructed tag, and ϵ is the effective efficiency for de-

Mode	Yield	$\mathcal{B}$ (%)	$\mathcal{B}$ (%) (PDG)
$D^0 \to K^- e^+ \nu_e$	1311 ± 37	$3.44 \pm 0.10 \pm 0.10$	3.58 ± 0.18
$D^0 \to \pi^- e^+ \nu_e$	116.8 ± 11.2	$0.26 \pm 0.03 \pm 0.01$	0.36 ± 0.06
$D^0 \to K^{*-} e^+ \nu_e$	219.3 ± 15.6	$2.16 \pm 0.15 \pm 0.08$	2.15 ± 0.35
$D^0 \to \rho^- e^+ \nu_e$	31.1 ± 6.3	$0.19 \pm 0.04 \pm 0.01$	—
$D^+ \to \bar{K}^0 e^+ \nu_e$	545 ± 24	$8.71 \pm 0.38 \pm 0.37$	6.7 ± 0.9
$D^+ \to \pi^0 e^+ \nu_e$	63.0 ± 8.5	$0.44 \pm 0.06 \pm 0.03$	0.31 ± 0.15
$D^+ \to \bar{K}^{*0} e^+ \nu_e$	422 ± 21	$5.56 \pm 0.27 \pm 0.23$	5.5 ± 0.7
$D^+ \to \rho^0 e^+ \nu_e$	27.4 ± 5.7	$0.21 \pm 0.04 \pm 0.01$	0.25 ± 0.10
$D^+ \to \omega e^+ \nu_e$	$7.6^{+3.3}_{-2.7}$	$0.16^{+0.07}_{-0.06} \pm 0.01$	—

TABLE I: Signal yields and branching fractions in this work and a comparison to PDG [6]. The first uncertainty is statistical and the second systematic in the third column, and statistical or total in the other columns. The yield ($\mathcal{B}$) for $D^0 \to K^{*-} e^+ \nu_e$ is summed (averaged) over the two K^{*-} submodes of $K^- \pi^0$ and $K^0_S \pi^-$. Signal yields for $D^0 \to \rho^- e^+ \nu_e$ and $D^+ \to \omega e^+ \nu_e$ are significant and represent the first observations of these modes.

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

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

tecting the semileptonic decay in an event with an identified tag.

The largest contributors to the systematic uncertainty are associated with the tracking efficiency, the π^0 and K^0_S reconstruction efficiencies, the extraction of D tag yields, the positron and hadron identification efficiencies, background shapes and normalizations, imperfect knowledge of form factors, and the simulation of final state radiation. The non-resonant contribution in the $D \to K^* e \nu_e$ reconstruction and the associated systematic uncertainty are accounted for as described in Ref. [2, 3]. The the total systematic uncertainty ranges from 2.8% to 7.8% by mode (Table I). Most systematic uncertainties are measured in data and will be reduced with a larger data set.

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 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 [6]. Using our results and the lifetimes of the D^0 and D^+ [6], we obtain: $\frac{\Gamma(D^0 \to K^- e^+ \nu_e)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu_e)} = 1.00 \pm 0.05(\mathrm{stat}) \pm 0.04(\mathrm{syst})$. The result is consistent with unity and with two recent less precise results: a measurement from BES II using the same technique [7] and an indirect measurement from FOCUS [8, 9]. The ratios of isospin conjugate decay widths for other semileptonic decay modes are given in Ref. [3] and are all consistent with isospin invariance.

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 II.

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 [10]. Using the results in Table II, we find $\frac{\Gamma(D^0 \to \pi^- e^+ \nu)}{\Gamma(D \to K e^+ \nu)} = (8.1 \pm 0.7(\mathrm{stat}) \pm 0.2(\mathrm{syst})) \times 10^{-2}$, consistent with LQCD and two recent results [11, 12]. 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. [8]). Using the isospin averages in Table II, we find $\frac{\Gamma(D \to K^* e^+ \nu)}{\Gamma(D \to K e^+ \nu)} = 0.63 \pm 0.03(\mathrm{stat}) \pm 0.02(\mathrm{syst})$.

The modest in size data sample used in this analysis produced the most precise measurements to date of the absolute branching fractions for all modes in Table I. The analysis already provides stringent tests of the theory. This precision is consistent with the expected performance of CLEO-c. CESR is running to collect a much larger $\psi(3770)$ data sample.

The future CLEO-c data sample (3.0 fb^{-1}) will allow measurements of the q^2 dependence ($f_+(q^2)$) and, assuming the unitarity of the CKM matrix, the absolute normalization ($f_+(0)$) of form factors at a percent level ($\mathcal{O}(1\%)$) in both $D \to K e^+ \nu_e$ and $D \to \pi e^+ \nu_e$ [1]. For $D \to K^* e^+ \nu_e$ and $D \to \rho e^+ \nu_e$, form factors $A_1(q^2)$, $A_2(q^2)$, and $V(q^2)$ can be measured to a few percent [1]. These measurements of form factors (and other precision measurements in the D, B, Υ and ψ systems) constitute calibration and validation data for LQCD and other theoretical approaches.

Theoretical predictions for form factors are required for measurements of the CKM matrix elements. In charm decays, the modes $D^0 \to K^- e^+ \nu_e$ and $D^0 \to \pi^- e^+ \nu_e$ are very important as they are the simplest for both the theory and the experiment. Assuming future theoretical uncertainties on the form factors in these decays of 3.0% and using the anticipated uncertainties for the absolute decay rates of $D^0 \to K^- e^+ \nu_e$ and $D^0 \to \pi^- e^+ \nu_e$ from CLEO-c of 1.2% and 1.5%, respectively, the following uncertainties on $|V_{cs}|$ and $|V_{cd}|$ are within reach: $|\sigma(V_{cs})/V_{cs}| \approx 1.6\%$ and $|\sigma(V_{cd})/V_{cd}| \approx 1.7\%$ [1].

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