Leptonic and Semileptonic Charm Decays from CLEO-c

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I describe CLEO-c purely leptonically decay results leading to $f_{D^+} = (222.6 \pm 16.7^{+21.6}_{-3.6})$ MeV, $f_{D_s^+} = (280.1 \pm 11.6 \pm 6.0)$ MeV, and $f_{D^+_s}/f_{D^+} = 1.26 \pm 0.11 \pm 0.03$. Form-factor measurements in Cabibbo favored and suppressed pseudoscalar decays are presented. Some comparisons are made with theoretical predictions.

I. INTRODUCTION

Threshold production of $D^0 \overline{D}^0$ and $D^+D^-$ mesons at 3770 MeV, and $D^+_s D^+_s + D^+_s D^+_s$ mesons at 4170 MeV in $e^+e^-$ annihilations have allowed CLEO-c to make precision measurements using purely leptonic and semileptonic charm meson decays.

II. PURELY LEPTONIC DECAYS

To extract precise information from $B$ mixing measurements the ratio of “leptonic decay constants,” $f_i$, for $B_d$ and $B_s$ mesons must be well known [1]. Indeed, the recent measurement of $B^0_s$ mixing by CDF [2] has pointed out the urgent need for precise numbers. The $f_i$ have been calculated theoretically. The most promising of these calculations are based on lattice-gauge theory that include the light quark loops [3]. In order to ensure that these theories can adequately predict $f_i$, it is critical to check the analogous ratio from charm decays $f_{D^+_s}/f_{D^+}$. Here I present the most precise measurements to date of $f_{D^+_s}$, $f_{D^+}$ [4,5] and $f_{D^+_s}/f_{D^+}$.

![Decay Diagram](image)

FIG. 1: The decay diagram for $D^+_s \rightarrow \ell^+\nu$.

In the Standard Model (SM) the $D^+_s(s)$ meson decays purely leptonically as shown in Fig. 1. The decay width is given by [6]

$$\Gamma(D^+_s \rightarrow \ell^+\nu) = \frac{G_F^2 f^2_{D^+_s} m^2_{\ell^+} M_{D^+_s}}{8\pi} \times \left( 1 - \frac{m^2_{\ell^+}}{M^2_{D^+_s}} \right)^2 |V_{cq}|^2 ,$$

where $m_{\ell^+}$ and $M_{D^+_s}$ are the $\ell^+$ and $D^+_s$ masses, $|V_{cq}|$ is the CKM element appropriate to either $D^+_s (V_{cd})$ or $D^+_s (V_{cs})$ decay and $G_F$ is the Fermi constant.

New physics can affect the expected widths; any undiscovered charged bosons would interfere with the SM $W^+$. These effects may be difficult to ascertain, since they would simply change the value of the $f_i$'s. The ratio $f_{D^+_s}/f_{D^+}$, however, is much better predicted in the SM than the values individually. Akeroyd predicts that the presence of a charged Higgs boson would suppress this ratio significantly [7]. In addition, the ratio of decay rates to different leptons are fixed only by well-known masses in Eq. 1. For example, the SM prediction for $\Gamma(D^+_s \rightarrow \tau^+\nu)/\Gamma(D^+_s \rightarrow \mu^+\nu)$ is 9.72. In general, any deviation from a predicted ratio would be a manifestation of physics beyond the SM, and would be a clear violation of lepton universality [8].

CLEO previously measured $f_{D^+_s}$ using 4.8 fb$^{-1}$ of continuum annihilation data at or just below the $Y(4S)$ [9]. This analysis introduced a number of new ideas: (i) The $\gamma$ and $\mu^+$ from $D^+_s \rightarrow \gamma D^+_s$; $D^+_s \rightarrow \mu^+\nu$ were detected directly, and the $\nu$ 4-vector was inferred from missing energy and momentum measurement in half of the event, where the event half was determined using the normal to the thrust axis. (ii) The $\nu$ 4-vector was corrected to get the right $D^+_s$ mass and $\Delta M = M(\gamma\mu^+\nu) - M(\mu^+\nu)$ was examined (see Fig. 2(a)). (iii) The background was measured using the same technique with $e^+$ identified instead of $\mu^+$, relying on the large suppression of the $e^+$ rate compared with the $\mu^+$ rate. (iv) The reaction $D^{*0} \rightarrow \gamma D^0$; $D^0 \rightarrow K^-\pi^+$, where the $\pi^+$ is first found and then ignored was used to evaluate efficiencies. The published result was

$$\frac{\Gamma(D^+_s \rightarrow \mu^+\nu)}{\Gamma(D^+_s \rightarrow \phi\pi^+)} = 0.173 \pm 0.023 \pm 0.035 .$$

BaBar recently performed an improved analysis based on these techniques [10]. They used 230 fb$^{-1}$ of continuum data. To reduce the background and systematic errors they fully reconstruct a $D^0$, $D^+$ or $D^*$ meson in the event with the $\gamma$ and $\mu^+$ candidate. Their data are shown in Fig. 2(b). They find

$$\frac{\Gamma(D^+_s \rightarrow \mu^+\nu)}{\Gamma(D^+_s \rightarrow \phi\pi^+)} = 0.143 \pm 0.018 \pm 0.006 .$$
Both of these results, however, need to assume a value for $B(D_s^+ \to \phi \pi^+)$ [11], in order to extract the decay constant. Because of interferences among the final state $K^+ K^- \pi^+$ particles, the rate for $\phi \pi^+$ depends on experimental cuts [12], and thus has an inherent, sizable, systematic error. (Other experiments also normalize with respect to this or other less well known modes.)

CLEO-c eliminates this uncertainty by making absolute measurements. We tag a $D_s^-$ decay and search for three separate decay modes of the $D_s^+$: (1) $\mu^+ \nu$ and $\tau^+ \nu$, where (2) $\tau^+ \to \pi^+ \nu$ or (3) $\tau^+ \to e^+ \nu\nu$ [13]. For the first two analyses we require the detection of the $\gamma$ from the $D_s^\ast$ to $\gamma D_s$ decay, irrespective if the $D_s^\ast$ is the parent of the tag or the leptonic decay. In either case, for real $D_s^\ast D_s$, the missing mass squared recoiling against the photon and the $D_s^\ast$ tag should peak at $M_{D_s}$ and is given by

$$MM^2 = (E_{CM} - E_D - E_\gamma)^2 - (\vec{p}_{CM} - \vec{p}_D - \vec{p}_\gamma)^2,$$

where $E_{CM}$ ($\vec{p}_{CM}$) is the center of mass energy (momentum), $E_D$ ($\vec{p}_D$) and $E_\gamma$ ($\vec{p}_\gamma$) are the energy of the fully reconstructed $D_s^\ast$ tag, and the additional photon. In performing this calculation we use a kinematic fit that constrains the decay products of the $D_s^\ast$ to $M_{D_s}$ and conserves overall momentum and energy.

The $MM^2$ from the $D_s^-$ tag sample data is shown in Fig. 3. There are 11880±399±511 signal events in the interval $3.978 < MM^2 < 3.776$ GeV$^2$.

Candidate $D_s^+ \to \mu^+ \nu$ events are searched for by selecting events with only a single extra track with opposite sign of charge to the tag; we also require that there not be an extra neutral energy cluster in excess of 300 MeV. Since here we are searching for events where there is a single missing neutrino, the missing mass squared, $MM^2$, evaluated by taking into account the seen $\mu^+ \ D_s^+$, and the $\gamma$ should peak at zero, and is given by

$$MM^2 = (E_{CM} - E_D - E_\gamma - E_\mu)^2 - (\vec{p}_{CM} - \vec{p}_D - \vec{p}_\gamma - \vec{p}_\mu)^2,$$

where $E_\mu$ ($\vec{p}_\mu$) is the energy (momentum) of the candidate muon track.

We also make use of a set of kinematical constraints and fit the $MM^2$ for each $\gamma$ candidate to two hypotheses one of which is that the $D_s^\ast$ tag is the daughter of a $D_s^\ast$ and the other that the $D_s^\ast$ decays into $\gamma D_s^\ast$, with the $D_s^\ast$ subsequently decaying into $\mu^+ \nu$.

The kinematical constraints are the total momentum and energy, the energy of the either the $D_s^\ast$ or the $D_s$, the appropriate $D_s^\ast - D_s$ mass difference and the invariant mass of the $D_s$ tag decay products. This gives us a total of 7 constraints. The missing neutrino four-vector needs to be determined, so we are left with a three-constraint fit. We perform a standard iterative fit minimizing $\chi^2$. As we do not want to be subject to systematic uncertainties that depend on understanding the absolute scale of the errors, we do not make a $\chi^2$ cut, but simply choose the photon and the decay sequence in each event with the minimum $\chi^2$.

We consider three mutually exclusive cases: (i) the track deposits < 300 MeV in the calorimeter, characteristic of a non-interacting $\pi^+$ or a $\mu^+$; (ii) the track deposits > 300 MeV in the calorimeter, characteristic of an interacting $\pi^+$; (iii) the track satisfies our $e^+$ selection criteria. The $MM^2$ distributions are shown in Fig. 4. The separation between $\mu^+$ and $\tau^+$ is not unique. Case (i) contains 99% of the $\mu^+$ but also 60% of the $\pi^+$, while case (ii) includes 1% of the $\mu^+$ and 40% of the $\pi^+$. There is a clear peak in Fig. 4(i), due to $D_s^+ \to \mu^+ \nu$. Furthermore, the events in the region between $\mu^+ \nu$ peak and 0.20 GeV$^2$ are dominantly due to the $\tau^+ \nu$, $\tau^+ \to \pi^+ \nu$, decay. The best result comes from summing case (i) and case (ii) below $MM^2$ of 0.20 GeV$^2$; higher values of $MM^2$ admit background from $\eta \pi^+$ and $K^0 \pi^+$ final states. The branching fractions are summarized in Table I. The absence of any detected $e^+$ opposite to our tags allows us to set the upper limit listed in Table I.

CLEO-c also uses $D_s^+ \to \tau^+ \nu$, $\tau^+ \to e^+ \nu\nu$. Electrons of opposite sign to the tag are detected in events without any additional charged tracks, and determining the unmatched energy in the crystal calorimeter ($E_{CC}^{extra}$). This energy distribution is shown in Fig. 5. Requiring $E_{CC}^{extra} < 400$ MeV, enhances the signal. The branching ratio resulting from this analysis is also listed in Table I.

CLEO-c’s published result for $f_{D_s}$ [5] uses the “double-tag” method at 3770 GeV, where $D^+ D^-$ final states are
produced without any extra particles. Here one $D^-$ is fully reconstructed and then there are enough kinematic constraints to search for $D^+ \rightarrow \mu^+ \nu$ by constructing the missing mass-squared ($M^2$) opposite the $D^-$ and the muon. Fifty signal events are found of which 2.8 are estimated background, resulting in:

$$B(D^+ \rightarrow \mu^+ \nu) = (4.40 \pm 0.66^{+0.09}_{-0.12}) \times 10^{-4}.$$  \hspace{1cm} (5)

The decay constant $f_{D^+}$ is obtained from Eq. (1) using $1.040 \pm 0.007$ ps as the $D^+$ lifetime, and $|V_{cd}| = 0.2238 \pm 0.0029$, giving

$$f_{D^+} = (222.6 \pm 16.7^{+2.8}_{-3.9}) \text{ MeV}.$$ \hspace{1cm} (6)

CLEO-c also sets limits on $B(D^+ \rightarrow e^+ \nu_e) < 2.4 \times 10^{-5}$ \cite{4} and $B(D^+ \rightarrow \tau^+ \nu)$ branching ratio to $< 2.1 \times 10^{-3}$ at 90\% C.L. \cite{14}. These limits are consistent with SM expectations.

For $D_s^+$ decays, we first test lepton universality in

$$R \equiv \frac{\Gamma(D_s^+ \rightarrow \tau^+ \nu)}{\Gamma(D_s^+ \rightarrow \mu^+ \nu)} = 9.9 \pm 1.9,$$ \hspace{1cm} (7)

consistent with the predicted value of 9.72. Combining our branching ratios determinations and using $\tau_{D_s^+} = 0.49$ ps and $|V_{cs}| = 0.9737$, we find

$$f_{D_s} = (280.1 \pm 11.6 \pm 6.0) \text{ MeV}, \hspace{1cm} (8)$$

$$f_{D_s^+}/f_{D^+} = 1.26 \pm 0.11 \pm 0.03.$$ \hspace{1cm}

These preliminary results are consistent with most recent theoretical models. As examples, unquenched lattice \cite{15} predicts $1.24 \pm 0.01 \pm 0.07$, while one quenched lattice calculation \cite{10} gives $1.13 \pm 0.03 \pm 0.05$, with other groups having similar predictions \cite{20}.

III. SEMILEPTONIC DECAYS

One of the best ways to measure magnitudes of CKM elements is to use semileptonic decays since they are far simpler to understand than hadronic decays and the decay width is $\sim |V_{cq}|^2$. On the other hand, measurements using other techniques have obtained useful values for $V_{cs}$ and $V_{cd}$ \cite{17}, and thus semileptonic $D$ decay measurements are a good laboratory for testing theories of QCD. For a $D$ meson decaying into a single hadron ($h$), the decay rate can be written exactly in terms of the four-momentum transfer defined as:

$$q^2 = (p_D^\mu - p_h^\mu)^2 = m_D^2 + m_h^2 - 2E_h m_D.$$ \hspace{1cm} (9)

For decays to pseudoscalar mesons and “virtually massless” leptons, the decay width is given by:

$$\frac{d\Gamma(D \rightarrow Pe^+\nu)}{dq^2} = |V_{cq}|^2 G_F^2 p_D^3 24\pi^3 |f_+(q^2)|,$$ \hspace{1cm} (10)
where $p_P$ is the three-momentum of $P$ in the $D$ rest frame, and $f_+(q^2)$ is a “form-factor,” whose normalization must be calculated theoretically, although its shape can be measured.

The shape measurements can distinguish between form-factor parameterizations. In general,

$$f_+(q^2) = \frac{f_+(0)}{(1 - \frac{q^2}{m_{\text{pole}}^2})} + \frac{1}{\pi} \int_{(M_D + M_P)^2}^{\infty} dq'' \frac{f(q''^2)}{q''^2 - q^2},$$

which incorporates the possibility of a virtual of a nearby pole (first term) with fractional strength $\alpha_p$. The integral term can be expressed in terms of an infinite series [18].

Eventually combined results will be quoted; they should not be averaged as there are a substantial number of events in common.

Form-factor shapes using the tagged sample are shown in Fig. 5. The unquenched lattice QCD model [21] is systematically higher than our data, but not in significant disagreement. Properties of these decays are listed in Table II.

Measurements of the vector decays $D \rightarrow K^0 e^+\nu$ and $\rho e^+\nu$ can be used to determine $|V_{ub}|$ along with measurements of $B \rightarrow \rho\ell^-\bar{\nu}$ and $B \rightarrow K^+\ell^-\ell^-$. CLEO-c has examined $D$ vector semileptonic decays. Non-parametric form-factors in the Cabibbo favor $D^0 \rightarrow \pi^-\nu$ and $D^+ \rightarrow \pi^-\nu$. CLEO-c uses two methods to analyze pseudoscalar decays. The first method tags are fully reconstructed and events with a missing $\nu$ are inferred using the variable $U = E_{\text{miss}} - |P_{\text{miss}}|$, similar to MM. CLEO-c uses two methods to analyze pseudoscalar decays. The first method tags are fully reconstructed and events with a missing $\nu$ are inferred using the variable $U = E_{\text{miss}} - |P_{\text{miss}}|$, similar to MM.

FIG. 8: CLEO-c form-factor shapes using the tagged sample. The lower curves are fits to the modified pole model, while the upper curves are fits to unquenched lattice QCD [21].

TABLE II: Properties of $D^0 \rightarrow P^- e^+\nu$ decays (preliminary) [22].

| Quantity | $K^- e^+\nu$ | $\pi^- e^+\nu$ | Source |
|----------|---------------|----------------|--------|
| $B(\%)$  | 3.58(5)(12)   | 0.390(12)(6)   | CLEO-c Tag |
| $\alpha$ | 0.2(5)       | 0.17(10)      | CLEO-c Tag |
| $m_{\text{pole}}$ (GeV) | 1.96(3) (1) | 1.95(4) (2) | CLEO-c Tag |
| $m_{\text{pole}}$ (GeV) | 1.97(2) (1) | 1.89(3) (1) | CLEO-c NoTag |

FIG. 7: $M_{bc}$ distributions for events containing an identified electron of opposite flavor plus a single hadron candidate. The shaded regions indicate various backgrounds.

The second method consists of also using missing energy and momentum, skipping the step of reconstructing the tag, but using all of the measured charged tracks and photons. Then the $D$ mass is reconstructed. The beam-constrained mass ($M_{bc}$) distributions are shown in Fig. 6.

Both cases have excellent signal to background in these modes. The $\nu$-reconstruction has better statistical albeit poorer systematic errors. Eventually combined results will be quoted; they should not be averaged as there are a substantial number of events in common.

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using both charge and neutral modes [22].

Other results on semileptonic decays from CLEO-c include measurement of the inclusive $D^0$ and $D^+$ semileptonic branching fractions of $(6.46 \pm 0.17 \pm 0.13)\%$, and $(16.13 \pm 0.20 \pm 0.33)\%$, respectively, leading to a measurement of the partial width ratio of $\Gamma(D^+)/\Gamma(D^0) = (0.985 \pm 0.028 \pm 0.015)$, consistent with isospin symmetry [26].

IV. CONCLUSIONS

CLEO-c measurements of leptonic and semileptonic decays have already reached precisions that provide very useful benchmarks for testing of QCD theories. From leptonic decays we have

$$f_{D^+} = (222.6 \pm 16.7 \pm 2.8) \text{ MeV},$$
$$f_{D^+_s} = (280.1 \pm 11.6 \pm 6.0) \text{ MeV},$$
$$f_{D^+_s}/f_{D^+} = 1.26 \pm 0.11 \pm 0.03 .$$

These results are consistent with most theoretical calculations including those of unquenched lattice QCD [20].

CLEO-c is also breaking new ground in the study of semileptonic decays. Form-factors in Cabibbo suppressed decays are reaching an unprecedented level of accuracy and are also confronting theory.

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