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# Absolute Branching Fraction Measurements for $D^+$ and $D^0$ Inclusive Semileptonic Decays*

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## Abstract

We present measurements of the inclusive branching fractions for the decays $D^+ \to Xe^+\nu_e$ and $D^0 \to Xe^+\nu_e$, using 281 pb$^{-1}$ of data collected on the $\psi(3770)$ resonance with the CLEO-c detector. We find $\mathcal{B}(D^0 \to Xe^+\nu_e) = (6.46 \pm 0.17 \pm 0.13)\%$ and $\mathcal{B}(D^+ \to Xe^+\nu_e) = (16.13 \pm 0.20 \pm 0.33)\%$. Using the known $D$ meson lifetimes, we obtain the ratio $\Gamma^{\rm sl}_{D^+}/\Gamma^{\rm sl}_{D^0} = 0.985 \pm 0.028 \pm 0.015$, consistent with isospin invariance at the level of 3%. The positron momentum spectra from $D^+$ and $D^0$ have consistent shapes.

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The study of inclusive $D$ semileptonic decays is important for several reasons. First, by comparing the inclusive branching fractions of the $D^+$ and $D^0$ mesons with the sum of the measured exclusive branching fractions, one can determine whether there are semileptonic decay modes as yet unobserved. Previous data suggest that the lightest vector and pseudoscalar resonances saturate the hadronic spectra [1]. This may be due to the relatively low momentum of the daughter $s$ quark, that favors the formation of s-wave hadrons, but no stronger theoretical argument supports this saturation. Second, since accurate experimental determinations of the $D^0$ and $D^+$ lifetimes are available [1], measurements of semileptonic branching fractions determine the corresponding semileptonic widths, $\Gamma^{\rm sl}_{D^+}$ and $\Gamma^{\rm sl}_{D^0}$. These widths are expected to be equal, modulo small corrections introduced by electromagnetic effects. Weak annihilation diagrams can produce more dramatic effects on the Cabibbo suppressed partial widths [2]. As these terms may also influence the extraction of $V_{ub}$ from inclusive $B$ meson semileptonic decays, it is important to understand them well. Finally, improved knowledge of the inclusive positron spectra refines the modeling of the "cascade" decays $b \to c \to se^+\nu$ and thus is important in several measurements of $b$ decays.

The use of ratios of semileptonic branching fractions as a probe of relative lifetimes of the $D$ mesons was suggested by Pais and Treiman [3]. And indeed the early measurements of the ratio of the $D^+$ and $D^0$ semileptonic branching fractions gave the first surprising evidence for the lifetime difference between these two charmed mesons [4, 5]. Later, the first measurement of the individual charged and neutral $D$ inclusive semileptonic branching fractions was performed by Mark III [6], with an overall uncertainty of the order of 12-16% in the individual branching fractions, and 19% in their ratio.

We use a 281 pb$^{-1}$ data sample, collected at the $\psi(3770)$ center-of-mass energy, with the CLEO-c detector [7]. This detector encompasses a high resolution tracking system, complemented by a state of the art CsI electromagnetic calorimeter, and a Ring Imaging Cherenkov (RICH) hadron identification system. All these components are critical to an efficient and highly selective electron and positron identification algorithm. The CsI calorimeter measures the electron and photon energies with a resolution of 2.2% at $E = 1$ GeV and 5% at $E$=100 MeV, which, combined with the excellent tracking system, provides one of the $e$ identification variables, $E/p$, where $E$ is the energy measured in the calorimeter and $p$ is the momentum measured in the tracking system. The tracking system provides charged particle discrimination too, through the measurement of the specific ionization $dE/dx$. In addition, charged particles are identified over most of their momentum range in the RICH detector [8]. In particular, RICH identification plays a crucial role at momenta where the specific ionization bands of two particle species cross each other and $dE/dx$ has very limited discrimination power.

We use a tagging technique similar to the one pioneered by the Mark III collaboration [9]. Details on the tagging selection procedure are given in Ref. [10]. We select events containing either the decay $\bar{D}^0 \to K^+\pi^-$ or the decay $D^- \to K^+\pi^-\pi^-$. We use only these modes, because they have very low background, and thus we refer to them as "golden modes". Note that charge conjugate modes are implied throughout this paper. In this analysis we exploit the flavor information provided by the tagging $D$: the $D^-$ charge sign provides a flavor tag, whereas the charge of the tag daughter $K$ is used for $\bar{D}^0$ flavor assignment.

We analyze all the recorded events at the $\psi(3770)$ and retain the events that contain at least one candidate $\bar{D}^0 \to K^+\pi^-$ or $D^- \to K^+\pi^-\pi^-$. Two kinematic variables are used to select these candidates: the beam-constrained mass, $M_{\rm bc} \equiv \sqrt{E^2_{\rm beam} - (\Sigma_i \vec{p}_i)^2}$, and the energy difference $\Delta E$, where $\Delta E \equiv (\Sigma_i E_i - E_{\rm beam})$, where $E_{\rm beam}$ represents the beam energy and $(E_i, \vec{p}_i)$ represent the 4-vectors of the candidate daughters. We select events that are within 3 standard deviations ($\sigma$) of the expected $\Delta E$ (0 GeV) and $M_{\rm bc}$ ($M_D$) for the channels considered. In order to determine the total number of tags, we count the events within the selected $\Delta E$-$M_{\rm bc}$ intervals; then we subtract the combinatoric background inferred from two $3\sigma$ wide sideband regions on both sides of the $\Delta E = 0$ signal peak. The raw yields in the signal region are 48204 $\bar{D}^0$ and 76635 $D^-$. The corresponding raw yields in the sideband region are $788 \pm 28$ and $2360 \pm 49$. We correct the sideband yields with scale factors accounting for the relative area of the background in the signal and sideband intervals (1.047 for $D^0$ and 1.23 for $D^+$), and we obtain the net yields of $47379 \pm 29$ $\bar{D}^0-$, and $73732 \pm 60$ $D^-$ tagged events. Note that the estimated background is only 1.7% of the signal for $\bar{D}^0$ and 3.9% for $D^-$.

For each event selected, we study all the charged tracks not used in the tagging mode. We select the ones that are well-measured, and whose helical trajectories approach the event origin within a distance of 5 mm in the azimuthal projection and 5 cm in the polar projection, where the azimuthal view is the bend view of the solenoidal magnet. Each track must include at least 50% of the hits expected for its momentum. Moreover, it must be within the RICH fiducial volume ($|\cos(\theta)| \leq 0.8$), where $\theta$ is the angle with respect to the beams. Finally, we require the charged track momentum $p_{\rm track}$ to be greater than or equal to 0.2 GeV, as the particle species separation becomes increasingly difficult at low momenta.

Candidate $e^+$ are selected on the basis of a likelihood ratio constructed from three inputs: the ratio between the energy deposited in the calorimeter and the momentum measured in the tracking system, the specific ionization $dE/dx$ measured in the drift chamber, and RICH information [11]. Our selection criteria have an average efficiency of 0.95 in the momentum region 0.3-1.0 GeV, and 0.71 in the region 0.2-0.3 GeV.

The $e^+$ sample contains a small fraction of hadrons that pass our selection criteria. As the probability that a $\pi$ is identified as an $e$ ("fakes" an $e$) at a given momentum is different than the corresponding $K$ to $e$ "fake probability", we need to know the $K$ and $\pi$ yields separately to subtract this background; thus we measure these distributions. We select $\pi$ and $K$ samples using a particle identification variable (PID) that combines RICH and $dE/dx$ information, if the RICH identification variable [8] is available and $p_{\rm track} > 0.7$ GeV; alternatively PID relies on $dE/dx$ only. The $\pi$ group contains also a $\mu$ component, as our PID variable is not very selective; however, as our goal is to unfold the true $e$ spectrum, we do not need to correct for this effect.

We separate $e^\pm$, $\pi^\pm$, and $K^\pm$ into "right-sign" and "wrong-sign" samples according to their charge correlation to the flavor tag. Right-sign assignment is based on the expected $e$ charge on the basis of the flavor of the decaying $D$. The true $e$ populations in the right-sign and wrong-sign samples are obtained through an unfolding procedure, using the matrix:

$$\begin{pmatrix} n_e^m \\ n_\pi^m \\ n_K^m \end{pmatrix} = \begin{pmatrix} \varepsilon_e & f_{e\pi} & f_{eK} \\ f_{\pi e} & \varepsilon_\pi & f_{\pi K} \\ f_{Ke} & f_{K\pi} & \varepsilon_K \end{pmatrix} \times \begin{pmatrix} n_e^t \\ (n_\pi^t + \kappa n_\mu^t) \\ n_K^t \end{pmatrix};$$

here $n_e^m$, $n_\pi^m$, $n_K^m$ represent the raw measured spectra in the corresponding particle species, and the coefficient $\kappa$ accounts for the fact that the efficiency for $\pi$ and $\mu$ selection is not necessarily identical, especially at low momenta. The quantities $n_e^t$, $n_\pi^t$, and $n_K^t$ represent the true $e$, $\pi$ and $K$ spectra: the present paper focuses on the extraction of $n_e^t$. The efficiencies $\epsilon_e$, $\epsilon_\pi$, and $\epsilon_K$ account for track finding, track selection criteria, and particle identification losses. The tracking efficiencies are obtained from a MC simulation of $D\bar{D}$ events in the

CLEO-c detector. The generator incorporates all the known $D$ decay properties, and includes initial state radiation (ISR) and final state radiation (FSR) effects, modeled with the program PHOTOS [12]. The particle identification efficiencies are determined from data. We study the $\pi$ and $K$ selection efficiencies using a sample of $D^+ \to K^-\pi^+\pi^+$ decays. The $e^+$ identification efficiency is extracted from a radiative Bhabha sample. A correction for the difference between the $D\bar{D}$ event environment and the simpler radiative Bhabha environment (two charged tracks and one shower) is derived using a dedicated Monte Carlo sample, that merges a real electron track stripped from a radiative Bhabha event with tracks from a simulated hadronic environment. The off-diagonal elements are products of tracking efficiencies and fake probabilities, where $f_{ab}$ is defined as the probability that particle $b$ is identified as particle $a$. The $f_{ab}$ parameters are determined using $e^{\pm}$ samples from radiative Bhabhas, and $K$ and $\pi$ from $D^+ \to K^-\pi^+\pi^+$ and $K^0_S \to \pi^+\pi^-$. The hadron to $e^{\pm}$ fake probabilities are of the order of 0.1% over most of the momentum range and below 1% even in the regions where $dE/dx$ separation is less effective.

The wrong-sign unfolded yields account for the charge symmetric background, mostly produced by $\pi^0$ Dalitz decays and $\gamma$ conversions. MC studies show that the wrong-sign sample is an accurate representation of this background source. The same unfolding procedure is applied to control samples obtained from $\Delta E$ sidebands. The chosen tags $\bar{D}^0 \to K^+\pi^-$ and $D^- \to K^+\pi^-\pi^-$ have very little background: the $\bar{D}^0$ sidebands give a combinatoric background estimate of 0.2% of the signal yield and the $D^-$ sidebands give a combinatoric background estimate is 1.8% of the signal yield. Table I shows the results of the intermediate steps involved in the determination of the net $e^+$ yields. Efficiency corrections increase unfolded $e^+$ yields with respect to raw $e^+$ yields, while fake subtraction reduces them. The former effect is dominant for the right-sign positron sample, while it is comparable in size to the background subtraction in the wrong-sign sample. The corrected net $e^+$ sample includes acceptance correction accounting for the solid angle cut ($\cos\theta \leq 0.8$) and doubly-Cabibbo suppressed (DCSD) corrections in $D^0$ decays. As we are using the charge of the tagging $D^-$, rather than its $K$ daughter charge, this correction is not needed in the charged mode.

TABLE I: Positron unfolding procedure and corrections. The errors reported in the intermediate yields reflect only statistical uncertainties.

| | $D^+$ | $D^0$ |
|---|---|---|
| Signal $e^+$ | | |
| Right-sign (raw) | $8275 \pm 91$ | $2239 \pm 47$ |
| Wrong-sign (raw) | $228 \pm 15$ | $233 \pm 15$ |
| Right-sign (unfolded) | $9186 \pm 103$ | $2453 \pm 54$ |
| Wrong-sign (unfolded) | $231 \pm 19$ | $203 \pm 19$ |
| Sideband $e^+$(RS) | $168\pm 13$ | $15 \pm 4$ |
| Sideband $e^+$(WS) | $11 \pm 5$ | $11 \pm 4$ |
| Net $e^+$ | $8798 \pm 105$ | $2246 \pm 57$ |
| Corrected Net $e^+$ | $10998 \pm 132$ | $2827 \pm 72$ |

In order to extract the partial branching fractions for $p_e \geq 0.2$ GeV, we evaluate the ratio between the net positron yields corrected for geometric acceptance and the net number of tags. While the charge of $D^- \to K^+\pi^-\pi^-$ reliably tags the flavor of the charged $D$, in the

$\bar{D}^0$ case the $K$ charge occasionally produces an incorrect flavor assignment due to the DCSD $\bar{D}^0 \to K^-\pi^+$. This effect is estimated on the basis of the known value of the parameter $r_{\rm DCSD} \equiv N(D^0 \to K^+\pi^-)/N(D^0 \to K^-\pi^+) = 0.00362 \pm 0.00029$ [1].

We have considered several sources of systematic uncertainty. There are multiplicative errors that affect the overall scale of the spectrum, including tracking efficiency or electron identification efficiency, accounting for MC modeling uncertainties. The uncertainty on tracking and $K$ and $\pi$ identification are taken from the studies discussed in Ref. [10]. The systematic error on the electron identification efficiency (1%) is assessed comparing radiative Bhabha samples, embedded samples, and MC samples. These contributions are common to $D^+$ and $D^0$. In addition, we have accounted for FSR uncertainty by varying its amount, with a total systematic error of 0.5%. The last multiplicative error is the uncertainty on the number of tags, estimated by comparing the number of background tags in our signal window from the $\Delta E$ sidebands and from $\Delta M$ sidebands. In addition, there are terms that are affected by limited statistics, such as fake probabilities, or particle identification efficiencies. The systematic uncertainty associated with these terms has been evaluated with a toy MC, including $10^6$ iterations of the unfolding procedure, varying the matrix elements within error. The corresponding systematic error estimates are 0.56% (statistical errors on fake probability and particle identification efficiency) and 0.3% (statistical error on tracking efficiency). The uncertainty on the combinatoric background, accounted for with the sideband positron sample, is negligible compared with these components ($\leq 0.1\%$), because of the excellent purity of the "golden mode" samples. Thus the total systematic error on the branching fraction for $p_e \geq 0.2$ GeV is 1.7% ($D^0$) and 1.8 % ($D^+$).

The partial branching fractions for $p_e \geq 0.2$ GeV are evaluated as the ratio between the corrected net $e$ yields and the net number of tags:

$$\mathcal{B}(D^+ \to Xe^+\nu_e) = (14.92 \pm 0.19_{\rm stat} \pm 0.27_{\rm sys})\%;$$

$$\mathcal{B}(D^0 \to Xe^+\nu_e) = (5.97 \pm 0.15_{\rm stat} \pm 0.10_{\rm sys})\%.$$

The yield in the unmeasured region ($p_e < 0.2$ GeV) is estimated by fitting the measured spectra with a shape derived from Monte Carlo. The semileptonic decays are generated with the ISGW form factor model [13], with parameters tuned to experimental constraints such as measured branching fractions, and ratios $\Gamma_L/\Gamma_T$ between transverse and longitudinal components of the $D \to K^* e\nu$ semileptonic widths. FSR effects are included in the simulation. We obtain $f(p_e) \equiv \Delta\Gamma(p_e < 0.2\ {\rm GeV})/\Gamma_t = (7.5 \pm 0.5)\%$ for $D^+ \to Xe^+\nu$ and $\Delta\Gamma(p_e < 0.2\ {\rm GeV})/\Gamma_t = (7.7 \pm 0.9)\%$ for $D^0 \to Xe^+\nu$. The errors reflect fit uncertainty and introduce an additional 1% systematic error on the total semileptonic branching fractions. The total branching fractions, after the correction of the unmeasured part of spectrum below 0.2 GeV:

$$\mathcal{B}(D^+ \to Xe^+\nu_e) = (16.13 \pm 0.20_{\rm stat} \pm 0.33_{\rm sys})\%;$$

$$\mathcal{B}(D^0 \to Xe^+\nu_e) = (6.46 \pm 0.17_{\rm stat} \pm 0.13_{\rm sys})\%.$$

Using the well-measured lifetimes of the $D^+$ and $D^0$ mesons, $\tau_{D^+} = 1.040 \pm 0.007$ ps, and $\tau_{D^0} = 0.4103 \pm 0.0015$ ps [1], we normalize the measured partial branching fractions to obtain differential semileptonic widths. Fig. 1 shows such spectra in the laboratory frame, where the $D^+$ momentum is 0.243 GeV, and the $D^0$ momentum is 0.277 GeV. No final state radiation correction is applied to the data points. Table II shows the corresponding partial yields. The errors shown are evaluated adding in quadrature the statistical errors and the additive systematic errors. In addition, an overall systematic error of about 1.5%

needs to be considered in evaluating derived quantities such as the total semileptonic width. The total inclusive semileptonic widths are $\Gamma(D^+ \to Xe^+\nu_e) = 0.1551 \pm 0.0020 \pm 0.0031$ ps$^{-1}$, and $\Gamma(D^0 \to Xe^+\nu_e) = 0.1574 \pm 0.0041 \pm 0.0032$ ps$^{-1}$. The corresponding ratio of the semileptonic widths of charged and neutral $D$ mesons is $\Gamma^{sl}_{D^+}/\Gamma^{sl}_{D^0} = 0.985 \pm 0.028 \pm 0.015$, consistent with isospin invariance.

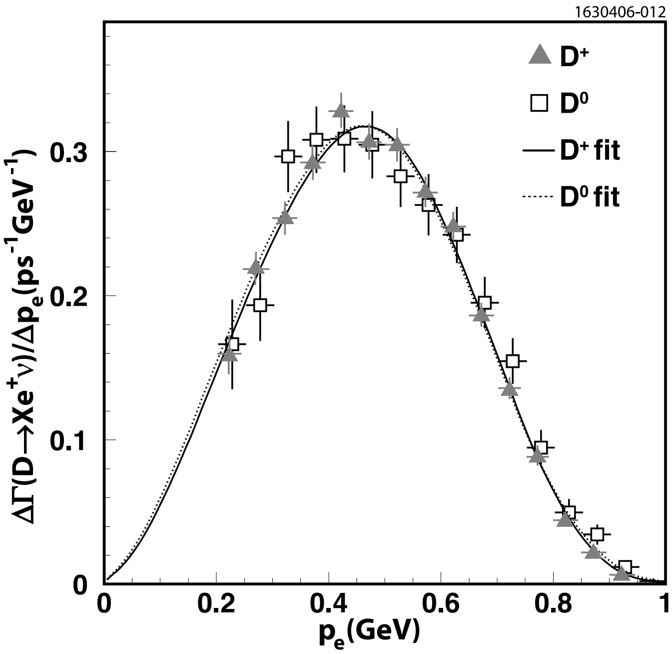


FIG. 1: Positron differential semileptonic widths $d\Gamma^{sl}/dp_e$ for the decays $D^+ \to Xe^+\nu_e$ (filled triangles) and $D^0 \to Xe^+\nu_e$ (open squares) in the laboratory frame. The errors shown include statistical errors and additive systematic errors. The symbols for $D^+$ and $D^0$ spectra are slightly shifted horizontally to avoid overlapping. The curves are derived from the fits used to extrapolate the measured spectra below the $p^{\min}$ cut.

Finally, we can compare these widths with the sum of the semileptonic decay widths for the pseudoscalar and vector hadronic final states recently published by CLEO [14]. They obtain $\mathcal{B}(D^+ \to Xe^+\nu_e)_{\text{excl}} = (15.1 \pm 0.5 \pm 0.5)\%$ and $\mathcal{B}(D^0 \to Xe^+\nu_e)_{\text{excl}} = (6.1 \pm 0.2 \pm 0.2)\%$: the measured exclusive modes are consistent with saturating the inclusive widths, although there is some room left for higher multiplicity modes. The composition of the inclusive spectra is dominated by the low lying resonances in the $c \to s$ and $c \to d$, in striking contrast with $B$ semileptonic decays, where a sizeable component of the inclusive branching fraction is still unaccounted for [1].

In conclusion, we report improved measurements of the absolute branching fractions for the inclusive semileptonic decays $D^+ \to Xe^+\nu_e$ and $D^0 \to Xe^+\nu_e$: $\mathcal{B}(D^+ \to Xe^+\nu_e) = (16.13 \pm 0.20 \pm 0.33)\%$ and $\mathcal{B}(D^0 \to Xe^+\nu_e) = (6.46 \pm 0.17 \pm 0.13)\%$. Using the measured $D$ meson lifetimes, the ratio $\Gamma^{sl}_{D^+}/\Gamma^{sl}_{D^0} = 0.985 \pm 0.028 \pm 0.015$ is extracted, consistent with isospin invariance. The shapes of the spectra are consistent with one another within error.

TABLE II: $D^+$ and $D^0$ positron differential semileptonic widths $d\Gamma/dp_e(\mathrm{ps}^{-1}\mathrm{GeV}^{-1})$ in the laboratory frame. The errors shown include statistical errors and additive systematic errors .

| $p_e$ (GeV) | $d\Gamma/dp_e(D^+)$ | $d\Gamma/dp_e(D^0)$ |
|---|---|---|
| 0.20 - 0.25 | 0.1598 ± 0.0142 | 0.1664 ± 0.0311 |
| 0.25 - 0.30 | 0.2185 ± 0.0121 | 0.1935 ± 0.0248 |
| 0.30 - 0.35 | 0.2538 ± 0.0116 | 0.2966 ± 0.0247 |
| 0.35 - 0.40 | 0.2925 ± 0.0121 | 0.3081 ± 0.0231 |
| 0.40 - 0.45 | 0.3281 ± 0.0127 | 0.3088 ± 0.0233 |
| 0.45 - 0.50 | 0.3064 ± 0.0130 | 0.3047 ± 0.0233 |
| 0.50 - 0.55 | 0.3047 ± 0.0115 | 0.2828 ± 0.0214 |
| 0.55 - 0.60 | 0.2716 ± 0.0111 | 0.2631 ± 0.0212 |
| 0.60 - 0.65 | 0.2479 ± 0.0104 | 0.2422 ± 0.0196 |
| 0.65 - 0.70 | 0.1864 ± 0.0088 | 0.1951 ± 0.0179 |
| 0.70 - 0.75 | 0.1359 ± 0.0076 | 0.1547 ± 0.0158 |
| 0.75 - 0.80 | 0.0892 ± 0.0060 | 0.0948 ± 0.0121 |
| 0.80 - 0.85 | 0.0444 ± 0.0042 | 0.0498 ± 0.0091 |
| 0.85 - 0.90 | 0.0221 ± 0.0028 | 0.0344 ± 0.0070 |
| 0.90 - 0.95 | 0.0065 ± 0.0015 | 0.0120 ± 0.0044 |
| 0.95 - 1.00 | 0.0007 ± 0.0005 | 0.0020 ± 0.0020 |

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