Measurement of the $D^*(2010)$ Branching Fractions

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We report a measurement of the D^{*+} and D^{*0} decay branching fractions based on 780 pb^{-1} of data collected with the CLEO II detector. For radiative D^{*+} decay, we obtain an upper limit, $\mathcal{B}(D^{*+} \to D^+\gamma) < 4.2\%$ (90% confidence level), which is substantially below previous results, and eliminates the need for an anomalously large charm quark magnetic moment.

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Branching fractions for D^{*+} and D^{*0} decays have been measured in a number of experiments [1,2]. The Particle Data Group (PDG) [3] average value for the branching fraction, $\mathcal{B}(D^{*+}\to D^+\gamma)=(18\pm4)\%$, is dominated by a single measurement [2] and is surprisingly large. This value cannot be accommodated by theoretical models [4,5] without invoking a large anomalous charm quark magnetic moment. In this paper we report new measurements of the D^* decay branching fractions using data collected with the CLEO II detector operating at the Cornell Electron Storage Ring (CESR). This analysis is based on a total integrated luminosity of 780 pb^{-1} from the center-of-mass energy region at and around the $\Upsilon(4S)$ resonance, and takes advantage of the excellent photon detection capability of the CLEO II detector to reconstruct the low-energy photons and π^0's from the D^* decays. The branching fractions measured in this analysis, using a data sample an order of magnitude larger than for any previous measurement, are significantly different from the PDG average values. The small value for $\mathcal{B}(D^{*+}\to D^+\gamma)$ that we observe is consistent with theoretical expectation. The hadronic D^* branching fractions are substantially larger than the previous measurements. This has a noticeable impact, particularly on the measurements of the branching fractions for B meson decays.

Three decay modes [6], $D^0\pi^+$, $D^+\pi^0$, and $D^+\gamma$, are possible for the D^{*+}, while only the $D^0\pi^0$ and $D^0\gamma$ modes are possible for the D^{*0} because the $D^+\pi^-$ mode is not kinematically allowed. The requirement that the decay branching fractions sum to 1 leads to the equations $\mathcal{B}(D^{*0}\to D^0\pi^0)=1/(1+R_\gamma^0)$ and $\mathcal{B}(D^{*+}\to D^+\pi^0)=1/(1+R_\gamma^+ +R_\pi^+)$, where $R_\gamma^0=\mathcal{B}(D^{*0}\to D^0\gamma)/\mathcal{B}(D^{*0}\to D^0\pi^0)$, $R_\gamma^+=\mathcal{B}(D^{*+}\to D^+\gamma)/\mathcal{B}(D^{*+}\to D^+\pi^0)$, and $R_\pi^+=\mathcal{B}(D^{*+}\to D^0\pi^+)/\mathcal{B}(D^{*+}\to D^+\pi^0)$. Use of these ratios suppresses systematic errors. For R_γ^0 and R_γ^+, we measure the ratio of the number of observed events in the respective $D\gamma$ and $D\pi^0$ modes and correct for the relative efficiencies for γ and π^0 detection. The corresponding measurement of R_π^+, however, has large systematic errors due to the uncertainties in the $D^0\to K^-\pi^+$ and $D^+\to K^-\pi^+\pi^+$ branching fractions [3]. This uncertainty can be eliminated by using the fact that $D^*\to D\pi$ branching fractions are related by isospin conservation and the p^3 dependence of p-wave widths:

$$R_\pi^+=2(p_{+0}/p_{++})^3=2.21\pm0.07\,, \tag{1}$$

where p_{+0} and p_{++} are, respectively, the momenta of the D^0 and D^+ mesons in the D^{*+} rest frame. The quoted error arises mostly from uncertainties in the D^*-D mass differences [7] and to a lesser extent from the absolute error in the D masses [3]. The theoretical uncertainties in this ratio from isospin breaking, form factors, and radiative corrections are thought to be of order 1% [5] and that is included in the systematic error on R_π^+.

The CLEO II detector is designed to detect both charged particles and photons with high resolution and efficiency: A detailed description can be found elsewhere [8]. We select hadronic events for this analysis [9]. Photon candidates are used only in the best barrel region of the detector, $|\cos\theta|<0.71$, where θ is the angle with respect to the beam direction. Each neutral energy cluster is required to have at least 30 MeV of energy and not match a projected charged track. Charged tracks used as candidates for tracks from D decays are required to have measured ionization losses (dE/dx) within 2.5 standard deviations of those expected for the hypothesis under consideration.

Neutral pion candidates are selected from two-photon combinations with invariant mass within 3.0 standard deviations ($\sigma_{\pi^0}=5$ MeV) of the measured π^0 mass. To reduce random combinations we require $|\cos\theta_\pi|<0.8$, where θ_π is the angle between the photon direction in the π^0 rest frame and the π^0 direction measured in the laboratory frame. Candidate two-photon combinations are kinematically fitted to the known π^0 mass in order to improve the π^0 energy and angle measurement. The $D^0\to K^-\pi^+$ decay mode is used in reconstructing D^0 mesons while the $D^+\to K^-\pi^+\pi^+$ mode is used for D^+ mesons. In the $D\gamma$ mode there is a large background due to combinations with the many low-energy photons moving in the direction opposite to the D mesons. To reduce this background we require $\cos\theta_\gamma>0$, where θ_γ is the angle of the γ in the D^* rest frame with respect to the D^* direction in the laboratory frame.

We first consider D^{*0} decays. Each D^0 candidate is combined with a π^0 or a γ candidate in the event to form D^{*0} candidates. Since the D^* momentum spectrum peaks at high momentum and the combinatorial background peaks at low momentum, we require $x_{D^*}>0.5$ where $x_{D^*}=p_{D^*}/p_{\max}$. To select D^* candidates, we choose D candidates that have invariant masses within 2.5 standard deviations of the D mass. We then calculate $\delta\equiv M^*-M-Q$, where M^* is the mass of the D^* candidate, M is the mass of the corresponding D candidate, and Q is the value of the D^*-D mass difference [3].

In Fig. 1(a) we show the mass difference plot for the $D^{*0}\to D^0\gamma$ mode. The enhancement at $\delta<-40$ MeV in the figure is due to a large background from $D^{*0}\to D^0\pi^0$ decays. Monte Carlo calculations indicate that this background does not contribute in the signal region and the region is excluded from our fits [10]. We also calculate δ using "fake" D candidates from the K-π mass sideband region together with photon or π^0 candidates, in order to estimate the combinatorial background under the mass difference signals. The histogram in Fig. 1(a) indicates the contribution to the background from D^{*0}'s formed using fake D^0's. We subtract the δ distribution for fake D candidates from our mass difference spectrum before fitting. The data are fitted by a bifurcated Gaussian signal function plus a polynomial background. The asymmetric line shape accounts for photon energy loss due to interactions in the detector upstream of the calorimeter. The mass difference plots from the signal

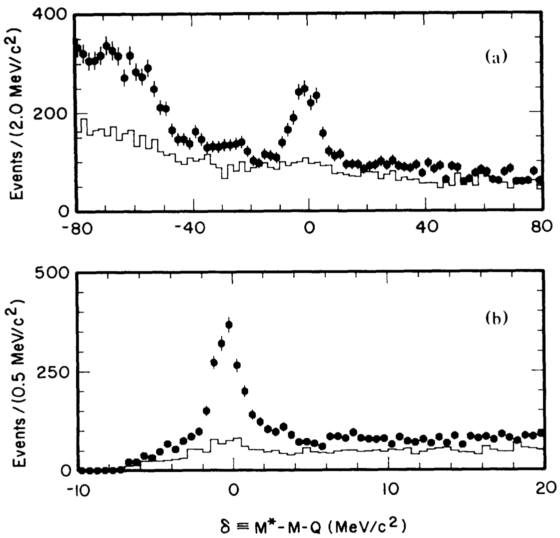

FIG. 1. The distribution of mass difference $\delta \equiv M^* - M - Q$ for (a) $D^{*0} \to D^0\gamma$ candidates and (b) $D^{*0} \to D^0\pi^0$ candidates, where M^* is the mass of the D^* candidate, M is the mass of the D candidate, and Q is the value of the D^*-D mass difference. The points indicate the δ distribution for D^{*0} candidates formed from D^0 candidates in the D mass signal region. The histogram shows the δ distribution for D^{*0} candidates formed from fake D^0 candidates in the D mass sideband region.

and D^0 sideband regions for the $D^{*0} \to D^0\pi^0$ mode are shown in Fig. 1(b). The data are fitted by a Gaussian signal function plus a background function [11] which simulates the threshold behavior expected in the plot. We find the yields $n(D^0\gamma) = 621 \pm 52$ and $n(D^0\pi^0) = 1097 \pm 59$ resulting from the fits to the sideband subtracted δ distributions.

The branching fraction ratio R_γ^0 is $R_\gamma^0 = n(D^0\gamma) \times \epsilon_{\pi^0}/n(D^0\pi^0)\epsilon_\gamma$. The efficiency ratio $\epsilon_{\pi^0}/\epsilon_\gamma = 1.01 \pm 0.06 \pm 0.05$ [12] is calculated from Monte Carlo simulation. The systematic error on the efficiency ratio is determined from a study of the well-measured [3] ratio of branching fractions $\mathcal{B}(\eta \to \pi^0\pi^0\pi^0)/\mathcal{B}(\eta \to \gamma\gamma)$. We obtain $R_\gamma^0 = 0.572 \pm 0.057 \pm 0.081$. The systematic error for R_γ^0 is evaluated by varying the fitting method [13], which contributes 7%, by varying cuts on photon and π^0 candidates, which contributes 9%, by varying the minimum momentum cut for our candidate D^*'s from $x_{D^*} > 0.5$ to $x_{D^*} > 0.7$, which contributes 2%, and including the error on the efficiency ratio. The resulting D^{*0} branching fractions are given in Table I.

We now consider the D^{*+} decays and the measurement of R_γ^+. We reconstruct D^+ mesons using the decay mode $D^+ \to K^-\pi^+\pi^+$ and each D^+ candidate is combined with a π^0 or a γ candidate in the event to form a D^{*+} candidate. We then calculate the mass difference $\delta \equiv M^* - M - Q$ as was done for the D^{*0} decays. For the $D^+\gamma$ mode we are searching for a small signal with substantial background so we tighten some of our selection

TABLE I. The measured branching fractions of the $D^*(2010)$ mesons. To determine the D^{*0} branching fractions we have used the constraint that the branching fractions sum to unity. To determine the D^{*+} branching fractions we have used the constraint on the ratio of the pion decay modes from isospin conservation in the strong interaction and the constraint that the branching fractions sum to unity.

	Branching fraction	
Decay mode	CLEO II (%)	PDG (%)
$D^{*+} \to D^+\gamma$	$1.1 \pm 1.4 \pm 1.6$	18 ± 4
$D^{*+} \to D^+\pi^0$	$30.8 \pm 0.4 \pm 0.8$	27.2 ± 2.5
$D^{*+} \to D^0\pi^+$	$68.1 \pm 1.0 \pm 1.3$	55 ± 4
$D^{*0} \to D^0\gamma$	$36.4 \pm 2.3 \pm 3.3$	45 ± 6
$D^{*0} \to D^0\pi^0$	$63.6 \pm 2.3 \pm 3.3$	55 ± 6

criteria for both modes that enter into the ratio R_γ^+. For both decay modes, $D^{*+} \to D^+\gamma$ and $D^{*+} \to D^+\pi^0$, we require that the mass of the D^+ candidate be within 1.5 standard deviations of the D^+ mass and we require $x_{D^*} > 0.7$. For the $D^+\pi^0$ decay, we require candidate two-photon combinations to be within 2.5 standard deviations of the π^0 mass, and for the radiative decay mode, we do not accept photon candidates which form a mass consistent with a π^0 when combined with any other photon candidate in the event.

The δ distribution for the $D^{*+} \to D^+\gamma$ decay is shown as the dashed histogram in Fig. 2(a). There is an enhancement in the signal region ($\delta = 0$) but there is also a known background in this decay mode from $D_s^{*+} \to D_s^+\gamma$ decays that cannot be removed by a sideband subtraction. This background arises when a kaon from a $D_s^+ \to \phi\pi^+$ or $D_s^+ \to \bar{K}^*(892)K^+$ decay is misinterpreted as a pion. (There is also a small contribution from nonresonant $D_s^+ \to K^+K^-\pi^+$ decays.) The resulting $m_{K\pi\pi}$ distribution is broad, but a significant portion appears in the D^+ signal region. In addition, the photon from the D_s^{*+} decay has the same energy as the photon from D^{*+} decay, so this background is not removed by the fit to the δ distribution. By reinterpreting our $D^{*+} \to D^+\gamma$ candidates as $D_s^{*+} \to D_s^+\gamma$ with $D_s^+ \to K^-K^+\pi^+$, we observe signals in both the $D_s^+ \to \phi\pi^+$ and $D_s^+ \to \bar{K}^*(892)K^+$ modes.

We reduce this background by vetoing D^+ candidates that are consistent with being a D_s^+ when the particle assignment for a π is changed to a K. Vetoed events have masses within 3 standard deviations of the D_s mass and have either (a) a $K^-\pi^+$ combination consistent with a K^* or (b) a K^+K^- combination consistent with a ϕ. This veto rejects approximately 73% of D_s^{*+} decays (calculated using the Monte Carlo simulation), while keeping 84% of true D^{*+} decays (measured using identified $D^{*+} \to D^+\pi^0$ decays in data). The δ distribution for the $D^{*+} \to D^+\gamma$ mode, after the D_s veto for the D^+ signal region (solid points) and for the D^+ sideband region (solid histogram), is shown in Fig. 2(a).

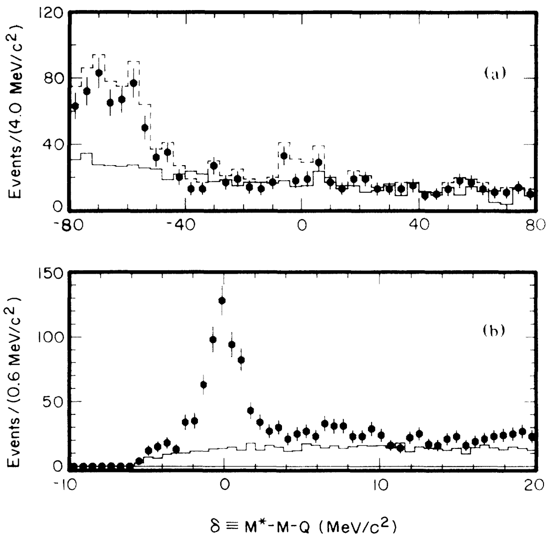

FIG. 2. The distribution of mass difference $\delta \equiv M^* - M - Q$ for (a) $D^{*+} \to D^+\gamma$ candidates and (b) $D^{*+} \to D^+\pi^0$ candidates, where M^* is the mass of the D^* candidate, M is the mass of the D candidate, and Q is the value of the D^*-D mass difference. The points indicate the δ distribution for D^{*+} candidates formed from D^+ candidates in the D mass signal region. The histogram shows the δ distribution for D^{*+} candidates formed from D^+ candidates in the D mass sideband region. The dashed histogram indicates the contribution to the $D^+\gamma$ signal before the $D_s^{*+} \to D_s^+\gamma$ events are vetoed.

After subtracting sidebands, we fitted the δ distribution both before and after the D_s veto by a bifurcated Gaussian signal and a polynomial background. Before the D_s veto, the fit to the δ distribution gives $N_+ + N_s = 48.2 \pm 14.2 \pm 1.9$ events, where $N_+ = n(D^+\gamma)$ is the number of $D^+\gamma$ decays and N_s is the number of $D_s\gamma$ decays in the signal region. After the D_s veto, the fit to the δ distribution yields $(0.843 \pm 0.028)N_+ + (0.267 \pm 0.056)N_s = 19.8 \pm 12.3 \pm 0.6$ events, where the factors in parentheses are the efficiencies of the $D^+\gamma$ and the $D_s\gamma$ events to pass the veto. From these two equations we can extract $n(D^+\gamma) = 12 \pm 16 \pm 17$ events.

Figure 2(b) illustrates the data for the $D^{*+} \to D^+\pi^0$ mode where the same tight D^+ mass and x_{D^*} cuts used in the analysis of the $D^{*+} \to D^+\gamma$ mode are applied. For the signal, we use a Gaussian, and for the background, we use a function which simulates the threshold behavior expected in the δ plot [11]. We find $n(D^+\pi^0) = 410 \pm 29$ events resulting from the fit. The branching fraction ratio is $R_\gamma^+ = 0.035 \pm 0.047 \pm 0.052$, where $\epsilon_{\pi^0}/\epsilon_\gamma = 1.20 \pm 0.09 \pm 0.06$ [12]. The systematic error on R_γ^+ is dominated by variations of the yield from fitting the δ distribution before and after the sideband subtraction.

To determine the D^{*+} branching fractions we still need the ratio R_π^+ of the branching fractions for the $D^{*+} \to D^0\pi^+$ and $D^{*+} \to D^+\pi^0$ modes. We use the theoretical estimate of R_π^+ given in Eq. (1) [14]. The resulting D^{*+} branching fractions are given in Table I. The systematic errors include the contribution from the uncertainty in the R_π^+ due to the errors in the measurements of the relevant masses and mass differences. Combining statistical and systematic errors in quadrature, we obtain an upper limit $\mathcal{B}(D^{*+} \to D^+\gamma) < 4.2\%$ at 90% confidence level [15]. If we had ignored the contributions from $D_s^{*+} \to D_s^+\gamma$ decays, we would have concluded that $\mathcal{B}(D^{*+} \to D^+\gamma) = (4.3 \pm 1.2 \pm 1.4)\%$.

The ratio of the radiative partial widths for D^{*+} and D^{*0} decay can be obtained from the experimental data using

$$\Gamma_\gamma^+/\Gamma_\gamma^0 \equiv \Gamma(D^{*+} \to D^+\gamma)/\Gamma(D^{*0} \to D^0\gamma) = R_\gamma^+ \Gamma(D^+\pi^0)/R_\gamma^0 \Gamma(D^0\pi^0),$$

where $\Gamma(D^+\pi^0)$ and $\Gamma(D^0\pi^0)$ are the partial widths for $D^{*+} \to D^+\pi^0$ and $D^{*0} \to D^0\pi^0$ decays, respectively. These widths are related by isospin and the p^3 dependence of p-wave widths $\Gamma(D^+\pi^0)/\Gamma(D^0\pi^0) = (p_{++}/p_{00})^3 = 0.702 \pm 0.022$, where p_{++} and p_{00} are the momenta of the D^+ and D^0 in the D^{*+} and D^{*0} rest frames, respectively. Using our measured values of R_γ^0 and R_γ^+, we find the ratio of the radiative widths is $0.04 \pm 0.06 \pm 0.06$ or < 0.17 at the 90% confidence level.

In conclusion, we have measured the $D^*(2010)$ branching fractions and find results significantly different from the world average values for these quantities. In particular, we find $\mathcal{B}(D^{*+} \to D^+\gamma) < 4.2\%$ at 90% confidence level. This is in accordance with theoretical predictions and does not support the need for an anomalously large charm quark magnetic moment.

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[6] Mention of a specific particle or decay always implies the charge conjugate particle or decay as well.

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[9] To be classified as hadronic, an event must have at least three charged tracks originating near the interaction point, and the total visible energy of the event must be greater than $0.15E_{\text{c.m.}}$, where $E_{\text{c.m.}}$ is the center-of-mass energy.

[10] As an independent check of our measurement of the D^{*0} branching ratios, we can fit the entire plot to get the ratio of yields for $D^{*0} \to D^0\gamma$ and $D^{*0} \to D^0\pi^0$. This gives an answer consistent with the result we get when we reconstruct the π^0.

[11] The background function near threshold is $c_1[(\delta - c_0)^{1/2} + c_2(\delta - c_0)^{3/2}]$, where the c_i are parameters determined by the fit.

[12] Both the π^0 and the γ finding efficiency for this analysis are approximately 33%. The requirement that $\cos\theta_\gamma > 0$ reduces the photon finding efficiency for the radiative decay mode and makes it comparable to the π^0 efficiency.

[13] In varying the fitting method, we include fits to the δ distribution before sideband subtraction and we also do a two-dimensional fit in the δ-D^0 plane.

[14] As a check, we also determine R_π^+ directly by measuring the ratio of the yield of $D^{*+} \to D^0\pi^+$ to the yield of $D^{*+} \to D^+\pi^0$ following procedures analogous to the other modes. We find $R_\pi^+ = 2.17 \pm 0.26 \pm 0.43 \pm 0.32$ where the third error is the error due to the uncertainties in the D meson branching fractions.

[15] We have used the procedure for calculating upper limits as described in Ref. [3], p. III.39.