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Measurement of the $D^+ \to \bar{K}^{*0} l^+ \nu_l$ Branching Fraction

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Abstract

Using 13.53 fb^{-1} of CLEO data, we have measured the ratios of the branching fractions $R_e^+ = \frac{\mathcal{B}(D^+ \to \bar{K}^{*0} e^+ \nu_e)}{\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)}$, $R_\mu^+ = \frac{\mathcal{B}(D^+ \to \bar{K}^{*0} \mu^+ \nu_\mu)}{\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)}$ and the combined branching fraction ratio $R_l^+ = \frac{\mathcal{B}(D^+ \to \bar{K}^{*0} l^+ \nu_l)}{\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)}$. We find $R_e^+ = 0.74 \pm 0.04 \pm 0.05$, $R_\mu^+ = 0.72 \pm 0.10 \pm 0.06$ and $R_l^+ = 0.74 \pm 0.04 \pm 0.05$, where the first and second errors are statistical and systematic, respectively. The known branching fraction $\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)$ leads to: $\mathcal{B}(D^+ \to \bar{K}^{*0} e^+ \nu_e) = (6.7 \pm 0.4 \pm 0.5 \pm 0.4)\%$, $\mathcal{B}(D^+ \to \bar{K}^{*0} \mu^+ \nu_\mu) = (6.5 \pm 0.9 \pm 0.5 \pm 0.4)\%$ and $\mathcal{B}(D^+ \to \bar{K}^{*0} l^+ \nu_l) = (6.7 \pm 0.4 \pm 0.5 \pm 0.4)\%$, where the third error is due to the uncertainty in $\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)$.

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The transition amplitude of the semileptonic decay $D^+ \to \bar{K}^{*0} l^+ \nu_l$ is proportional to the product of the leptonic and hadronic currents. The hadronic current is represented by three analytic functions called form factors, $A_1(q^2)$, $A_2(q^2)$, and $V(q^2)$ [1], where q^2 is the invariant mass squared of the virtual W boson. The form factors cannot be easily computed in quantum chromodynamics (QCD) since they are affected by significant non-perturbative contributions. Further, unlike the case of $B \to D^* l\nu$, Heavy Quark Effective Theory (HQET) [2–4] cannot be applied in a straightforward way since the transition is to the light strange quark. Precise experimental measurements are needed to guide theoretical progress in this area. Measurements of these form factors are also valuable since, using HQET, they can be related to the form factors for the important decay $b \to ul\nu$, a heavy to light transition like the $c \to sl\nu$ process we study here. This approach could reduce theoretical uncertainties on the value of $|V_{ub}|$ measured in $b \to ul\nu$.

In this work, the ratio of the branching fraction of $D^+ \to \bar{K}^{*0} l^+ \nu_l$ to that of $D^+ \to K^-\pi^+\pi^+$ (R_l^+) was measured, where l stands for either an electron or a muon. In other experiments [5], the form factor ratios $r_2 = \frac{A_2}{A_1}$ and $r_V = \frac{V}{A_1}$ of $D^+ \to \bar{K}^{*0} l^+ \nu_l$ were obtained from angular correlations between the daughter particles. Combining these, we can calculate the form factors A_1, A_2 and V.

The data used in this study was collected with the two configurations of the CLEO detector [6] at the Cornell Electron Storage Ring (CESR). It consists of 9.13 fb^{-1} of integrated luminosity on the $\Upsilon(4S)$ resonance and 4.40 fb^{-1} below $B\bar{B}$ threshold. The investigated decay chain for this analysis was $D^{*+} \to D^+\pi^0$, $D^+ \to \bar{K}^{*0} l^+ \nu$, and $\bar{K}^{*0} \to K^-\pi^+$. The use of D^+ produced in $D^{*+} \to D^+\pi^0$ decays reduced the background. This analysis assumes that the thrust axis [7] of the event approximates the direction of the D meson, as will be explained below. This approach does not work well for isotropic events. Thus, events whose ratio of the second and zeroth Fox-Wolfram moments [8] was less than or equal to 0.2 were rejected. Specific ionization in the drift chamber and shower information in the electromagnetic calorimeter were used to select good electron candidates. Muon candidates were required to penetrate at least 5 interaction lengths in our muon detector. To select good π^0's, all $\gamma\gamma$ pairs for which $|M_{\gamma\gamma} - M_{\pi^0}| < 2.5\sigma$ were accepted, where σ is the standard deviation of the π^0 mass measurement, obtained as a function of π^0 momentum using clean π^0 data samples. Other kinematic criteria chosen to optimize our sensitivity are given in Table I.

To reconstruct the momentum of the ν, two methods were used to obtain up to three values of $\vec{p}_\nu$. In the first method, one or two values for the ν momentum were obtained assuming that the thrust direction of the event represents the D direction. Given $\vec{p}_{K\pi l}$, the constraint that $m_{K\pi l\nu} = m_{D^+}$ provided an ellipsoid of allowed D momenta. We then took the two intersections between the ellipsoid and the direction of the D. When there was no intersection, the point on the ellipsoid that lay closest to the D direction was used. The values for the ν momentum were then the difference between these D momenta and $\vec{p}_{K\pi l}$. The second method used the missing momentum of each event as an estimate of the ν momentum. If the missing momentum gave a value of $m_{K\pi l\nu}$ much greater than the mass of the D^+ (we used $m_{D^{*+}}$ for the limit for convenience), then the ν momentum estimate from the second method was discarded. Among these three ν momentum estimates, the one that gave the value of $\delta m = m_{K\pi l\nu\pi^0} - m_{K\pi l\nu}$ closest to the known value of $m_{D^{*+}} - m_{D^+}$ [9] was chosen. According to our simulation, this selection method gave the ν momentum closest to

TABLE I. Requirements on the kinematic variables. Here, θ is the polar angle between the e^+e^- axis and the momentum of the particle candidate.

Variables	Requirements
$\lvert\vec{p}_{\pi^+}\rvert$	> 0.5 GeV/c
$\lvert\vec{p}_{K^-}\rvert$	> 0.5 GeV/c
$\lvert\vec{p}_{\pi^0}\rvert$	> 0.18 GeV/c
$\lvert\vec{p}_e\rvert$	> 0.7 GeV/c for $\lvert\cos\theta\rvert \leq 0.81$
$\lvert\vec{p}_\mu\rvert$	> 1.4 GeV/c for $\lvert\cos\theta\rvert \leq 0.61$
$\lvert\vec{p}_\mu\rvert$	> 1.9 GeV/c for $0.61 < \lvert\cos\theta\rvert \leq 0.81$
$\lvert\vec{p}_{K\pi l}\rvert$	> 2.0 GeV/c
$m_{K\pi l}$	$1.2 - 1.8$ GeV/c^2
$\lvert\vec{p}_{K\pi}\rvert$	> 0.7 GeV/c

the generated ν momentum 75% of the time.

The previous CLEO analysis of this decay [10] superseded by this study did not use ν reconstruction. Instead it used the pseudo mass difference, $\delta m_p = m_{K\pi l\pi^0} - m_{K\pi l}$, and the resolution of δm_p was much inferior to δm. The ν reconstruction reduced the statistical uncertainty in the $\mathcal{B}(D^+ \to \bar{K}^{*0}l^+\nu_l)$ measurement by 20% based on studies using signal and generic continuum Monte Carlo (MC) events. However, since our method for choosing among the three solutions for $|\vec{p}_\nu|$ tends to bias the δm distribution of the background toward the signal region, it is important to understand the contribution of the background that peaks in the signal region. The uncertainty coming from this effect was included in the systematic errors.

Two quantities were fitted to obtain the number of signal events: $m_{K\pi}$ and δm. First, the data were divided into 50 bins (25 bins for the smaller muon data) over the δm range from 0.135 GeV/c^2 to 0.235 GeV/c^2. For each δm bin, the $K\pi$ mass distribution was plotted and the number of K^*'s was extracted by a fit. Second, these yields were plotted as a function of δm, and the number of signal events was obtained by another fit. In the $K\pi$ mass fit, the signal shape was described by a p-wave K^* Breit-Wigner distribution. The mass and width of K^* obtained by the fit were consistent with the Particle Data Group (PDG) values [9]. An analytic threshold function

$$(m_{K\pi} - 0.64)^\alpha \times e^{\beta(m_{K\pi}-0.64)+\gamma(m_{K\pi}-0.64)^2} \quad (1)$$

parameterized the shape of the background. The appropriateness of this function was tested using generic continuum MC events after discarding the signal among those events. The parameters α, β and γ in this background function were unconstrained in the data fits. A typical $K\pi$ mass fit in the δm signal region is shown in Fig. 1.

The signal shapes for the δm fits were obtained from signal MC samples, and the background shape was described by a continuous function which was designed to accommodate the excess at $m_{D^{*+}} - m_{D^+}$ due to our neutrino momentum selection method. The shapes of these functions in the δm fits for data were determined using a generic continuum MC sample. The δm fit of the electron data is shown in Fig. 2.

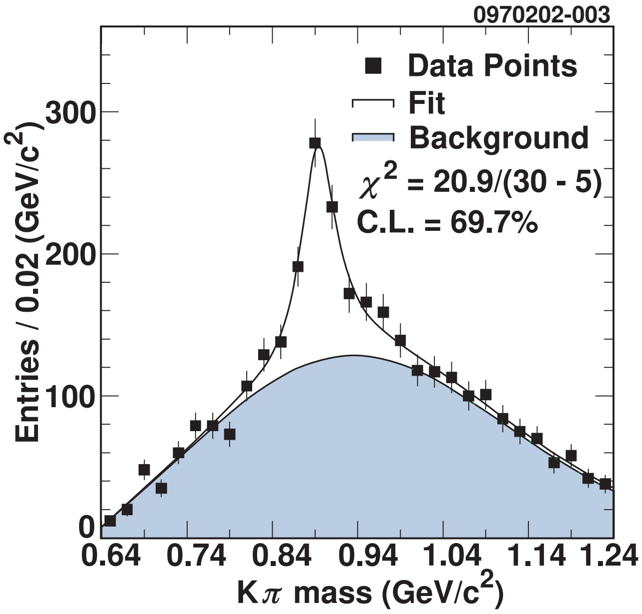

FIG. 1. $K\pi$ mass distribution in the third δm bin of the $D^+ \to \bar{K}^{*0} e^+ \nu_e$ analysis using 8.78 fb^{-1} data.

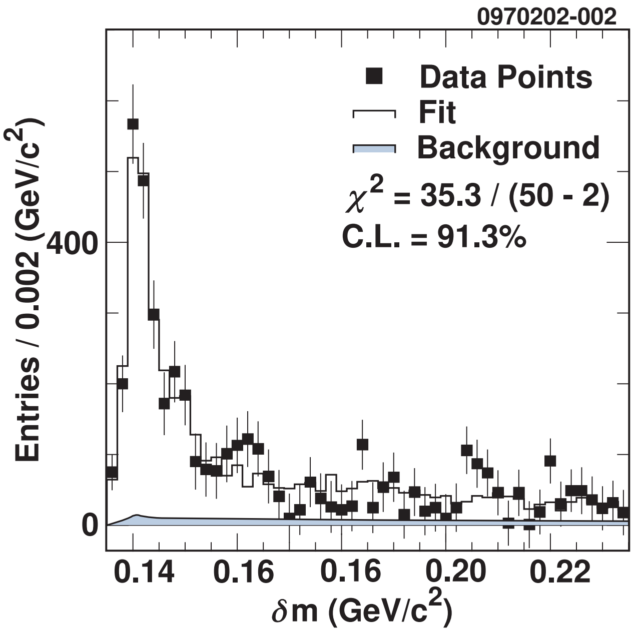

FIG. 2. The δm distribution for $D^+ \to \bar{K}^{*0} e^+ \nu_e$ using 8.78 fb^{-1} data.

TABLE II. The electron, muon and electron-muon combined systematic errors in units of 10^{-2}. The combined systematic errors of the electron and muon modes are denoted as the l.

Source		e	μ	l
fits				
	δm sig. shape	2.2	3.3	1.9
	δm bgr. shape	1.2	1.4	1.0
	data MC diff.(sig.)	0.34	3.8	0.68
	data MC diff.(bgr.)	2.6	2.5	2.6
lepton id		1.1	0.27	0.89
fake leptons		0.064	0.95	0.17
sig MC model dep.		0.74	0.72	0.74
efficiency by fragmnt.		0.53	0.54	0.53
feed down		0.18	0.17	0.18
$D^+ \to K^{*0}\pi^0 l^+\nu_l$		2.6	2.5	2.6
normalization mode				
	sig. shape	1.1	1.1	1.1
	bgr. shape	0.81	0.79	0.81
TOTAL		4.8	6.0	4.7

The decay chain, $D^{*+} \to D^+\pi^0$, $D^+ \to K^-\pi^+\pi^+$, was used for the normalization mode. One advantage of this mode is that many systematic errors in its "measurement" are common with the $D^+ \to \bar{K}^{*0}l^+\nu$ mode and cancel in their ratio. Furthermore, the branching fraction of $D^+ \to K^-\pi^+\pi^+$ is well measured: $(9.0 \pm 0.6)\%$ [9]. Most of the kinematic requirements were the same as those in the semileptonic analysis, but the requirement on $|\vec{p}_{D^*}|$ was tuned to minimize our sensitivity to the uncertainty in the fragmentation of the charm quarks.

For the normalization mode analysis, two successive fits of m_{D^+} and δm were used. The data were divided into 50 δm bins from 0.135 GeV/c^2 to 0.185 GeV/c^2. For each δm bin, a D^+ mass fit was used to extract the number of D^+'s. These yields of D^+'s were plotted as a function of δm. Then, this δm plot was fitted to obtain the number of the normalization mode events.

Table II lists the important contributions to the systematic error. The dominant sources are the δm signal shape estimation due to finite MC statistics, potential flaws in the estimate of the background shape obtained from the simulation of $e^+e^- \to q\bar{q}$ and background arising from $D^+ \to \bar{K}^{*0}\pi^0 l^+\nu_l$.

The systematic error due to a potential difference in the background between the MC and data was estimated using a π^0 mass sideband, $3.5\sigma < |M_{\gamma\gamma} - M_{\pi^0}| < 15.0\sigma$. The π^0 mass sideband data were analyzed as π^0 signal band data and the difference in yields of data and generic continuum MC sample was used in the estimation of the systematic error due to the deficiency of the background MC in reproducing the data.

The upper limit of the branching fraction for $D^+ \to \bar{K}^{*0}\pi^0\mu^+\nu_\mu$ with respect to $D^+ \to K^-\pi^+\mu^+\nu_\mu$ is 0.042 [11] at the 90% confidence level. We used the product of this upper limit and the ratio of "efficiencies" that $K^*\pi^0 l\nu$ and $K^* l\nu$ are detected as signal in our analysis as the systematic error due to this source.

The systematic errors from each source were estimated individually for the electron and muon modes and then combined to obtain the overall lepton mode systematic errors.

The ratio R_l^+ was calculated using

TABLE III. Results of the R_e^+, R_μ^+ and R_l^+ measurements and the branching fractions $\mathcal{B}_e$, $\mathcal{B}_\mu$ and $\mathcal{B}_l$ (see text). The first and second errors in the R and $\mathcal{B}$ measurements are due to statistical and systematic errors, respectively. The third errors in the $\mathcal{B}$ measurements are due to the uncertainty in $\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$.

R_e^+	$0.74 \pm 0.04 \pm 0.05$
R_μ^+	$0.72 \pm 0.10 \pm 0.06$
R_l^+	$0.74 \pm 0.04 \pm 0.05$
$\mathcal{B}_e$	$(6.7 \pm 0.4 \pm 0.5 \pm 0.4)\%$
$\mathcal{B}_\mu$	$(6.5 \pm 0.9 \pm 0.5 \pm 0.4)\%$
$\mathcal{B}_l$	$(6.7 \pm 0.4 \pm 0.5 \pm 0.4)\%$

TABLE IV. Comparison of the measured values of R_e^+ and R_μ^+.

Group	R_e^+	Group	R_μ^+
CLEO(2001)	$0.74 \pm 0.04 \pm 0.05$	CLEO(2001)	$0.72 \pm 0.10 \pm 0.06$
PDG [9]	0.54 ± 0.05	PDG [9]	0.53 ± 0.06
CLEO [10]	$0.67 \pm 0.09 \pm 0.07$	E687 [11]	$0.56 \pm 0.04 \pm 0.06$
OMEG [12]	$0.62 \pm 0.15 \pm 0.09$	E653 [15]	$0.46 \pm 0.07 \pm 0.08$
ARGUS [13]	$0.55 \pm 0.08 \pm 0.10$		
E691 [14]	$0.49 \pm 0.04 \pm 0.05$		

$$R_l^+ = \frac{N_{sl}}{\epsilon_{sl} \cdot \mathcal{B}(\bar{K}^{*0} \to K^-\pi^+)} \cdot \frac{\epsilon_{had}}{N_{had}}, \tag{2}$$

where N_{sl} and ϵ_{sl} are the observed number of events and the efficiency for $D^+ \to \bar{K}^{*0} l^+ \nu_l$, respectively. Similarly, N_{had} and ϵ_{had} are the corresponding quantities for $D^+ \to K^-\pi^+\pi^+$. The measured branching ratios R_e^+, R_μ^+ and R_l^+, including their errors, are summarized in Table III. The values of R_e^+ and R_μ^+ agree well. The PDG value of $\mathcal{B}(D^+ \to K^-\pi^+\pi^+) = (9.0 \pm 0.6)\%$ [9] was used to calculate the branching fractions of $D^+ \to \bar{K}^{*0} e^+ \nu_e$ ($\mathcal{B}_e$), $D^+ \to \bar{K}^{*0} \mu^+ \nu_\mu$ ($\mathcal{B}_\mu$), and $D^+ \to \bar{K}^{*0} l^+ \nu_l$ ($\mathcal{B}_l$).

Table IV compares the results of this work with previous measurements [10–15] and the PDG averages [9]. Note that the E691 measurement of R_e^+ and ours are the two most significant measurements, and they differ by about three standard deviations. We studied whether this difference (or part thereof) may arise from differences between the $D^+ \to \bar{K}^{*0} e^+ \nu_e$ model used here (ISGW2) [16] and the one used in the E691 analysis (WSB) [17]. Since the lepton momentum distribution expected from this decay has a significant effect on its detection efficiency in both experiments, we compared the electron energy and q^2 distributions from the two models, but found no significant differences. We did not identify any other explanations for the discrepancy.

Table V shows the decay rate for $D^+ \to \bar{K}^{*0} e^+ \nu_e$ measured in this work and the theoretical predictions [16,18–22]. Most predictions are consistent with both our result and that of E691. Using our branching ratio measurements and the ratios between the form factors measured by E791 [23], we calculate $A_1(0) = 0.69 \pm 0.07$, $A_2(0) = 0.48 \pm 0.08$, and

TABLE V. Comparison of the decay rate for $D^+ \to \bar{K}^{*0} e^+ \nu_e$ measured in this work with those theoretically predicted and the present PDG value. All values are in units of $10^{10} |V_{cs}|^2$ sec^{-1}.

Group	Decay Rate ($10^{10} \lvert V_{cs} \rvert^2$ s^{-1})
CLEO(2001)	6.67 ± 0.75
PDG [9]	4.79 ± 0.40
UKQCD (2001) [18]	5.8 ± 0.5
APE [19]	6.9 ± 1.8
UKQCD (1994) [20]	$6.0^{+0.8}_{-1.6}$
ELC [21]	6.4 ± 2.8
LMMS [22]	5.0 ± 0.9
ISGW2 [16]	5.7

$V(0) = 1.25 \pm 0.15$, where the errors are the quadratic sums of the statistical and systematic errors in this analysis and in the E791 measurement.

The ratio of the vector and pseudo-scalar decay widths, $r_{vp} = \frac{\Gamma(D \to K^* e^+ \nu_e)}{\Gamma(D \to K e^+ \nu_e)}$, tests quark models. This ratio was predicted to be in the range 0.9 to 1.2 by early quark models [17,24–27] and lattice gauge calculations [28,29]. The E691 result implied that $r_{vp} = 0.48 \pm 0.10$. The newer ISGW2 model [16] accommodated this measurement well, predicting $r_{vp} = 0.54$. Our measurement of R_l^+, on the other hand, implies that $r_{vp} = 0.99 \pm 0.06 \pm 0.07 \pm 0.06$, where the first, second and third errors are due to our statistical and systematic errors and the uncertainty in $\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e)$, respectively, using the PDG value of $\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e) = (6.8 \pm 0.8)\%$ [9]. Our ratio is consistent with older models and disagrees with the ISGW2 prediction by four standard deviations.

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