ICHEP94 Ref. GLS0250 **CLNS 94/1290**
Submitted to Pa 16,2 Pl 9,19 **July 12, 1994**

Measurement of the Ratios of Form Factors in the decay $D_s^+ \to \phi e^+ \nu_e$.

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Abstract

The dynamics of the decay $D_s^+ \to \phi e^+ \nu_e$ are studied using a sample of 474 events recorded by the CLEO II detector. A three dimensional fit to the decay angles and q^2 is performed to extract the ratios of form factors $R_2 = A_2(0)/A_1(0)$ and $R_V = V(0)/A_1(0)$, where $A_1(0)$ and $A_2(0)$ are the two axial vector form factors and $V(0)$ is the vector form factor evaluated at $q^2 = 0$. By assuming the single pole parameterization for the form factors, we obtain: $R_2 = 1.4 \pm 0.5 \pm 0.3$ and $R_V = 0.9 \pm 0.6 \pm 0.3$.

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The semileptonic decay rate of charmed mesons is characterized using the CKM matrix element V_{cs}, the weak leptonic current, and the hadronic current. The hadronic current is parameterized by the form factors. Since V_{cs} is well constrained by unitarity [1], the measurement of form factors in semileptonic charmed meson decays probes the non-perturbative nature of the hadronic current. The ability of theoretical models to predict the form factors in charm meson decay constitutes an important step in establishing the reliability of such models for other heavy quark to light quark transitions. These models are used to extract the CKM matrix element V_{ub}. [2]

In the limit of negligible lepton mass, the semileptonic decay of a pseudoscalar meson to a vector meson may be parameterized in terms of three form factors: two axial vector form factors A_1, A_2 and one vector form factor V; these form factors are functions of the dilepton mass squared, $M^2_{e\nu} = q^2$. Measurements [3–6] of the $D^+ \to \overline{K}^*(892)^0 e^+ \nu_e$ form factors (especially for the value of A_1) disagreed with the quark model predictions[1]. Several theoretical calculations [7–14] predict the ratios of form factors $R_2 = A_2(0)/A_1(0)$ and $R_V = V(0)/A_1(0)$ for the decay $D^+ \to \overline{K}^*(892)^0 e^+ \nu_e$. Assuming $SU(3)$ symmetry, R_2 and R_V for the decays $D_s^+ \to \phi e^+ \nu_e$ and $D^+ \to \overline{K}^*(892)^0 e^+ \nu_e$, evaluated at $q^2 = 0$, should be approximately equal[2]. Two recent measurements [15,16] of R_2 and R_V for $D_s^+ \to \phi \mu^+ \nu_\mu$ were of insufficient precision to constitute a rigorous examination of this hypothesis. In this paper, we present results on the form factor ratios R_2 and R_V from the decay $D_s^+ \to \phi e^+ \nu_e$ using data collected with the CLEO II detector located at the Cornell Electron Storage Ring (CESR).

The data sample for this analysis consists of approximately 4 million $e^+e^- \to c\bar{c}$ events recorded by the CLEO II detector at CESR. The detector is described in detail elsewhere [17]. The integrated luminosity of this sample corresponds to 3.06 fb^{-1} taken at or below the $\Upsilon(4S)$ resonance. Candidates for the decay $D_s^+ \to \phi e^+ \nu_e$, $\phi \to K^+K^-$, are selected by searching for a $K^+K^-e^+$ combination contained in one jet, of continuum-like events (those events possessing a two jet topology). The detailed selection criteria follow those described in the measurement of the ratio of branching ratios $B(D_s^+ \to \phi e^+ \nu_e)/B(D_s^+ \to \phi \pi^+)$ [18] [3]. For this study, a more stringent criterion is applied to the dikaon mass M_{KK}, shown in Figure 1, in order to increase

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[1]Charge conjugation states are implied throughout this paper.

[2]Further, equality of the form factors for the two decays would imply equal partial widths. The latter point constitutes the basic assumption for determining the absolute branching ratio $Ds^+ \to \phi\pi^+$ from the ratio of branching ratios $B(D_s^+ \to \phi e^+ \nu_e)/B(D_s^+ \to \phi \pi^+)$.

[3]The principal cuts we require are $1.1 \leq p_{KK} < 2.9$ GeV/c, $2.4 \leq p_{KKe} < 4.6$ GeV/c, and $p_e \geq 0.9$ GeV/c as in reference [18]. The muonic data sample is not used for the decay angle analysis; the additional minimum momentum cut required for improved muon identification reduced the signal to background ratio to an unacceptable level.

the ratio of signal to background. We require $1.017 \leq M_{KK} < 1.023\,\mathrm{GeV/c^2}$. The final data set is 474 events, of which 166 ± 19 events are consistent with background. The background results from three principal sources: fake ϕ's due to random K^+K^- combinations (80 ± 9 events obtained from a fit to the K^+K^- mass); fake electrons due to hadron misidentification (46 ± 14 events [18]); and random ϕ-electron combinations not from D_s decay (40 ± 10 events [18]).

The decay $D_s^+ \rightarrow \phi e^+ \nu_e$ [10] is described by five kinematic variables: (1) the mass of the K^+K^- system, M_{KK} ; (2) the squared mass of the $e^+\nu_e$ (virtual W) system, q^2 ; (3) the strong decay angle, θ_V, defined as the angle in the ϕ rest frame between the kaon with the same charge as the D_s and the direction of the D_s; (4) the weak decay angle, θ_e, defined as the angle in the $e^+\nu_e$ rest frame between the e^+ and the direction opposite that of the D_s^+ ; and (5) the angle χ between the planes of the $e^+\nu_e$ and the K^+K^- systems in the D_s^+ rest frame. Since the ϕ resonance is narrow, and since the resolution on the axial angle is poor, the variables M_{KK} and χ are not used in the determination of the form factor ratios. In this study, R_2 and R_V are determined by performing a two parameter likelihood fit to the full expression for the decay rate using the three kinematic variables[4] $|\cos\theta_V|$, $\cos\theta_e$ and q^2/q^2_{max}, where the maximum q^2 for a given decay is $q^2_{max} = (M_{D_s} - M_{KK})^2$.

Various methods of obtaining the kinematic variables were explored; those which gave the best resolution were applied. We determine q^2 from the expression $q^2 = M_e^2 + 2(E_e E_\nu - P_e P_\nu \cos\theta_{e\nu})$, using quantities evaluated in the $K^+K^-e^+$ rest frame, and where $\theta_{e\nu}$ is the angle between the electron and the neutrino in this frame. One can calculate the neutrino energy in this frame using the mass of the D_s [1], and derive a maximum and minimum value for q^2. By assuming the D_s direction is along the thrust direction of the event, we can limit this allowed range. When the $K^+K^-e^+$ mass is near the D_s mass, the resolution on the thrust axis direction is dominant, while at lower $K^+K^-e^+$ masses, the thrust axis information actually constrains the allowed range and we choose the minimum mass solution. Using the values of q^2 obtained, the values of $\cos\theta_e$ and $|\cos\theta_V|$ are evaluated. For $K^+K^-e^+$ masses below 1.6 GeV/c^2, $|\cos\theta_V|$ is calculated assuming the W direction follows that of the lepton. In this way, we obtain average resolutions of 0.22, 0.24, and 0.27 for q^2/q^2_{max}, $\cos\theta_e$, and $|\cos\theta_V|$, respectively.

In order to perform the fit to the expression for the decay rate, a functional form for the q^2 dependence of the form factors must be assumed. However, since the q^2 range in the decay is from 0 to $0.9\,(\mathrm{GeV/c^2})^2$, the results are rather insensitive to the particular parameterization chosen. Nevertheless, the analysis is performed for two functional forms: that due to a single pole [9,10], and that of the ISGW [7]

[4] We use the absolute value of $\cos\theta_V$ since the ϕ decay contains two kaons of identical mass, resulting in symmetric acceptance in this variable.

model[5].

The fitting technique follows that developed by the E691 experiment for the determination of the $D^+ \to \overline{K}^{*0} e^+ \nu_e$ form factor ratios [5,19]. This technique enables a multi-dimensional likelihood fit to be performed to observed kinematic distributions which have been modified by experimental acceptance and resolution, which is necessary for this analysis due to the substantial smearing. The essence of the method is to determine the probability density function by using the population of appropriately weighted Monte Carlo events in the three dimensional kinematic space. This is accomplished by generating one high statistics set of Monte Carlo events with known values of R_2 and R_V, and corresponding known values of the three kinematic variables $|\cos\theta_V|$, $\cos\theta_e$, and q^2/q^2_{max} for each event. The generated events are then processed through the full detector simulation, offline analysis programs and selection criteria. Using the generated kinematic variables, the accepted Monte Carlo events are weighted by the ratio of the decay distribution for trial values of R_2 and R_V to that of the generated distribution. The accepted Monte Carlo events are now, therefore, distributed according to the probability density corresponding to the trial values of R_2 and R_V. By such weighting, a probability may be evaluated for each data event for different trial values of the form factor ratios, and a fit performed. The probability for each event is determined by sampling this distribution using a search volume around each data point. The volume size is chosen so that the systematic effect from finite search volumes is small and the required number of Monte Carlo events is not prohibitively high.

Background is incorporated into the fit by constructing the probability $P = N_s p_s + N_b p_b$ where N_s is the number of signal events in the data sample, N_b is the number of background events in this sample, p_s is the probability density for the signal distribution (determined using the search volume technique discussed above) and p_b is the probability for the background distribution. Since the level of background in this analysis is greater than that for any previous analysis which used this fitting technique, the inclusion of background is studied using three different approaches. The primary approach involved determining p_b in the same manner as p_s, by constructing a search volume around each data point but using a sample of background events to determine the probability density function, p_b. Event samples are obtained for each background component: random K^+K^- background is modelled from real data by using sidebands of the M_{KK} mass distribution both greater than and less than the ϕ mass; fake electron background is also modelled from the data, by ap-

[5] The single pole form yields $A_1(q^2) = A_1(0)(1/(1 - q^2/M_A^2))$, $A_2(q^2) = A_2(0)(1/(1 - q^2/M_A^2))$ and $V(q^2) = V(0)(1/(1 - q^2/M_V^2))$ where the pole masses are $M_A = 2.53$ GeV/c^2 and $M_V = 2.11$ GeV/c^2. The ISGW model expresses the q^2 dependence as: $F_x(q^2) = f_x \exp\left[-\sigma_s(q^2_{max} - q^2)\right]$, where the F_x refer to A_1, A_2, and V, f_x are constants, and the slope, σ_s, is a tunable parameter in the model.

plying the logical negative of the electron identification criteria; random ϕ-electron background is modelled using Monte Carlo events for which the ϕ and the electron are known not to originate from D_s decay. Two other methods are used to quote a systematic error due to background incorporation: the first involves parameterizing the distributions of the kinematic variables for background events; the other method involved subtracting the log likelihood for scaled background from that of the data.

All methods of background incorporation are tested using data samples composed of Monte Carlo signal events to which have been added the appropriate number of background events. In each case, the fit yielded results for R_2 and R_V in good agreement with those with which the Monte Carlo signal events have been generated. Although all approaches of background inclusion are validated, we quote results using the first approach, that is determining p_b using background events. The parameterized background approach does not include correlations between the kinematic variables, while the third approach does not include fluctuations in the background in the statistical error on the fit parameters.

The 474 events of the final data set are fit to the expression for the decay rate in terms of the three kinematic variables using over 16000 accepted Monte Carlo events. Assuming the single pole form of the form factors, we find: $R_2 = 1.4 \pm 0.5$ and $R_V = 0.9 \pm 0.6$, where the errors are statistical. Figure 2 shows the projections of the q^2/q^2_{max}, $\cos\theta_e$, and $|\cos\theta_V|$ variables for the data and fit. By comparing the likelihood of the fit with the distribution of likelihoods obtained by fitting many Monte Carlo samples of the same number of events, the confidence level of the fit is determined to be 4%. Sensitivity of the results to the assumed q^2 dependence is investigated by varying the pole masses. A variation of ± 0.1 GeV/c^2 in these masses leads to variations of ± 0.1 in R_2 and R_V.

Systematic effects due to the following sources are explored: Monte Carlo statistics, Monte Carlo model and selection criteria, volume size used in the likelihood fit, amount of background, and method of background incorporation. These systematic uncertainties are summarized in Table I. The systematic errors from statistical fluctuations in the Monte Carlo sample are estimated using the difference between two fits performed with half of the full available Monte Carlo sample. To determine the uncertainty in the Monte Carlo model and selection criteria, Monte Carlo events are weighted with different fragmentation functions, and with different momentum dependent kaon identification efficiencies. The data is then fit using these weighted Monte Carlo samples. The systematic errors associated with volume size fluctuations are estimated by taking the largest difference between the quoted results and those for which the linear dimensions of each search volume has been raised or lowered by 50%. The systematic uncertainty associated with background normalization is determined by varying the estimated number of background events in the final data set by one sigma. Finally, the largest systematic error is due to the manner in which the background has been incorporated, including variations in the background shape; the fluctuation in the results for the three different approaches is added in quadrature to the fluctuation obtained using different background samples and parameterizations.

In conclusion, we have measured the ratios of form factors in the decay $D_s^+ \to \phi e^+ \nu_e$ from a sample of 474 events, by fitting the decay rate to the kinematic variables q^2/q^2_{max}, $\cos\theta_e$, and $|\cos\theta_V|$. We determine:

$$R_2 = 1.4 \pm 0.5 \pm 0.3 \qquad \text{and} \qquad R_V = 0.9 \pm 0.6 \pm 0.3,$$

assuming the single pole form of the form factors. The ratio of longitudinal to transverse polarization of the ϕ evaluated from these results is $\Gamma_L/\Gamma_T = 1.0 \pm 0.3 \pm 0.2$. Table 1 compares our results for the ratios of form factors with the most recent prediction of the ISGW model [20] and also with other measurements. The CLEO II results are consistent with the previous measurements of the $D_s^+ \to \phi e^+ \nu_e$ form factor ratios and are consistent with the world average measurements for $D \to K^* e^+ \nu_e$.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. J.P.A. and P.S.D. thank the PYI program of the NSF, I.P.J.S. thanks the YI program of the NSF, G.E. thanks the Heisenberg Foundation, K.K.G., I.P.J.S., and T.S. thank the TNRLC, K.K.G., H.N.N., J.D.R., T.S. and H.Y. thank the OJI program of DOE and P.R. thanks the A.P. Sloan Foundation for support. This work was supported by the National Science Foundation, the U.S. Dept. of Energy and the Natural Sciences and Engineering Research Council of Canada.

TABLES

TABLE I. Systematic error summary

Source	error on R_2	error on R_V
MC statistics	0.11	0.10
MC model and cuts	0.02	0.05
Volume size	0.08	0.07
Background normalization	0.10	0.09
Background shape	0.25	0.25
TOTAL	0.30	0.30

TABLE II. Measurements of the ratios of form factors for charmed meson decays to vector particles.

Mode	Experiment	R_2	R_V
$D_s^+ \to \phi e^+ \nu_e$	CLEO II	$1.4 \pm 0.5 \pm 0.3$	$0.9 \pm 0.6 \pm 0.3$
$D_s^+ \to \phi \mu^+ \nu_\mu$	E653 [15]	$2.1^{+0.6}_{-0.5} \pm 0.2$	$2.3^{+1.1}_{-0.9} \pm 0.4$
$D_s^+ \to \phi \mu^+ \nu_\mu$	E687 [16]	$1.1 \pm 0.8 \pm 0.1$	$1.8 \pm 0.9 \pm 0.2$
$D_s^+ \to \phi \ell^+ \nu$	ISGW Theory [20]	1.2	1.9
$D^+ \to \overline{K}^*(892)^0 \ell^+ \nu$ [3–5]	World Average	0.73 ± 0.15	1.89 ± 0.25

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FIGURES

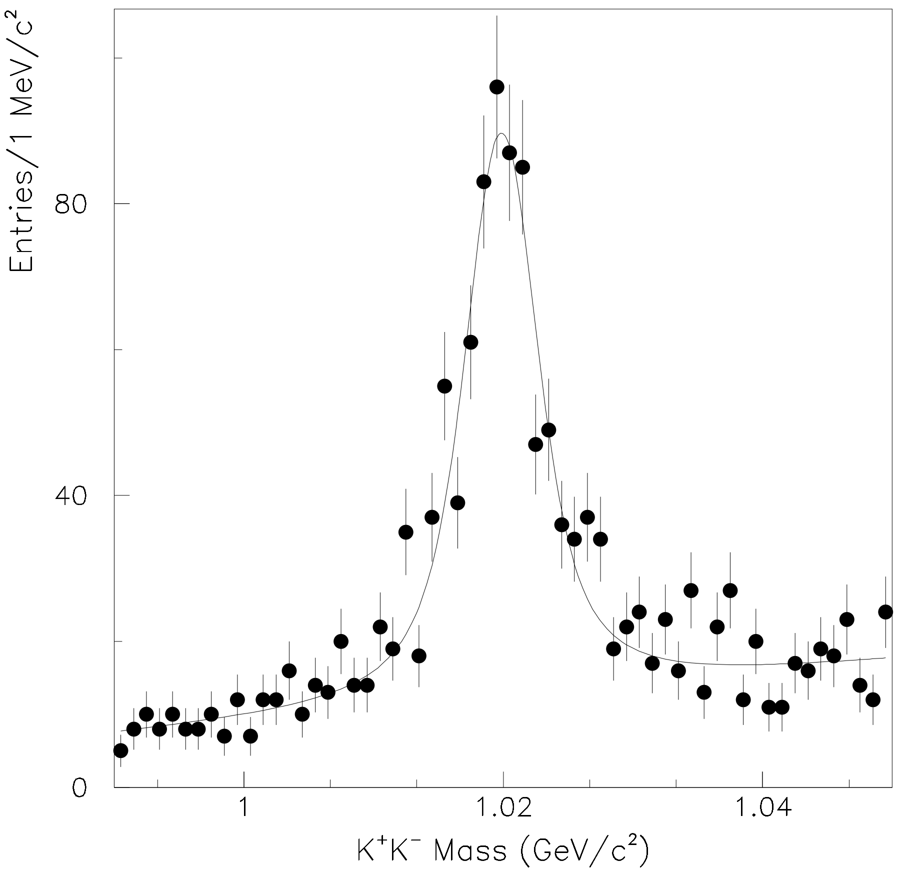

FIG. 1. Invariant mass spectrum of the K^+K^- combinations passing all other analysis cuts. The signal region is $1.017 \leq M_{KK} < 1.023$ GeV/c^2 and the background events are taken from the regions $0.990 \leq M_{KK} < 1.005$ GeV/c^2 and $1.035 \leq M_{KK} < 1.050$ GeV/c^2.

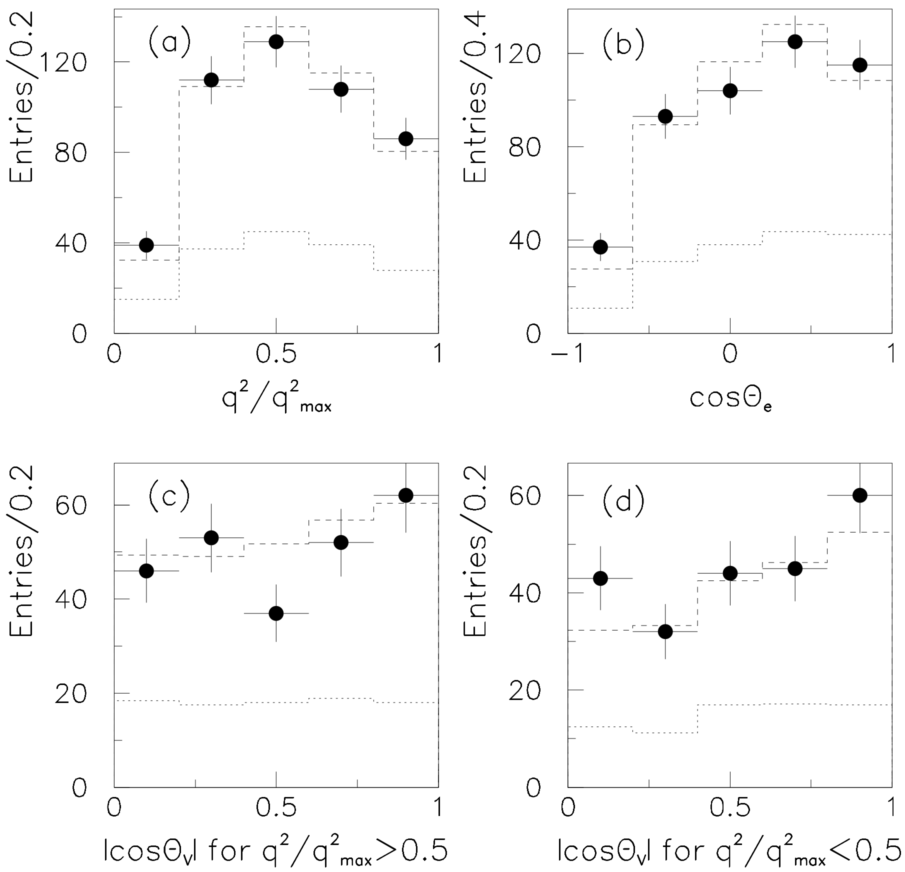

FIG. 2. Projections of the data (points with error bars) and fit (dashed histogram) for (a) the q^2/q^2_{max}, (b) $\cos\theta_e$, (c) $|\cos\theta_V|$ with $q^2/q^2_{max} > 0.5$, and (d) $|\cos\theta_V|$ with $q^2/q^2_{max} < 0.5$ distributions. The dotted lines show the background distributions. The amount of longitudinal polarization can be seen through the difference in slope apparent in (c) and (d). The acceptance is essentially flat in q^2/q^2_{max} and $|\cos\theta_V|$, however due to the electron momentum cut the acceptance in $\cos\theta_e$ is reduced at $\cos\theta_e = -1$ and rises linearly through the allowed range of $\cos\theta_e$.