Study of the Decay $D^+ \rightarrow \bar{K}^0 e^+ \nu_e$

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We have studied the exclusive semileptonic decay mode $D^+ \rightarrow \bar{K}^0 e^+ \nu_e$ in the Fermilab photoproduction experiment E691. We find the ratio $B(D^+ \rightarrow \bar{K}^0 e^+ \nu_e)/B(D^+ \rightarrow K^- \pi^+ \pi^+)$ to be $0.66 \pm 0.09 \pm 0.14$, corresponding to a $D^+ \rightarrow \bar{K}^0 e^+ \nu_e$ branching ratio of $(6.1 \pm 0.9 \pm 1.6)\%$. Combining this result with our measurement of the D^+ lifetime, we find $\Gamma(D^+ \rightarrow \bar{K}^0 e^+ \nu_e) = (5.6 \pm 0.8 \pm 1.5) \times 10^{10}\ \mathrm{s}^{-1}$. We also find, using E691 averages, the ratio of decay rates $\Gamma(D \rightarrow K^* e\nu)/\Gamma(D \rightarrow K e\nu)$ to be 0.55 ± 0.14.

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The exclusive semileptonic decays of mesons containing heavy quarks are particularly interesting because they are the simplest decays to interpret. The strong-interaction effects are completely contained in the form factors, which describe how the final-state quark from the weak decay combines with the spectator quark to produce a final-state meson, or mesons. Because of this simplicity, these decays are used to measure the Cabibbo-Kobayashi-Maskawa matrix elements, which parametrize the mixing between the quark mass eigenstates and the weak eigenstates. The form factors are interesting both because the precise measurement of the Kobayashi-Maskawa elements is important and because the form factors themselves represent a rare window on the structure of heavy mesons. There has been intense theoretical effort on calculating the form factors using both analytical models and lattice gauge techniques [1-9].

The matrix element V_{cs}, which is relevant for Cabibbo-favored charm decays, is known to an error of ± 0.001 assuming three-generation unitarity. It is therefore possible to measure the $c \rightarrow s$ form factors using semileptonic decays. There are arguments that these form factors are closely related to those in $b \rightarrow u$ semileptonic decays, and will therefore be useful in extracting an accurate value of V_{ub} when exclusive measurements of those decays are available [10].

The two dominant semileptonic decays are expected to be $D \rightarrow K e\nu$ and $D \rightarrow K^* e\nu$. The decay rates for D^+ and D^0 are equal, by isospin. We have already measured the decay rate $\Gamma(D^0 \rightarrow K^- e^+ \nu_e) = (9.1 \pm 0.7 \pm 1.7) \times 10^{10}\ \mathrm{s}^{-1}$ [11], which agrees well with various form-factor calculations. We have also measured the mode $D^+ \rightarrow K^- \pi^+ e^+ \nu_e$, and have found it to be dominated by the K^{*0} [12]. For the K^* final state, there are three form factors, which we have extracted directly [13]. The resulting form factors do not agree very well with model predictions. In this paper we present a measurement of the decay rate for $D^+ \rightarrow \bar{K}^0 e^+ \nu_e$. (Charge-conjugate states are implicitly included throughout this paper.) This gives a second measurement of the $K e\nu$ form factor with quite different systematic errors.

We have used the data from the Fermilab charm photoproduction experiment E691 in this analysis. The apparatus, the Tagged Photon Spectrometer, is an open geometry, two-magnet spectrometer. Photons with energy between 80 and 240 GeV interacted in a 5-cm beryllium target. The charged particles were tracked using silicon microstrip detectors (SMDs) and drift chambers. As in the earlier semileptonic decay studies, we take advantage of the precise vertex resolution of the SMDs and the good electron identification to isolate the signal of exclusive semileptonic decays. The spectrometer and the use of the silicon microstrip detector are discussed elsewhere [14].

The $\bar{K}^0$ sample was observed in the channel $K_s \rightarrow \pi^+ \pi^-$. Candidates were found by forming two track vertices with tracks seen in the drift chambers but not in the SMDs. The electron identification, which included a minimum-energy cut of 12 GeV, relied on the electromagnetic shower shape in the calorimeter and the agreement of the energy deposit with the momentum from the tracking chambers. We selected electrons with an electron probability corresponding to a typical efficiency for electrons and pions of 61% and 0.3%, respectively. These efficiencies were measured using conversion electrons and $K_s \to \pi^+\pi^-$ decays. To lower backgrounds, especially those due to electrons from $\pi^0 \to \gamma\gamma$, $\gamma \to e^+e^-$, we restricted the angle (θ^*) of the electron relative to the $\bar{K}^0e^+$ boost direction in the $\bar{K}^0e^+$ frame such that $\cos\theta^* < 0.7$. The electrons from the signal mode are distributed isotropically in this frame. The background conversion electrons have very low p_T; with the energy cutoff of 12 GeV the remaining background is peaked near $\cos\theta^* \simeq 1$.

In this experiment the K^0 decays well downstream of the precision vertex detector and so only one track, the electron track, is determined with enough precision to be useful for identifying a separated D^+ vertex. We selected electrons which formed no more than one well-defined vertex with any other single track in the event. This removed $\bar{K}^0\pi^-e^+\nu_e$ and other semileptonic decays from the sample. The present analysis proceeds in a manner similar to that in our analysis of $D^+ \to \bar{K}^0\pi^+$ [15]. In that analysis, we required that the production vertex lie in the plane defined by the kaon and pion, to within a resolution factor. Here we extend the technique to allow for the momentum of the neutrino. We define a vector **r** from the event production vertex to the electron track, such that **r** is perpendicular to the track. We resolve **r** into two components, a component ($r_{\rm in}$) in the $\bar{K}^0e^+$ plane and a component (r_t) transverse to that plane. If we assume the neutrino energy to be zero (a limit in which the present decay very nearly resembles $D^+ \to \bar{K}^0\pi^+$), we can relate $r_{\rm in}$ to the decay distance through

$$d = r_{\rm in}\frac{\gamma(p^*\cos\theta^* + \beta E^*)}{p^*\sin\theta^*} = r_{\rm in}\gamma\frac{\cos\theta^*+1}{\sin\theta^*}\,.$$

In this expression, $\gamma = E(\bar{K}^0e^+)/M(\bar{K}^0e^+)$, $\beta = p(\bar{K}^0e^+)/E(\bar{K}^0e^+)$, and p^* is the momentum of the electron in the $\bar{K}^0e^+$ rest frame. Thus an estimate of the proper decay time is

$$t' = \frac{r_{\rm in}}{c}\frac{\cos\theta^*+1}{\sin\theta^*}\,.$$

We required $r_{\rm in}$ to be greater than 210 μm, which removes tracks that come from the primary vertex. This cut removes 85% of the background and retains 50% of the signal. Since at long decay times backgrounds which have a flat distribution in decay time dominate, we also required $t' < 4\tau_{D^+}$. The distance r_t is maximized when the neutrino momentum is perpendicular to the $\bar{K}^0e^+$ plane in the laboratory frame, and is minimized (limited by resolution) when $E_\nu \to 0$. We require that r_t be less than the sum of 80 μm (twice the resolution) and the contribution to r_t assuming the maximum transverse momentum of the neutrino, added in quadrature. This cut depends on $\bar{K}^0e^+$ mass, because the neutrino energy in the center of mass of the D^+ is a function of $M(\bar{K}^0e^+)$. The $M(\bar{K}^0e^+)$ distribution of events which pass these cuts is shown in Fig. 1.

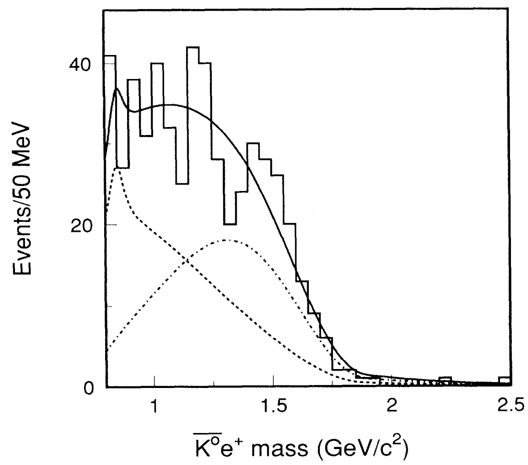

FIG. 1. Invariant $\bar{K}^0e^+$ mass distribution, with the final fit (solid curve), signal (dot-dashed curve), and background (dashed curve).

To extract the signal from the $\bar{K}^0e^+$ mass spectrum it is necessary to know the background shape. There is no wrong-sign background to use, as there was in the case of $D^+ \to K^-\pi^+e^+\nu_e$. There is fairly consistent experience from many background spectra observed in our experiment that the mass shape depends very little on vertex separation. We effectively factor the background shape into two parts: (a) a smooth shape which should be independent of vertex separation and should look like the other two-body mass spectra, and (b) a shape which describes the efficiency of the r_t cut for background, because the r_t cut depends on $\bar{K}^0e^+$ mass. To parametrize shape (a), we selected events with $r_{\rm in}$ below the cut used to select charm, a sample that has only a small fraction of charm. This sample, along with the parametrized shape, is shown in Fig. 2. The parametrization includes a small term for a signal feedthrough as well as a term for $K^{*+} \to K^0\pi^+$ background in which the pion is misidentified as an electron. This K^* peak is marginally significant, and its inclusion has almost no effect on the signal size.

To model the shape (b), we cannot use the low-$r_{\rm in}$ sample discussed above, since the efficiency of the r_t cut depends on $r_{\rm in}$. Instead we use background events with relatively low electron probability, but which pass all the vertex cuts. In Fig. 3 we show the measured efficiency of the r_t cut for this background sample. The curve is the function we use to parametrize the efficiency, using the fact that for $M(\bar{K}^0e^+) > M(D^+)$ the r_t cut and associated efficiency are constant. The shape of the curve is

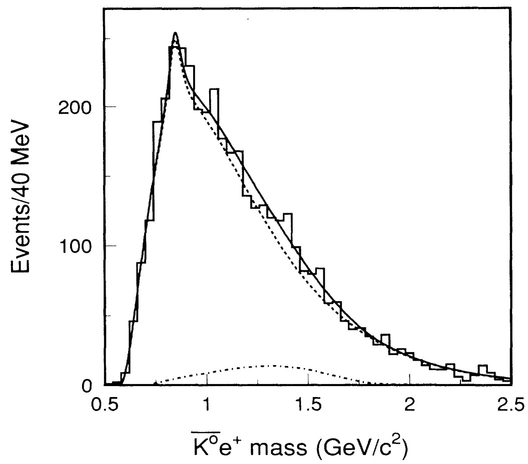

FIG. 2. Invariant $\bar{K}^0e^+$ mass distribution for background events prior to r_t cut. The solid line is the fit, the dashed line is the background shape, and the dot-dashed line is signal feedthrough.

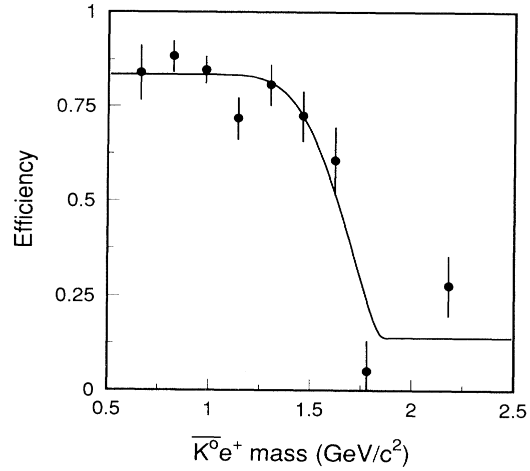

FIG. 3. Measured efficiency of r_t cut vs $M(\bar{K}^0e^+)$, with the best fit.

determined by the fact that the r_t spectrum does not depend on mass. The final background shape is obtained by multiplying this shape times the shape (a) discussed above.

The general shape of the $M(\bar{K}^0e^+)$ spectrum in Fig. 1 shows a rather flat shape from 1.0 to 1.7 GeV, dramatically different from the background shape of this or any other two-body sample. The signal shape and the reconstruction efficiency [$(0.77\pm0.02)\%$] were determined from Monte Carlo studies. We assumed the usual pole form for the semileptonic decay form factor, but have found our results to be insensitive to pole mass. The fit uses the signal shape, the background shape discussed above, and a feedthrough from the decay $D^+\to\bar{K}^{*0}e^+\nu_e(\bar{K}^{*0}\to\bar{K}^0\pi^0)$ of 40 ± 5 events. The fit gives $249\pm34\pm51$ $D^+\to K_se^+\nu_e$ events. The systematic errors stem mainly from uncertainty in the background shape (±40 events), electron efficiency (±17 events), and neutral-kaon efficiency (±21 events), and whether or not we include a K^* term in the background shape (±14 events). We studied a wide variety of background shapes and different background samples to estimate the uncertainty in this shape, which is the dominant systematic error. Normalizing this result with our $D^+\to K^-\pi^+\pi^+$ sample and using the absolute branching ratio for that mode from Mark III of $(9.1\pm1.3\pm0.4)\%$, we find $B(D^+\to\bar{K}^0e\nu_e)=(6.1\pm0.9\pm1.6)\%$. Using the E691 value for the D^+ lifetime we find $\Gamma(D^+\to\bar{K}^0e\nu_e)=(5.6\pm0.8\pm1.5)\times10^{10}\ \mathrm{s}^{-1}$.

As noted above, we have measured $\Gamma(D^0\to K^-e^+\nu_e)=(9.1\pm0.7\pm1.7)\times10^{10}\ \mathrm{s}^{-1}$. Our two measurements of $\Gamma(D\to Ke\nu)$ differ by 1.4 standard deviations. These measurements are effectively independent: The dominant systematic errors in $D^+\to\bar{K}^0e^+\nu_e$ are due to the uncertainty in the background shape, neutral-kaon and electron efficiencies, and the Mark III value for the absolute D^+ branching ratio, whereas the dominant systematic errors in $D^0\to K^-e^+\nu_e$ are due to the uncertainty in electron and charged-kaon efficiency, and the Mark III value for the absolute D^0 branching ratio. Only the electron detection efficiency is common. Our weighted average for $\Gamma(D\to Ke\nu)$ is $(7.3\pm1.3)\times10^{10}\ \mathrm{s}^{-1}$, where we have taken into account the part of the systematic error which is in common.

The semileptonic rate can be expressed as

$$\Gamma(D\to Ke\nu)=|V_{cs}|^2|f_+(0)|^2(1.53\times10^{11})\ \mathrm{s}^{-1}.$$

If we take $|V_{cs}|=0.975$, we find the form-factor intercept $|f_+(0)|=0.71\pm0.06$, in good agreement with theoretical predictions [1,2,4,6,9]. In a previous paper [13] we reported a measurement of the form factors in $D^+\to\bar{K}^{*0}e^+\nu_e$ and found that the axial-vector form factors

TABLE I. Summary of exclusive charm semileptonic rates. All widths in $10^{10}\ \mathrm{s}^{-1}$.

Group	$\Gamma(D^+\to\bar{K}^0l^+\nu_l)$	$\Gamma(D^0\to K^-l^+\nu_l)$	Average
E691 [a]	$5.6\pm0.8\pm1.5$	$9.1\pm0.7\pm1.7$	7.3 ± 1.2
Mark III [b]	$6.1^{+1.5}_{-1.0}\pm0.7$	$8.1\pm1.2\pm0.9$	7.0 ± 1.0
E653 [c]		$5.6\pm0.9\pm1.2$	5.6 ± 1.5
CLEO [d]		$8.8\pm0.7\pm1.4$	8.8 ± 1.6
Average	5.9 ± 1.1	7.6 ± 0.8	7.0 ± 0.7

Group	$\Gamma(D^+\to\bar{K}^{*0}l^+\nu_l)$	$\Gamma(D^0\to K^{*-}l^+\nu_l)$	Average
E691 [e]	$4.0\pm0.4\pm0.7$		4.0 ± 0.8
Mark III [b]	$4.0^{+1.8}_{-1.0}\pm0.6$	$8.3^{+4.5}_{-2.4}\pm1.4$	4.5 ± 1.2
ARGUS [f]	$3.9\pm0.6\pm0.9$		3.9 ± 1.1
CLEO [d]		$4.5\pm1.4\pm1.2$	
Average	4.0 ± 0.6	5.2 ± 1.6	4.2 ± 0.6

[a] Reference [11].
[b] Reference [16].
[c] Reference [17].
[d] Reference [18].
[e] Reference [13].
[f] Reference [19].

TABLE II. Summary of exclusive and inclusive charm decay rates.

Mode	Source	Decay width (10^{10} s^{-1})
$D\to Ke\nu$	E691	7.3 ± 1.2
$D\to K^*e\nu$	E691	4.0 ± 0.8
$D\to(K\pi)_{NR}e\nu$	E691	0.4 ± 0.4
$D\to(\pi,\rho)e\nu$	V_{cd}/V_{cs}	0.9 ± 0.3
Total		12.6 ± 1.5
$D\to Xe\nu$	Mark III avg. [a]	16.5 ± 1.6
Missing decays		3.9 ± 2.2

[a]Reference [16].

do not agree well with theory.

In Table I we give a summary of Cabibbo-favored charm semileptonic rates. For $D\to Kl\nu$ the measurements agree quite well. The world average for $\Gamma(D\to Kl\nu)$ is $(7.0\pm0.7)\times10^{10}$ s^{-1}. There is also good agreement in the rates for $D\to K^*l\nu$, and the world average is $\Gamma(D\to K^*l\nu)=(4.2\pm0.6)\times10^{10}$ s^{-1}.

In Table II we show data relevant to the question of whether the lowest resonances K and K^* saturate the $c\to se^+\nu_e$ rate. The total of exclusive decay rates is $(12.6\pm1.5)\times10^{10}$ s^{-1}, compared to $(16.5\pm1.6)\times10^{10}$ s^{-1} for the inclusive decay rate from Mark III. Thus the rate for missing decays is $(3.9\pm2.2)\times10^{10}$ s^{-1}, which is marginally consistent with zero, but is also consistent with being as large as the major decays. To determine the importance of the remaining channels it will be necessary to measure directly exclusive channels such as $D\to K\pi\pi e\nu$.

Using E691 averages we find the ratio $\Gamma(D\to K^*e\nu)/\Gamma(D\to Ke\nu)=0.55\pm0.14$. If we use world averages the same ratio is 0.60 ± 0.10. These numbers are significantly smaller than the predicted value of 1.0–1.2 [1,2]. Since the absolute rates agree with theory for the $D\to Ke\nu$ decay, the source of this discrepancy appears to be in the $K^*e\nu$, not the $Ke\nu$, form factors.

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