Study of the Semileptonic Decay Mode $D^0 \to K^- e^+ \nu_e$

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We present an analysis of the exclusive semileptonic decay mode $D^0 \to K^- e^+ \nu_e$. We have measured the ratio of decay rates $\Gamma(D^0 \to K^- e^+ \nu_e)/\Gamma(D^0 \to K^- \pi^+) = 0.91 \pm 0.07(\text{stat.}) \pm 0.11(\text{syst.})$, which corresponds to a $D^0 \to K^- e^+ \nu_e$ branching fraction of $(3.8 \pm 0.5 \pm 0.6)\%$. Combining our result with a measurement of the D^0 lifetime, we find $\Gamma(D^0 \to K^- e^+ \nu_e) = (9.1 \pm 1.1 \pm 1.4) \times 10^{10}\ \text{s}^{-1}$. We have also measured the vector form factor $f_+(t)$ and find that it is consistent with the single-pole form where the pole mass $M_{D_s^*} = 2.11\ \text{GeV}/c^2$.

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The study of exclusive semileptonic decays is particularly interesting because of the simplicity of the underlying interaction and the wide scope of physics one can learn from it. Cabibbo-favored decays can proceed only through flavor decay (spectator) processes and thus, unlike hadronic decays, there is no uncertainty due to the presence of other diagrams. Moreover, there is no possibility of interference between the leptons and the hadrons in the final state. The matrix element for semileptonic decays can be expressed as the product of a hadronic and a leptonic current. Since the leptonic current is well understood, a study of semileptonic decays probes the structure of the hadronic current.

The decay $D^0 \to K^- e^+ \nu_e$ is analogous to the decay $K^0 \to \pi^- e^+ \nu_e$ and has been widely discussed in the literature.[1] (Throughout the paper the charge-conjugate states are implicitly included.) The relevant matrix element is given by

$$M = (G/\sqrt{2}) V_{cs} [(p_D + p_K)_a f_+(t) + (p_D - p_K)_a f_-(t)] \bar{u}_\nu \gamma^a (1+\gamma_5) u_e \,, \tag{1}$$

where p_D and p_K are the four-momenta of the D and K, u_ν and u_e are Dirac bispinors of the leptons, and t is the four-momentum transfer from D to K (or $M_{e\nu}^2$). In the final result, the terms involving the form factor $f_-(t)$ are always multiplied by the electron mass and thus their contribution to the decay rate can be neglected. In the D^0 center-of-mass momentum system the decay rate is

$$d\Gamma = (G^2/8\pi^3) |V_{cs}|^2 |f_+(t)|^2 M_D [(E_K)^2 - (M_K)^2 - (M_D - E_K - 2E_e)^2] dE_K\, dE_e \,. \tag{2}$$

Using the above expression, an experimental measurement of the partial rate can be translated into a measurement of $|V_{cs}|^2 |f_+(t)|^2$. Given the value of $f_+(0)$ (the theoretical uncertainty of this calculation[2,3] is much larger in the $D^0 \to K^- e^+ \nu_e$ than in the $K^0 \to \pi^- e^+ \nu_e$ case), one can determine the $|V_{cs}|$ element of the Kobayashi-Maskawa (KM) matrix.

This paper presents the results from E691, a high-energy photoproduction experiment performed at the Fermilab Tagged Photon Spectrometer. The detector, a two-magnet spectrometer of large acceptance, good mass resolution, particle identification (Čerenkov counters, electromagnetic and hadronic calorimetry, muon filter), and equipped with a high-resolution silicon-microstrip detector, has been described elsewhere.[4] The electron identification used (a) the ratio of the energy seen in the electromagnetic calorimetry to the track momentum, (b) the sizes of the signals in the electromagentic and hadronic calorimeters, (c) the transverse shower shapes, and (d) the difference between the projected track position and that of the calorimeter shower centroid. The electron efficiency and the pion misidentification probability, while being position and energy dependent, had (for the cuts used) typical values of 72% and 0.5%, respectively. The incident photons, produced via the bremsstrahlung of 260-GeV electrons, had an average tagged energy of 145 GeV. We used an open trigger, based on the total transverse energy detected in the calorimeters. This accepted $\sim 30\%$ of the total hadronic cross section while being $\sim 80\%$ efficient for charm. The experiment recorded 10^8 triggers. This paper is based on an analysis of the full data sample.

We selected candidate events consistent with the cascade decay $D^{*+} \to D^0\pi^+$ followed by $D^0 \to K^-e^+\nu_e$. The technique used is based on the fact that it is possible to reconstruct the missing neutrino momentum providing that the D^0 direction is measured with sufficient precision in the vertex detector. The algebra is simplest in the Lorentz frame with the z axis chosen along the D^0 path, and such that $p_{Ke}^{\bar{z}}$ is equal to zero. Setting $M_{Ke\nu} = M_D$ and $M_\nu = 0$, one can easily obtain the longitudinal component of the neutrino momentum $p_\nu^{\bar{z}}$:

$$(p_\nu^{\bar{z}})^2 = \frac{F^2}{4(E_{Ke})^2} - (p_{Ke}^T)^2 , \quad (3)$$

$$F = (M_D)^2 - (p_{Ke}^T)^2 - (E_{Ke})^2 = 2E_{Ke}E_\nu \geq 0 . \quad (4)$$

Because of the finite vertex-position resolution, F and $(p^{\bar{z}})^2$ can acquire nonphysical, negative values. We required $F > 0$, which reduces background considerably while retaining about 62% of signal. In the Lorentz frame used in this analysis, the true distribution of $(p_\nu^{\bar{z}})^2$ is sharply peaked at very small values. A Monte Carlo simulation shows that our experimental resolution broadens the narrow distribution of generated events, and in about 40% of events the solution acquires a small negative value. In such cases we have set[5] $(p_\nu^{\bar{z}})^2 = 0$. In the remaining events, because Eq. (3) is quadratic, there exist two solutions for $E_{Ke\nu}$. In some cases, one of the them is nonphysical and can be discarded (e.g., $E_{Ke\nu} > 260$ GeV). In the remaining events, for every π^+ we will obtain two D^{*+} solutions, corresponding to the two $p_\nu^{\bar{z}}$ solutions. We choose the one which gives the lower D^* mass.[6]

The experimental procedure consists of selecting K^-e^+ pairs which originate from a downstream vertex significantly separated from a primary vertex, solving for the $\mathbf{p}_\nu$ and then combining the $K^-e^+\nu_e$ four-momentum (constrained to M_D) with that of a π^+ candidate. The random background distributions were obtained using the same approach, but using the *wrong-charge* $K^+e^+\nu_e\pi^+$, $K^+e^+\nu_e\pi^-$, and $K^+e^-\nu_e\pi^+$ combinations. To minimize the statistical fluctuations these distributions were added together and subtracted from the final $M_{K^-e^+\nu_e\pi^+}$ distribution, after being normalized to the integral over the mass interval 2.03–2.40 GeV/c^2. The three background distributions all have the same shape, as expected, and model the background well except for feedthrough from other D^0 modes, which is discussed below.

We required the kaon and electron candidates to be good quality and well identified tracks. The K^-e^+ vertex was required to be separated from the primary vertex by $\Delta x \gtrsim 7\sigma_x$ and both vertices were required to be well constrained. The primary vertex had to contain at least two tracks, with a bachelor pion from the D^* decay being one of them. A cut on electron momentum, $p_e \gtrsim 12$ GeV/c, was applied to suppress electrons from pair conversions and from π^0 decays. Primarily as a result of this momentum cutoff the event detection efficiency is sensitive to the electron radiation in the material downstream of the decay vertex and to radiative corrections, including real and virtual photons.[7] The combined effect of these corrections is to reduce the reconstruction efficiency by a factor of 0.84 ± 0.04.

Feedthroughs from the nonleptonic charm decay modes are negligible because of the good rejection of pions in the electron sample, $e/\pi \approx 7 \times 10^{-3}$, and the requirement that the candidate events originate from a $D^{*+} \to D^0\pi^+$ cascade. The latter requirement also suppresses any contribution from semileptonic decays of the D^+ or D_s^+ mesons. The only large feedthrough comes from another semileptonic decay mode of D^0, namely, $D^0 \to K^-e^+\pi^0\nu_e$. To estimate the feedthrough from the $D^0 \to K^-e^+\pi^0\nu_e$ channel, we have used Monte Carlo simulation. We have adopted the theoretical description of the $K^-e^+\pi^0\nu_e$ mode of Wirbel, Stech, and Bauer.[2] To determine the number of produced $D^0 \to K^-e^+\pi^0\nu_e$ events we used the relation $\Gamma(D^0 \to K^*e\nu) = \Gamma(D^+ \to \bar{K}^{*0}e\nu)$ (which follows from the $\Delta I = 0$ semileptonic rule inherent in the Glashow-Iliopoulos-Maiani scheme of the weak interactions[8]), the E691 measurement of $\Gamma(D^+ \to \bar{K}^{*0}e^+\nu_e)$, and the assumption of K^* dominance in $D^0 \to K^-e^+\pi^0\nu_e$ channel. [In a parallel analysis,[9] we measured $\Gamma(D^+ \to \bar{K}^{*0}e^+\nu_e) = (4.1 \pm 0.7 \pm 0.5) \times 10^{10}\ \mathrm{s}^{-1}$, and found that the $K^-\pi^+$ system is dominated by $K^*(890)$.] The net effect of this correction is small, 7% of the total $D^0 \to K^-e^+\nu_e$ rate. The contribution from $D^0 \to K^-e^+\nu_e + n\pi^0$ has also been estimated. It is found to be less than ten events and has been incorporated in the systematic error.

In Figs. 1(a)–1(c) we present $M_{Ke\nu\pi}$ distributions for the signal, normalized background, and background-subtracted signal, respectively. We found 347 events in the signal region (2.000–2.025 GeV/c^2), and 250 events after background subtraction. The reconstruction efficiency for this set of cuts was 1.45%.

The reconstruction efficiencies were obtained using Monte Carlo–generated events. The Monte Carlo $K^-e^+\nu_e$ events were weighted to reproduce the t distri-

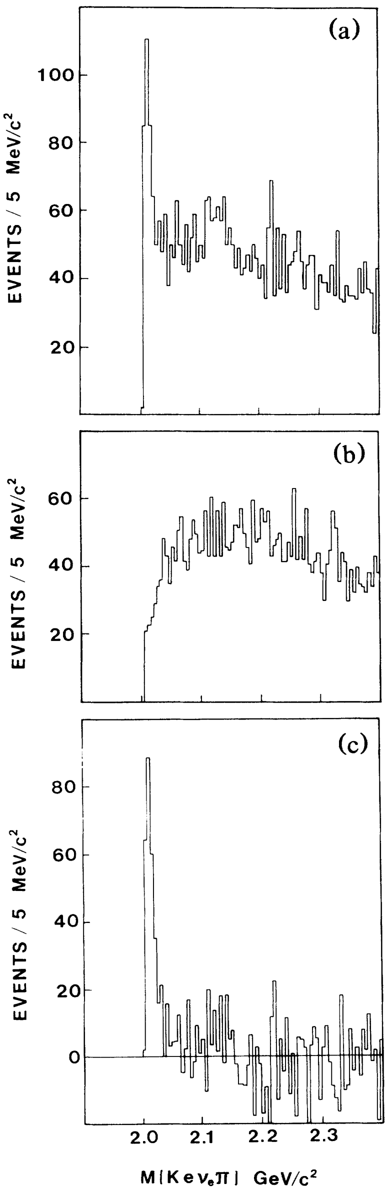

FIG. 1. (a) Effective-mass distribution for $K^-e^+\nu_e\pi^+$ (signal) combinations. The mass of the $K^-e^+\nu_e$ system was constrained to that of a D^0. (b) Effective-mass distribution for $K^+e^+\nu_e\pi^+$, $K^-e^-\nu_e\pi^+$, and $K^+e^-\nu_e\pi^+$ combinations (background), normalized to the integral over the mass interval 2.03–2.40 GeV/c^2 of the correct-sign (signal) distribution. (c) Background-subtracted effective-mass distribution for $K^-e^+\nu_e\pi^+$ (signal) combinations.

bution expected from a form factor with a single-pole form,

$$f_+(t)=f_+(0)M_{D_s^*}^2/(M_{D_s^*}^2-t)\,, \tag{5}$$

with $M_{D_s^*}=2.11$ GeV/c^2.

To estimate the systematic error due to the background subtraction and the uncertainties of the Monte

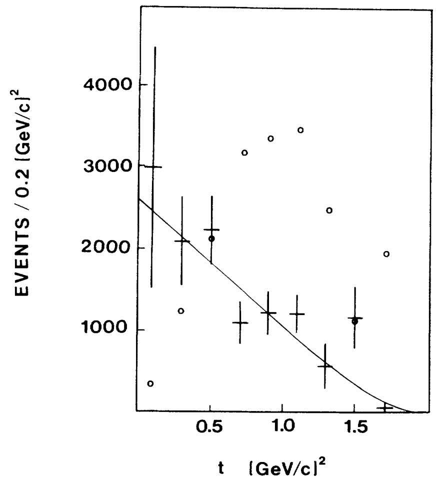

FIG. 2. Distribution of the four-momentum transfer from D to K ($t=M_{e\nu}^2$). The superimposed solid curve is the result of a fit by a t distribution expected, after integration over phase space, from the assumed single-pole form for the vector form factor. The open circles indicate the reconstruction efficiency as a function of t. The fit yields a value of $M_{D_s^*}=2.1^{+0.4}_{-0.2}$ GeV/c^2.

Carlo simulation, we varied the cuts on vertex separation, track quality cuts, and particle identification of the electron and kaon candidates. The uncertainty in the electron reconstruction efficiency was estimated to be 5%. The systematic error and statistical error in the reconstruction efficiencies were combined in quadrature. The number of events *produced* in the mode $D^{*+}\to D^0\pi^+$, $D^0\to K^-e^+\nu_e$, after having been corrected for the reconstruction efficiencies and for the feedthrough from $K^-e^+\pi^0\nu_e$ channel, was compared with the number of events *produced* in the mode $D^{*+}\to D^0\pi^+$, $D^0\to K^-\pi^+$ to deduce the ratio of decay rates

$$\Gamma(D^0\to K^-e^+\nu_e)/\Gamma(D^0\to K^-\pi^+)$$
$$=0.91\pm0.07(\text{stat.})\pm0.11(\text{syst.})\,.$$

Using the Mark III[10] branching fraction $B(D^0\to K^-\pi^+)=(4.2\pm0.4\pm0.4)\%$ we obtain the result

$$B(D^0\to K^-e^+\nu_e)=(3.8\pm0.5\pm0.6)\%\,.$$

This measurement agrees well with the Mark III measurement[11] $B(D^0\to K^-e^+\nu_e)=(3.4\pm0.5\pm0.4)\%$. Our measurement of the semileptonic branching fraction can be combined with the E691 measurement of the D^0 lifetime[4] to obtain the semileptonic partial rate

$$\Gamma(D^0\to K^-e^+\nu_e)=(9.1\pm1.1\pm1.4)\times10^{10}\,\text{s}^{-1}\,.$$

Figure 2 presents the distribution, with background subtracted and corrected for the reconstruction efficiencies, of the four-momentum transfer t (or $M_{e\nu}^2$). If the distribution is fitted by a form factor with a single pole, we find that the mass of the exchanged particle is $M_{D_s^*}=2.1^{+0.4}_{-0.2}\pm 0.2$ GeV/c^2. This is consistent with the value of $M_{D_s^*}=2.11$ GeV/c^2 measured *directly* by the Mark III and ARGUS Collaborations.[12] With the value of $M_{D_s^*}$ fixed at 2.11 GeV/c^2 we can use Eq. (2) to determine

$$\Gamma(K^- e^+ \nu_e) = |V_{cs}|^2 |f_+(0)|^2 (1.53\times 10^{11})\ \mathrm{s}^{-1}.$$

Comparing the predicted and measured values of the semileptonic partial rates we find $|V_{cs}|^2|f_+(0)|^2=0.59 \pm 0.07 \pm 0.09$.

If $|f_+(0)|$ were known, this measurement could be translated directly into a measurement of $|V_{cs}|$. If we take[2,3] $|f_+(0)|=0.76$ and assume a form factor with a single pole, then we have the model-dependent result $|V_{cs}|=1.01\pm 0.06\pm 0.08$. Reversing the argument, we can adopt a value of $|V_{cs}|=0.975$ (assuming three families and imposing the unitarity condition on the KM matrix) and obtain a measurement of $|f_+(0)|=0.79 \pm 0.05\pm 0.06$.

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[1]A. Ali and T. C. Yang, Phys. Lett. **65B**, 275 (1976); I. Hinchliffe and C. H. Llewellyn Smith, Nucl. Phys. **B114**, 45 (1976); F. Bletzacker, H. T. Nieh, and A. Soni, Phys. Rev. D **16**, 732 (1977); W. J. Wilson, Phys. Rev. D **16**, 742 (1977); V. Barger, T. Gottschalk, and R. J. N. Phillips, Phys. Rev. D **16**, 746 (1977); D. Fakirov and B. Stech, Nucl. Phys. **B133**, 315 (1978); X. Y. Pham and J. M. Richard, Nucl. Phys. **B138**, 453, (1978); K. Kudoh, Prog. Theor. Phys. **60**, 1834 (1978); M. Suzuki, Nucl. Phys. **B145**, 420 (1978); N. Cabibbo and L. Maiani, Phys. Lett. **79B**, 109 (1978); G. L. Kane, W. B. Rolnick, and K. Stowe, Nucl. Phys. **B152**, 390 (1978); N. Cabibbo, G. Corbo, and L. Maiani, Nucl. Phys. **B155**, 93 (1979); M. Gluck, Phys. Lett. **84B**, 459 (1979).

[2]M. Wirbel, B. Stech, and M. Bauer, Z. Phys. C **29**, 637 (1985).

[3]T. M. Aliev, V. L. Eletskii, and Ya.I. Kogan, Yad. Fiz. **40**, 823 (1984) [Sov. J. Nucl. Phys. **40**, 527 (1984); B. Grinstein and M. B. Wise, Phys. Lett. B **197**, 249 (1987); C. A. Dominguez and N. Paver, Phys. Lett. B **197**, 423 (1987); DESY Report No. 88-035, 1988 (to be published).

[4]J. R. Raab, Phys. Rev. D **37**, 2391 (1988); J. R. Raab, Ph. D. thesis, University of California, Santa Barbara, Report No. UCSB-HEP-87-8, 1987, (unpublished), and references therein.

[5]With a complete Monte Carlo simulation of the experiment we have checked that this procedure does not introduce any serious biases in the subsequent analysis.

[6]Accepting only one solution per event makes the subsequent interpretation of results straightforward. A Monte Carlo study shows that we find the correct solution in 75% of the accepted events. In the remaining events the two solutions are nearly identical and choosing the incorrect solution does not bias the final results.

[7]The radiative corrections have been evaluated using the modified calculation of K_{e3} decay; see M. Dremin, Zh. Eksp. Teor. Fiz. **35**, 355 (1959) [Sov. Phys. JETP **8**, 247 (1959)]; E. S. Ginsberg, Phys. Rev. **142** 1035 (1966); **162**, 1570 (1967).

[8]A. Pais and S. B. Treiman, Phys. Rev. D **15**, 2529 (1977).

[9]J. C. Anjos *et al.*, Phys. Rev. Lett. **62**, 722 (1989).

[10]Mark III Collaboration, J. Adler *et al.*, Phys. Rev. Lett. **60**, 89 (1988).

[11]Mark III Collaboration, J. Adler *et al.*, SLAC Report No. SLAC-PUB-4745, 1988 (to be published).

[12]Mark III Collaboration, G. Blaylock *et al.*, Phys. Rev. Lett. **58**, 2171 (1987); ARGUS Collaboration, Albrecht *et al.*, Phys. Lett. B **207**, 349 (1987).