Experimental Study of the Semileptonic Decay $D^+ \to \bar{K}^{*0} e^+ \nu_e$

J. C. Anjos,(3) J. A. Appel,(5) A. Bean,(1) S. B. Bracker,(8) T. E. Browder,(1),(f) L. M. Cremaldi,(4),(a) J. E. Duboscq,(1) J. R. Elliott,(4),(b) C. O. Escobar,(7) P. Estabrooks,(2) M. C. Gibney,(4) G. F. Hartner,(8) P. E. Karchin,(9) B. R. Kumar,(8) M. J. Losty,(6) G. J. Luste,(8) P. M. Mantsch,(5) J. F. Martin,(8) S. McHugh,(1) S. R. Menary,(8) R. J. Morrison,(1) T. Nash,(5) P. Ong,(8) J. Pinfold,(2) G. Punkar,(1),(f) M. V. Purohit,(5),(c) J. R. Raab,(1),(d) A. F. S. Santoro,(3) J. S. Sidhu,(2),(g) K. Sliwa,(5) M. D. Sokoloff,(5),(e) M. H. G. Souza,(3) W. J. Spalding,(5) M. E. Streetman,(5) A. B. Stundžia,(8) and M. S. Witherell(1)

(The Tagged Photon Spectrometer Collaboration)

(1)*University of California at Santa Barbara, Santa Barbara, California 93106*
(2)*Carleton University, Ottawa, Ontario, Canada*
(3)*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
(4)*University of Colorado, Boulder, Colorado 80309*
(5)*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
(6)*National Research Council, Ottawa, Ontario, Canada*
(7)*Universidade de São Paulo, São Paulo, Brazil*
(8)*University of Toronto, Toronto, Ontario, Canada*
(9)*Yale University, New Haven, Connecticut 06520*

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The decay $D^+ \to K^- \pi^+ e^+ \nu_e$ has been studied in the Fermilab photoproduction experiment E691. The ratio of branching ratios, $B(D^+ \to \bar{K}^{*0} e^+ \nu_e)/B(D^+ \to K^- \pi^+ \pi^+)$, is found to be $0.49 \pm 0.04 \pm 0.05$, corresponding to a $D^+ \to \bar{K}^{*0} e^+ \nu_e$ branching ratio of $(4.5 \pm 0.7 \pm 0.5)\%$. The branching ratio to the nonresonant $(K^- \pi^+)_{\rm NR} e \nu_e$ final state is found to be less than 0.7% at the 90% confidence level. The $\bar{K}^{*0}$ mesons have a ratio of longitudinal to transverse polarization of $2.4^{+1.7}_{-0.9} \pm 0.2$.

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The heavy-quark decays which are least complicated by the strong interactions are semileptonic decays of the pseudoscalar mesons. With only two quarks in the final state there are not interfering diagrams or final-state interactions. Because of this simplicity, the semileptonic decays are used to evaluate the Kobayashi-Maskawa (KM) matrix elements which define the weak quark eigenstates. For the D^0 and D^+ the semileptonic final states $Ke\nu_e$ and $K^*e\nu_e$ are expected to dominate, while for B_d^0 and B^+, $De\nu_e$ and $D^*e\nu_e$ play the analogous role. In order to extract the KM matrix elements from experimental data the transition form factors must be computed from theory. This is easiest in the pseudoscalar final-state meson case, where only one form factor is needed. Consequently, the psuedoscalar modes will almost certainly be our main source of information on the KM matrix for heavy quarks, as they have been in the past for the light and strange quarks. The only independent test of the models[1] for the form-factor evaluation is in the more complicated vector final states. In this paper we present data for such a decay, $D^+ \to \bar{K}^{*0} e^+ \nu_e$ (and $D^- \to K^{*0} e^- \bar{\nu}_e$).

The observation of this state, in which the neutrino is unobserved, is possible in Fermilab photoproduction experiment E691 because we can require a well-isolated decay vertex of the proper topology. The high-precision silicon-microstrip detector, used for this purpose, and the E691 spectrometer have previously been described in detail.[2,3] The signal-to-background ratio is improved further by requiring well identified electrons. Electrons are identified by the pattern of energy deposition in the electromagnetic calorimeter. An electron probability is defined using (a) the ratio of shower energy to track momentum, (b) the transverse shower width, (c) the fraction of energy deposited in the downstream hadron calorimeter, and (d) the difference between the projected track position and that of the shower centroid. For this semileptonic study we use electrons with an electron probability corresponding to a typical efficiency for electrons and pions of 61% and 0.3%, respectively. A cleaner electron sample with electron and pion efficiencies of 44% and 0.13%, respectively, is also discussed. To suppress electrons from pair conversions from π^0 decays we eliminate electrons for which the other member of the pair is also seen in the spectrometer, and only electrons of energy greater than 12 GeV are used. Electrons consistent with beam pair conversions are not allowed.

Three-particle $K\pi e$ combinations are selected using only tracks which are well defined in the microstrip and drift-chamber systems. The pion is required to pass through at least the first magnet while the electron and kaon must pass through both magnets. The kaon, pion, and electron tracks must emanate from a decay vertex separated from the primary event vertex by 10 standard deviations plus an additional distance corresponding to 0.2-ps proper decay time. The χ^2 per degree of freedom of the decay vertex is required to be less than 3.5. The Čerenkov probability for both the kaon and pion must be greater than 0.4. Only neutral $K\pi$ combinations are used. Combinations in which the kaon and the electron have opposite (same) charges are labeled right- (wrong-) sign combinations.

Another vertex cut requires that the D^+ line of flight point back to the primary vertex. The maximum neutrino momentum, transverse to that of the $K\pi e$ momentum, is given by the energy of the neutrino in the D^+ frame, which is calculated from the $K\pi e$ mass. This defines the maximum displacement of the $K\pi e$ line of flight at the primary vertex due to the missing neutrino. The $K\pi e$ line of flight must point back to the primary to within this distance plus 2.5 times the resolution. Backgrounds are further reduced by requiring that all of the decay tracks pass closer to the decay vertex than to any other possible vertex. No other track is allowed to pass within 65 μm (typically 3.3 standard deviations) of the decay vertex. Seven events in which the electron could have been a misidentified pion from the dominant $D^+ \to K^-\pi^+\pi^+$ decay are removed, of which 3 ± 3 actually are due to $K^-\pi^+\pi^+$ decays. A number of $D^{*+} \to \pi^+ D^0$, $D^0 \to K^- e^+ \nu_e$ events in which the bachelor pion appears to come from the decay vertex due to the low Q value of the D^{*+} decay are also removed. The few events with $K\pi e$ masses greater than the D^+ mass or with decay times longer than 4 D^+ lifetimes are also eliminated.

The $K\pi e$ mass spectrum of the remaining 318 right-sign and 66 wrong-sign combinations is shown in Fig. 1. The shape of this spectrum, with the wrong-sign background subtracted, is in very good agreement with the shape predicted in a Monte Carlo simulation of the experiment, to be discussed below. The decay-time distribution of the signal is also in excellent agreement with the Monte Carlo simulation. The major sources of the background are conversion electrons and misidentified pions, both of which lead to charge-symmetric backgrounds. The first, which is the largest background, is manifestly charge symmetric; the charge symmetry of the second one has been checked using backgrounds for hadronic decay modes. The source of backgrounds which are not symmetric are misidentified D^+ decays. As discussed below, these contribute a small fraction of the total background and are subtracted from the signal. An additional check that wrong-sign events are a good measure of the background is obtained by studying the data with a variety of tighter cuts. For example, by requiring the tighter electron-identification probability, a kaon probability greater than 0.5, and a χ^2 per degree of freedom for the secondary vertex less than 1.75, a sample of 169 right-sign and 14 wrong-sign events is obtained. While the background has been reduced by a factor of 5, the signal is smaller by the ratio of efficiencies within the statistical errors.

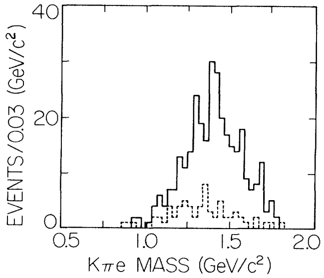

FIG. 1. Spectrum of $K^{\mp}\pi^{\pm}e^{\pm}$ masses for the standard cuts. The wrong-sign ($K^{\mp}\pi^{\pm}e^{\mp}$) distribution is superimposed (dashed line).

The $K\pi$ mass spectrum for the right- and wrong-sign events, using the standard cuts, is shown in Fig. 2(a). It is clear that the D^+ decays are dominated by the K^* resonance. The $K\pi$ mass spectrum for the case of the tight cuts is shown in Fig. 2(b).

We evaluate $B(D^+ \to K^-\pi^+e^+\nu_e)$ by comparing the number of events observed in this mode and in the mode $D^+ \to K^-\pi^+\pi^+$, and use the Mark III value[4] for $B(D^+ \to K^-\pi^+\pi^+)$. This requires knowledge of the ratio of our detection efficiencies for the two modes. The $D^+ \to \bar{K}^{*0} e^+ \nu_e$ Monte Carlo events were generated using the three transition form factors taken from Wirbel, Stech, and Bauer.[5] The nonresonant $D^+ \to K^-\pi^+e^+\nu_e$ event generation uses a phase-space mass distribution with the $K\pi$ system in an S-wave state. The Monte Carlo events are processed through the same reconstruction and analysis programs as the real data. Using electron

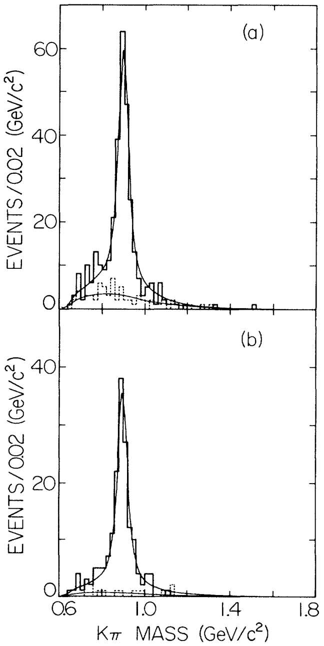

FIG. 2. The $K\pi$ mass spectrum with right-sign (solid) and wrong-sign (dashed) combinations: (a) loose cuts, (b) tight cuts. The curves are the fits described in the text.

pairs in the data, the electron detection efficiency has been measured as a function of the electron energy, the electron angle, and the total transverse energy in the electromagnetic calorimeter. The measured electron detection efficiencies have been incorporated into the Monte Carlo simulation.

On account of, primarily, the 12-GeV electron energy cutoff, the detection efficiency is sensitive to the electron energy spectrum. Including the effects of real radiation by electrons in target and detector material, and of the radiative correction to the electron energy spectrum,[6] the detection efficiencies for the cases of longitudinal and transverse $\bar{K}^{*0}$'s are [1.55 ± 0.06(stat)]% and [1.20 ± 0.05(stat)]%, respectively. Using the observed ratio of longitudinal to transverse rates of $2.4^{+1.7}_{-0.9} \pm 0.2$, to be described below, the effective detection efficiency is ($1.41 \pm 0.05 \pm 0.11$)%, where the systematic error includes the uncertainty in the electron efficiency (7%), the D^+ production model (2%), the amount of radiating material (2%), and the effect of the uncertainty in the longitudinal-to-transverse ratio (2%). The detection efficiency $\epsilon(M_{K\pi})$ has been evaluated for each set of cuts as a function of the $K\pi$ mass for the S-wave case. The efficiency for the case of the K^* is $C\epsilon(M_{K^*})$, where $C = 1.064$.

Shown in Figs. 2(a) and 2(b) are results of maximum-likelihood fits of the loose- and tight-cut data by the form

$$\epsilon(M_{K\pi})[(CN_{K^*})F_{\mathrm{BW}}(M_{K\pi}) + N_1 S(M_{K\pi})] ,$$

where N_{K^*} is the efficiency-corrected number of K^* events, N_1 is the efficiency-corrected number of nonresonant and background events, $F_{\mathrm{BW}}(M_{K\pi})$ is the Breit-Wigner distribution, and $S(M_{K\pi})$ is the S-wave mass distribution. The wrong-sign data are fitted by the S-wave form with N^{WS} the resulting efficiency-corrected number of wrong-sign events. The fits to the data are shown in Figs. 2(a) and 2(b), where it can be seen that the background is well fitted by the S-wave phase-space distribution. The number of observed K^*'s from the fit is 227 ± 20. The $D^+ \to (K^-\pi^+)_{\mathrm{NR}} e^+ \nu_e$ contribution is calculated by subtracting N^{WS} from N_1, with the resulting observed nonresonant contribution of 25 ± 18 events. The efficiency-corrected numbers are used in the evaluation of the branching ratios. The efficiency-corrected numbers of K^* and nonresonant events are the same with the tight cuts, within statistical errors.

The most serious non-charge-symmetric background is due to the decay $D^+ \to K^-\pi^+\pi^+\pi^0$ where one of the charged pions is misidentified as an electron and the π^0 is undetected. Using a Monte Carlo simulation of this decay, which uses experimentally determined misidentification probabilities, we find that, for the K^* and the nonresonant cases, corrections of 1 ± 1 event and 3 ± 3 events, respectively, are required. Smaller backgrounds are obtained for all of the remaining D^+ decay modes.

From our $D^+ \to K^-\pi^+\pi^+$ sample, using similar vertex and Čerenkov cuts, we find a ratio of branching ratio

$$\frac{B(D^+ \to \bar{K}^{*0} e^+ \nu_e)}{B(D^+ \to K^-\pi^+\pi^+)} = 0.49 \pm 0.04 \pm 0.05 ,$$

where the correction for the unobserved $\bar{K}^{*0} \to \bar{K}^0\pi^0$ decay is included. The systematic error includes the errors in the relative detection efficiency of the two modes (9%), uncertainties in the ratio of luminosities for the two modes (1.4%), and the effects of uncertain background and nonresonant spectrum shapes (2.5%). Using the Mark III value[4] ($9.1 \pm 1.3 \pm 0.4$)% for $B(D^+ \to K^-\pi^+\pi^+)$ we obtain

$$B(D^+ \to \bar{K}^{*0} e^+ \nu_e) = (4.5 \pm 0.7 \pm 0.5)\% .$$

Here the statistical and systematic errors from the two experiments have been combined separately in quadrature. The branching ratio to the nonresonant $K\pi$ state is found to be

$$B(D^+ \to (K^-\pi^+)_{\mathrm{NR}} e^+ \nu_e) = (0.3 \pm 0.2 \pm 0.2)\% ,$$

which is less than 0.7% at the 90% confidence level.

The polarization is determined from the angular distribution $W(\theta) = 1 + \alpha \cos^2\theta$, where θ is the angle of the K^* decay pion with respect to the D^+ direction in the K^* frame. The ratio of longitudinal to transverse polarization is $\Gamma_L/\Gamma_T = (1+\alpha)/2$, which has the value 0.5 for unpolarized decays. To define the kinematics, with the missing neutrino, the direction between the primary and decay vertices is chosen as the direction of the D^+ momentum. The D^+ momentum is then defined within a twofold ambiguity. Monte Carlo studies indicate that the solution with the lowest momentum for the D^+ is more often the correct one. This produces the $\cos\theta$ distribution shown in Fig. 3(a). Here only events in the $K\pi$ mass range $0.840 < M_{K\pi} < 0.960$ GeV/c^2 are used. This plot contains an estimated 9% background and 3% non-

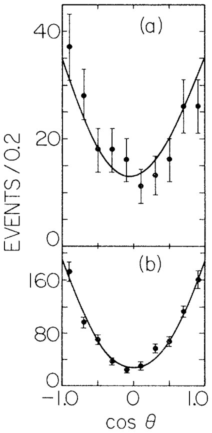

FIG. 3. The $\cos\theta$ distributions: (a) The $\cos\theta$ distribution of the data. The fit shown is for $\Gamma_L/\Gamma_T = 2.4$. (b) A Monte Carlo simulation for a 100% longitudinally polarized case (perfect $\cos\theta^2$ distribution). The effect of the experimental resolution and the quadratic ambiguity is to make a distribution which is well fitted by $1 + K\cos^2\theta$, where K is a constant.

resonant events. To see the effect of the experimental resolution and of the twofold ambiguity, the Monte Carlo simulation of a 100% longitudinal distribution is shown in Fig. 3(b). The result of the fit to the data, shown in Fig. 3(a), after correcting for the different detection efficiencies for the longitudinal and transverse components is

$$\Gamma_L/\Gamma_T = 2.4^{+1.7}_{-0.9} \pm 0.2 .$$

Using the value,[2] $\tau_{D^+} = 1.090 \pm 0.030 \pm 0.025$ ps, the $D^+ \to \bar{K}^{*0} e^+ \nu_e$ transition rate is

$$\Gamma(D^+ \to \bar{K}^{*0} e^+ \nu_e) = (4.1 \pm 0.7 \pm 0.5) \times 10^{10}\,\mathrm{s}^{-1} .$$

This rate is equal to the transition rate $\Gamma(D^0 \to K^{*-} e^+ \nu_e)$ by isospin invariance and can be compared with the transition rate for the pseudoscalar semileptonic decay,[7]

$$\Gamma(D^0 \to K^- e^+ \nu_e) = (9.0 \pm 1.1 \pm 1.2) \times 10^{10}\,\mathrm{s}^{-1} ,$$

which is in general agreement with predictions.[4,8] The ratio of transition rates can be expressed as

$$\frac{\Gamma(D^+ \to \bar{K}^{*0} e^+ \nu_e)}{\Gamma(D^0 \to K^- e^+ \nu_e)} = A \frac{B(D^+ \to K^- \pi^+ \pi^+)}{B(D^0 \to K^- \pi^+)} .$$

In this expression A is the combination of quantities measured in E691,

$$A = \frac{B(D^+ \to \bar{K}^{*0} e^+ \nu_e)}{B(D^+ \to K^- \pi^+ \pi^+)} \frac{B(D^0 \to K^- \pi^+)}{B(D^0 \to K^- e^+ \nu_e)} \frac{\tau_{D^0}}{\tau_{D^+}} ,$$

in which some of the systematic effects cancel. The value of A is $0.208 \pm 0.025 \pm 0.027$. Taking the ratio of hadronic branching ratios from Mark III[4] and separately combining in quadrature the statistical and systematic errors for the two experiments, we have

$$\frac{\Gamma(D^+ \to \bar{K}^{*0} e^+ \nu_e)}{\Gamma(D^0 \to K^- e^+ \nu_e)} = 0.45 \pm 0.09 \pm 0.07 ,$$

which is about half of the theoretically expected value.

The $D^+ \to \bar{K}^{*0} e^+ \nu_e$ results presented here and the $D^0 \to K^- e^+ \nu_e$ branching ratio from this experiment[7] are in rough agreement with preliminary results from Mark III.[9] The DELCO[10] determination of the fraction of semileptonic D decays containing a $K\pi$ is in good agreement with these results. The very small nonresonant branching ratio is less than that found by Mark III,[9] but is consistent with results of the Amsterdam-CERN-Cracow-Munich-Oxford-Rutherford (ACCMOR) Collaboration.[11] The very large ratio of longitudinal to transverse polarization appears to be consistent with the small $D^+ \to \bar{K}^{*0} e^+ \nu$ transition rate in a model by Bauer and Wirbel.[12]

It is interesting to compare the sum of the exclusive semileptonic decay rates with the measured inclusive decay rates. The branching ratio $D^+ \to e^+ X$ measured by Mark III[13] corresponds to a total semileptonic decay rate of $(15.6 \pm 1.8 \pm 0.7) \times 10^{10}\,\mathrm{s}^{-1}$. If we add the decay rates for $D^+ \to \bar{K}^{*0} e^+ \nu_e$ and $D^0 \to \bar{K}^0 e^+ \nu_e$, given above, the total is $(13.1 \pm 1.3 \pm 1.3) \times 10^{10}\,\mathrm{s}^{-1}$. Using the measured nonresonant branching ratio, multiplied by 1.5 for the unobserved $\bar{K}^0 \pi^0$, we calculate the nonresonant rate to be $(0.4 \pm 0.3 \pm 0.3) \times 10^{10}\,\mathrm{s}^{-1}$. We also add the expected rates for Cabibbo-suppressed decays, 8% of $K e \nu_e$ and 7% of $K^* e \nu_e$,[5] to get a total rate of $(14.5 \pm 1.3 \pm 1.3) \times 10^{10}\,\mathrm{s}^{-1}$, in agreement with the Mark III inclusive result.

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[a] Now at University of Mississippi, Oxford, MS 38677.

[b] Now at Electromagnetic Applications, Inc., Denver, CO 80226.

[c] Now at Princeton University, Princeton, NJ 08544.

[d] Now at CERN, Division EP, CH-1211 Genève, Switzerland.

[e] Now at University of Cincinnati, Cincinnati, OH 45221.

[f] Now at Stanford Linear Accelerator Center, Stanford, CA 94309.

[g] Deceased.

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