# Measurement of the Relative Branching Fraction $\Gamma(D^0 \to K\mu\nu)/\Gamma(D^0 \to \mu X)$

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The fraction $f$ of $D^0$ semimuonic decays which occur through the $K\mu\nu$ mode has been measured in a hybrid emulsion spectrometer. Analysis of 124 semimuonic $D^0$-decay candidates gives $f = 0.32 \pm 0.05(\text{stat}) \pm 0.05(\text{syst})$. From this measurement and existing data on the $D^0$ semileptonic branching ratio and lifetime, we obtain the branching ratio $R(D^0 \to K^-\mu^+\nu) = (2.4 \pm 0.4 \pm 0.5)\%$ and partial decay rate $\Gamma(D^0 \to K^-\mu^+\nu) = (5.6 \pm 0.9 \pm 1.2) \times 10^{10}\ \text{s}^{-1}$.

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Semileptonic decays of charm are interesting because they appear to be relatively straightforward to calculate.[1-6] The simplest such process is the pseudoscalar decay[7] $D \to Kl\nu$. Data on the partial rate for this decay have been used in some models[1,3,4] to fix parameters for calculating other rates such as that for $D \to K^*l\nu$, which is expected to be roughly equal to that for $K\mu\nu$. The $Kl\nu$ rate has recently been measured in two ways: (1) by comparing[8] the yield of $D^0 \to K^-e^+\nu$ to that of $D^0 \to K^-\pi^+$ for photoproduced $D^0$'s tagged by charged $D^*$'s, and (2) by measuring[9] the yield of $D^0 \to K^-e^+\nu$ in a sample of tagged charm pairs produced in $e^+e^-$ collisions. We present here the results of a complementary measurement of the fraction $f$ of all $D^0$ semimuonic decays which occur through the $K^-\mu^+\nu$ mode.

The data were taken in the first run of Fermilab Experiment E653, using a hybrid emulsion spectrometer described in detail elsewhere.[10,11] An 800-GeV/$c$ proton beam struck a nuclear-emulsion target 1.47 cm long, in which the primary vertex and at least one decay vertex were measured. The trigger, which was optimized for semimuonic decays of charm particles, required a beam particle to interact in the target and a muon candidate track to penetrate 5 m of steel; 5% of all interactions triggered the apparatus, and $5.4\times10^6$ events were recorded. Tracks were reconstructed in a silicon-microstrip vertex detector and momentum analyzed in a large-aperture magnetic spectrometer. Final muon identification by the off-line analysis required double momentum measurement: The candidate track had to be linked by tracking chambers through both the dipole spectrometer magnet and also an iron toroid which was part of the range steel. Initial event selection required the muon momentum to be greater than 8 GeV/$c$ and its transverse momentum to be greater than 0.2 GeV/$c$. In 56000 events the reconstructed muon track appeared to miss the primary vertex or to belong to a secondary vertex. For each of these events in the fiducial volume of the emulsion the primary vertex was located visually, and the muon track in the spectrometer was compared to the tracks in the emulsion in order to find a match. Most such events were rejected because the muon-tagged track was found to originate from the primary vertex (muonic decay of a pion or a kaon), or because the secondary vertex was an obvious interaction with dark nuclear-breakup tracks or apparent nonconservation of charge.

The sample for the $D^0$ semimuonic decay study consists of 121 two-prong and 3 four-prong decay candidates with all emulsion tracks matched and momentum analyzed. All were required to have one track identified as a muon, and to have an emulsion-measured decay length $>1$ mm. These candidates survived careful scrutiny at high magnification for very short nuclear-breakup tracks or other evidence of interactions. Because of the micron resolution and high grain density of the emulsion there is negligible chance of miscounting the number of prongs in the decays, or of failing to see the track of a charged parent. At least one track was required to have a transverse momentum $p_\perp$ relative to the charm direction of more than 0.25 GeV/$c$; this cut eliminated all decays of strange particles.

Acceptances, reconstruction efficiencies, and resolutions for the spectrometer were determined with a GEANT-based Monte Carlo (MC) program which simulated charge deposition in the silicon detectors and drift time and time over threshold in the drift chambers. Uncorrelated charm pairs were superimposed on proton-emulsion collisions generated by the FRITIOF program.[12] These simulated data were processed by the same routines used for real data, and thus provided a test of the analysis procedure as well as determination of efficiency. The charm pairs were generated with a distribution in Feynman $x_F$ and transverse momentum $p_T$ of $(1-|x_F|)^n\exp(-bp_T^2)$, with $n=8$ and $b=1.0$, consistent both with measured proton-proton charm production at 800 GeV and with preliminary measurements from this experiment.[13]

There are two categories of background in the two-prong sample: secondary vertices which are not charm decay (interactions of neutral hadrons), and charm decays which are not semimuonic (false muon identification). We have estimated the neutral-interaction background from the measured number of two-prong secondary vertices which are flagged as interactions by nuclear-breakup tracks, and which also contain an identified muon meeting the above criteria: $14\pm6$ events. This number must be multiplied by the known fraction[14] of low-multiplicity, high-energy interactions in emulsion which have no evidence of nuclear breakup [$(21\pm8)\%$], and by $\frac{1}{2}$ for the requirement of apparent charge conservation, giving $1.5\pm0.9$ interactions in the two-prong sample of 121 decays. The estimated interaction background in the four-prong sample is comparable to the number (3) of decay candidates, and we have taken the true number of four-prong events to be $1.5\pm1.5$.

The contamination from two-prong hadronic decays of charm followed by $K^\pm$ and $\pi^\pm$ decay to tagged muons was determined to be $(3\pm1)\%$ by using nonmuonic two-prong decays[15] of $D^0$ as input to the MC program. A second potential source of hadronic feedthrough, track mismatches between emulsion and spectrometer, was estimated to be $(3\pm3)\%$ from the number of decay candidates which have charge $\pm2$.

The fraction $f$ of semimuonic decays which are $K\mu\nu$ is determined from the shape of the distribution of the "minimum parent mass" $M_{\min}$:[16]

$$M_{\min}=(m_{\text{vis}}^2+p_\perp^2)^{1/2}+(m_{\text{neu}}^2+p_\perp^2)^{1/2},$$

where $m_{\text{vis}}$ is the invariant mass of the detected charged particles from the decay (with a kaon mass assigned to the hadron), $p_\perp$ is the measured transverse momentum of the detected particles relative to the charm direction, and $m_{\text{neu}}$ is the assumed mass of the missing neutral or neutrals, taken here to be zero. Most $K\mu\nu$ decays have $M_{\min}>1.6$ GeV, and the $M_{\min}$ distribution for $K\mu\nu$ has a prominent cusp at the $D^0$ mass. Decays with one or more neutral hadrons in addition to the neutrino give $M_{\min}$ distributions with a broad maximum at lower mass. In this experiment the resolution in $M_{\min}$ is limited mainly by the measurement of the charm direction in the emulsion with a typical error of $\pm1.0$ mrad. The E653 spectrometer had no particle identification to distinguish between charged pions and kaons above 5 GeV/$c$. Our analysis of both data and MC decays always calculates $M_{\min}$ with a kaon mass assigned to the charged hadron.[17]

It is important to demonstrate the charm origin of events at both low and high $M_{\min}$. Figure 1 presents comparisons of data and MC events (using our final value of $f$) for distributions of three quantities, each for

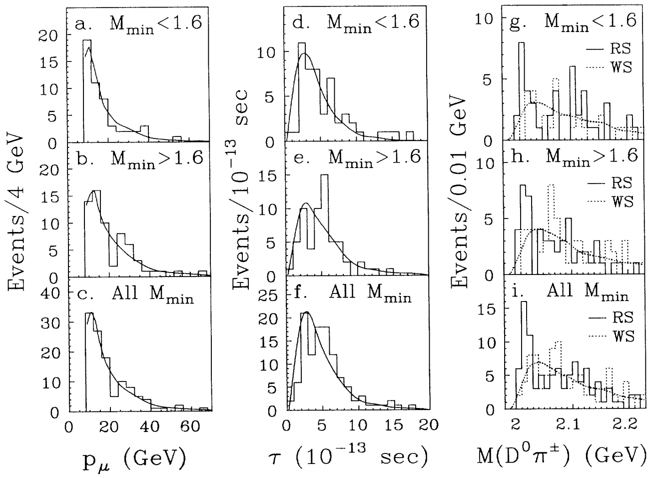

FIG. 1. Comparison of data (histograms) and Monte Carlo events (curves) for (a)-(c) muon momentum $p_\mu$, (d)-(f) proper decay time $\tau$, and (g)-(i) smallest invariant mass of $D^0\pi^\pm$ for right-sign (solid) and wrong-sign (dotted) pions. Each quantity is shown for three ranges of $M_{\rm min}$: $0.8 < M_{\rm min} < 1.6$, $1.6 < M_{\rm min} < 2.1$, and $0.8 < M_{\rm min} < 2.1$ GeV.

three ranges of $M_{\rm min}$. The distributions of muon momentum $p_\mu$ in Figs. 1(a)-1(c) agree very well with MC predictions. If the hadronic feedthrough had been seriously underestimated, one would expect an excess (not seen) of low-$p_\mu$ events because a larger fraction of slow hadrons decay. The distribution of proper decay time[18] $\tau$ in Figs. 1(d) and 1(e) have a 95% Kolmogorov probability of coming from the same parent distribution, supporting a common lifetime for events from both low and high $M_{\rm min}$. In addition, the average $\tau$ of the data in Fig. 1(f) is within 14% of the corresponding average of MC events generated with the accepted $D^0$ lifetime. Figures 1(g)-1(i) show the $D^0\pi^\pm$ invariant mass[18] for the right-sign (RS) and wrong-sign (WS) combinations[19] of lowest mass; the curves are the MC predictions for WS. After acceptance corrections, the $D^*$ fractions in these three $M_{\rm min}$ ranges are respectively $0.21 \pm 0.13$, $0.24 \pm 0.12$, and $0.23 \pm 0.09$, all consistent with the $(27 \pm 3)\%$ measured[20] in hadronic charm production.

The fraction $f$ is determined as follows: A maximum-likelihood fit to the experimental $M_{\rm min}$ distribution below 2.1 GeV finds the single parameter $f_{\rm raw}$, which is the $K\mu\nu$ fraction in the experimental two-prong distribution:

$$\ln\mathcal{L} = \sum_{\rm events} \ln\{0.97[f_{\rm raw}(I_{K\mu\nu} + 0.11 I_{\pi\mu\nu}) + (1 - 1.11 f_{\rm raw}) I_{K\mu\nu X}] + 0.03 I_{\rm had}\}\,,$$

where the $I_i(M_{\rm min})$ are MC $M_{\rm min}$ distributions[21] (normalized to unity) for $D^0 \to K\mu\nu$, for $D^0 \to \pi\mu\nu$ (fixed[9] at 11% of $K\mu\nu$), for $D^0 \to K\mu\nu X$, and for the 3% feedthrough of hadronic decays. Figure 2 shows the results of the best such fit. $f$ is then obtained from $f_{\rm raw}$ by correcting each contribution (including $1.5 \pm 1.5$ four-prong events) for experimental acceptance and efficiency.

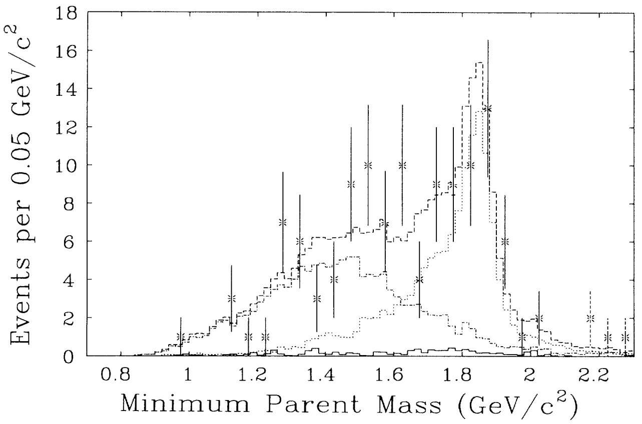

FIG. 2. Comparison of the experimental $M_{\rm min}$ distribution (error flags) with fitted Monte Carlo $M_{\rm min}$ distributions (histograms) from total contribution (dashed); $K\mu\nu$ plus $\pi\mu\nu$ contribution (dotted); $K\mu\nu X^0$ contribution (dot-dashed); hadronic decay feedthrough (solid). Events above 2.1 GeV were not used in the fits.

The values of $f$ from the fits are not very sensitive to the choice of decay modes which comprise $I_{K\mu\nu X}$. We have tried mixtures of the two-neutral mode $K^{*-}\mu^+\nu$ and the multineutral modes $K^{*-}\pi^0\mu^+\nu$, $\rho^-K^0\mu^+\nu$, and $\eta^0K^-\mu^+\nu$. The maximum contribution of the multineutral modes is constrained by the observed number of four-prong candidates. For example, every assumed two-prong decay $D^0 \to \eta^0K^-\mu^+\nu$ with $\eta \to \gamma\gamma$ or $3\pi^0$ implies[15] 0.41 four-prong decay with $\eta \to \pi^+\pi^-\pi^0$ or $\pi^+\pi^-\gamma$. We have not allowed multineutral mixtures which would contribute more than three observed four-prong events. This restricts the sum of the multineutral branching ratios to be comparable to or less than that for $K^{*-}\mu^+\nu$.

The fits from all allowed mixtures for $I_{K\mu\nu X}$ have confidence levels (C.L.) of (13-58)%. The values of $f$ from these fits range from $0.29 \pm 0.04$(stat) for the maximal $\rho^-K^0\mu^+\nu$ content to $0.35 \pm 0.05$ for the maximal $\eta^0K^-\mu^+\nu$ content. These extremes both have C.L. $\approx 25\%$. If $I_{K\mu\nu X}$ contains only $K^{*-}\mu^+\nu$, $f = 0.32 \pm 0.05$, with a C.L. of 44%. Our final value of $f$ is determined by taking the average of the highest and lowest values of $f$ among the allowed fits. We find

$$f = 0.32 \pm 0.05({\rm stat}) \pm 0.05({\rm syst})\,.$$

The systematic error includes contributions (combined in quadrature) from uncertainties in multineutral composition ($\pm 0.030$), in $M_{\rm min}$ resolution ($\pm 0.016$), in the number of real four-prong events ($\pm 0.016$), in MC statistics and parametrization ($\pm 0.016$), in the treatment of backgrounds ($\pm 0.010$), in the fraction of $\pi\mu\nu$ ($\pm 0.016$), and in the $x_F$ and $p_T$ dependence ($\pm 0.006$). $f$ is quite insensitive to assumed production parameters; e.g., changing $n$ by $\pm 3$ changes $f$ by $\pm 2\%$ of itself. $f$ is stable within 1 statistical standard deviation for cuts on decay length out to 4 mm (which remove up to half the data sample), and stable to 0.67 statistical standard deviation for cuts on the lowest allowed $M_{\rm min}$ from 0.8 to 1.3 GeV.

An independent analysis[22] of the same data was conducted using the distribution in transverse momentum of the muon from $D^0$ decay. The value of $f$ obtained is in good agreement with that from the $M_{\rm min}$ analysis.

The branching ratio and partial decay rate for $D^0 \to K\mu\nu$ have been calculated by combining our value for $f$ with the world-average values[15] for semileptonic branching ratio, $R_e = R(D^0 \to e^+X) = (7.7 \pm 1.2)\%$, and for the $D^0$ lifetime, $(4.21 \pm 0.10)\times 10^{-13}$ s; we take[23] $R_\mu = R(D^0 \to \mu^+X) = 0.96R_e$. Then $R(D^0 \to K\mu\nu) = (2.4 \pm 0.4 \pm 0.5)\%$, and

$$\Gamma(D^0 \to K^-\mu^+\nu) = (5.6 \pm 0.9 \pm 1.2)\times 10^{10}\,{\rm s}^{-1}.$$

This rate is smaller than previously measured values[8,9] of $(8.9 \pm 1.2 \pm 1.4)\times 10^{10}$ and $(7.9 \pm 1.2 \pm 0.9)\times 10^{10}\,{\rm s}^{-1}$.

The rate for $D^+ \to K^{*0}e^+\nu$ has been measured[24] to be $(4.1 \pm 0.7 \pm 0.5)\times 10^{10}\,{\rm s}^{-1}$, or $(23 \pm 5)\%$ of the $D^+$ semielectronic rate.[15] Our $K\mu\nu$ result suggests that the difference between the $D^0 \to Kl\nu$ and $D^+ \to K^*l\nu$ rates may not be as significant as previous results have indicated. However, if ≈(30–40)% of $Kl\nu$ and ≈25% of $K^*l\nu$ are both correct, then a comparable fraction of the $D$ semileptonic rate must be into as yet unidentified multineutral modes.

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[17] If this hadron is really a pion (as occurs, for example, in $D^0 \to \pi^-\mu^+\nu$ or in $D^0 \to K^{*-}\mu^+\nu$, with $K^{*-} \to \pi^-K^0$), the $M_{\rm min}$ distribution is shifted upward and has a tail extending above the $D^0$ mass.

[18] For the $\tau$ and $M(D^0\pi^\pm)$ plots the laboratory $D^0$ momentum was estimated from $p_D = M_{D^0}E_{\rm vis}/(p_\perp^2 + m_{\rm vis}^2)^{1/2}$, which is appropriate for any decay mode.

[19] A $D^0\pi^\pm$ combination is called RS (WS) if the $\pi^\pm$ has charge equal (opposite) to that of the muon. We obtain the $D^*$ signal by subtracting WS from RS events in the mass interval 2.00–2.03 GeV and correcting for a $\pi^\pm$ acceptance of 0.70.

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