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Measurement of the ratio of branching fractions $B(D^0 \to \pi^- e^+ \nu_e)/B(D^0 \to K^- e^+ \nu_e)$

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Using 3.0 fb^{-1} of data collected with the CLEO-II detector, we study the Cabibbo-suppressed decay $D^0 \to \pi^- e^+ \nu_e$. The ratio of the branching fractions $B(D^0 \to \pi^- e^+ \nu_e)/B(D^0 \to K^- e^+ \nu_e)$ is measured to be $(10.3 \pm 3.9 \pm 1.3)\%$, corresponding to an upper limit of 15.6% at the 90% confidence level.

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Semileptonic decays of D mesons provide important information about the structure of hadrons containing a heavy quark. The differential decay rate for $D \to \pi\ell\nu$ is

$$\frac{d\Gamma}{dq^2} = \frac{G^2}{24\pi^3} |V_{cd}|^2 P_\pi^3 \left[f_+^\pi(q^2)\right]^2, \tag{1}$$

where $q^2 = m^2(\ell\nu)$ and P_π is the momentum of the pion in the D rest frame. The wave functions of the initial and final state mesons determine the single vector form factor $f_+^\pi(q^2)$. Measuring the branching fraction $B(D^0 \to \pi^-\ell^+\nu)$ determines the normalization of the form factor $f^\pi(0)$, which can be compared with predictions from lattice gauge techniques, quark models, and quark sum rules. This knowledge also improves our understanding of the similar form factor in the decay $B \to \pi\ell\nu$.

The variable q^2 is directly related to the energy of the pion in the D frame; $q^2_{\rm min} \approx 0$ corresponds to maximum energy for the pion, and the form factor is conventionally normalized at this value. There are experimental and theoretical advantages in measuring the ratio of the form factor for $D^0 \to \pi^-\ell^+\nu$ to the well-measured form factor for $D^0 \to K^-\ell^+\nu$. The ratio of the branching fractions $R_0 = \frac{B(D^0\to\pi^-\ell^+\nu)}{B(D^0\to K^-\ell^+\nu)}$ can be expressed as

$$R_0 = C_{\pi K}\frac{|V_{cd}f_+^\pi(0)|^2}{|V_{cs}f_+^K(0)|^2}, \tag{2}$$

where the factor $C_{\pi K}$ is given by the expression

$$C_{\pi K} = \frac{\int P_\pi^3 \left|\frac{f_+^\pi(q^2)}{f_+^\pi(0)}\right|^2 dq^2}{\int P_K^3 \left|\frac{f_+^K(q^2)}{f_+^K(0)}\right|^2 dq^2}. \tag{3}$$

The ratio $|V_{cd}/V_{cs}|$ is determined well from unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, so the measurement of $B(D^0 \to \pi^-\ell^+\nu)/B(D^0 \to K^-\ell^+\nu)$ determines the ratio of the form factors $f_+^\pi(0)/f_+^K(0)$.

The Mark III Collaboration established the existence of the decay $D^0 \to \pi^-\ell^+\nu$ when they observed 7 events. This observation yields $B(D^0 \to \pi^-\ell^+\nu) = (0.39^{+0.23}_{-0.11} \pm 0.04)\%$, corresponding to $R_0 = (11.5^{+7.3}_{-3.7} \pm 1.8)\%$ [1]. CLEO II observed about 30 events of $D^{*+} \to \pi^0 D^+$, $D^+ \to \pi^0\ell^+\nu$, corresponding to $B(D^+ \to \pi^0\ell^+\nu)/B(D^+ \to \overline{K}^0\ell^+\nu) = (8.5 \pm 2.7 \pm 1.4)\%$ [2]. Since isospin invariance requires $\Gamma(D^+ \to \pi^0\ell^+\nu)/\Gamma(D^0 \to \pi^-\ell^+\nu) = 1/2$, this result implies $R_0 = (17.0 \pm 5.4 \pm 2.8)\%$. The theoretical calculations for R_0 are in the range 5–10 % [3–7]. In this paper we report a measurement of the ratio of the branching fractions $B(D^0 \to \pi^-e^+\nu_e)/B(D^0 \to K^-e^+\nu_e)$.

This analysis is closely related to that used to study $D^0 \to K^-\ell^+\nu$ [8]. To reduce backgrounds, we use the decay $D^{*+} \to \pi_s^+ D^0$ to tag D^0 mesons, where π_s refers to the "slow" pion, which has a momentum of only 40 MeV/c in the D^{*+} rest frame. (The charge conjugate mode is implicitly included throughout the paper.) The process $D^{*+} \to D^0\pi^+$, $D^0 \to \pi^-e^+\nu_e$ gives a small average value of $\delta m = m(\pi_f e \pi_s) - m(\pi_f e)$, where π_f is the "fast" pion from the D^0 decay. In addition, the distribution in δm is reasonably narrow, which helps in suppressing backgrounds. The signal is extracted by fitting the two-dimensional distribution of the variables δm and $m(\pi_f e)$, which is shown in Fig. 1 for a Monte Carlo sample of $D^0 \to \pi^-e^+\nu_e$ decays. We also show Monte Carlo events for the largest background source, $D^0 \to K^-e^+\nu_e$ decays in which the kaon is misidentified as a pion. The distributions are very similar, except that the misidentified $D^0 \to K^-e^+\nu_e$ decay distribution is offset to lower $m(\pi_f e)$ by about 100 MeV. The band of $D^0 \to \pi^-e^+\nu_e$ events lying outside the kinematically allowed region for $D^0 \to K^-e^+\nu_e$ makes it possible to separate the two components. To reduce the kaon contamination, we use information on the energy loss (dE/dx) and the time-of-flight (TOF) of the fast pion.

The analysis uses a sample of 3×10^6 $e^+e^- \to c\,\bar{c}$ events collected with the CLEO-II detector [9] at the Cornell Electron Storage Ring (CESR). The integrated luminosity is 2.1 fb^{-1} at the $\Upsilon(4S)$ energy and 0.9 fb^{-1} in the continuum just below the resonance. We first select events containing a possible $\pi_f^- e^+ \pi_s^+$ combination, including requirements for good tracks and for a clean electron. The spherical $B\overline{B}$ events are suppressed by requiring that the ratio of Fox-Wolfram moments [10], $H_2/H_0 > 0.2$; the combinatoric backgrounds are reduced by demanding that the momentum $P_{\pi_f e} > 1.8$ GeV/c. We also impose an upper limit on the tranverse momentum of the $e\nu$ combination relative to the thrust axis to reduce background combinations.

Only electrons from kinematic regions in which the efficiency is well known are used in the analysis. This leads to the requirements $P_e > 0.7$ GeV/c and $|\cos\theta| < 0.81$, where θ is the angle of the electron momentum relative to

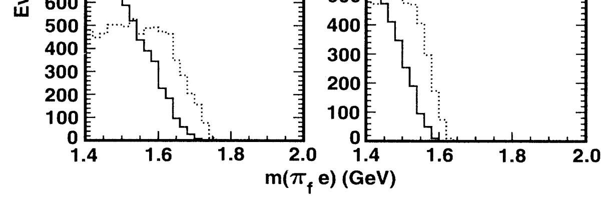

FIG. 1. Distribution in δm vs $m(\pi_f e)$ for Monte Carlo (MC) samples of $\pi e\nu$ and $Ke\nu$. The four plots of $m(\pi_f e)$ correspond to regions of δm: (a) 0.140–0.144 GeV, (b) 0.144–0.148 GeV, (c) 0.148–0.152 GeV, and (d) 0.152–0.156 GeV. The solid line is for $\pi e\nu$ MC events and the dashed line is for $Ke\nu$ MC events. The relative normalizations are chosen such that they have about the same number of events at low values of δm and $m(\pi_f e)$.

the beam line. We do not use muons because the probability of a hadron faking a muon is significantly higher than the probability of it faking an electron.

Since $D^0 \to K^- e^+ \nu_e$ is the major background, kaon and pion separation is of special importance in this analysis. Because we need to model the TOF and dE/dx distributions very accurately, we use data, rather than Monte Carlo events, to determine cuts and measure efficiencies. In particular, $D^0 \to K^- \pi^+$ events provide a clean sample of identified kaons and pions in a kinematic region very similar to that needed for the semileptonic decay.

The variable used to select pions by time of flight is $\delta(t) \equiv (t - t_\pi)/\sigma(t)$, where t is the measured TOF, t_π is the mean TOF for a pion, and $\sigma(t)$ is the resolution in the TOF. Thus, the $\delta(t)$ distribution should be centered at zero with a standard deviation of one. Figure 2(a) shows this distribution for pions and kaons for the momentum region 0.5–1.2 GeV/c, where there is substantial separation. We require $\delta(t) < 1.0$ for $p =$ 0.5–1.2 GeV/c, and $\delta(t) < 0.5$ for $p =$ 1.2–1.5 GeV/c, where the separation is somewhat less, but is still useful.

The corresponding variable containing dE/dx information from the drift chamber is $\delta(dE/dx) \equiv (dE/dx - dE/dx_\pi)/\sigma(dE/dx)$. Figure 2(b) shows the $\delta(dE/dx)$ distribution for pions and kaons in the momentum region $p > 1.5$ GeV/c. We require $\delta(dE/dx) > -1.0$ for $p > 1.5$ GeV/c, and $\delta(dE/dx) > -0.5$ for $p =$ 1.2–1.5 GeV/c, where the separation is somewhat less. In Table I we list the efficiencies for the combination of TOF and dE/dx cuts, with errors, for six momentum bins.

Besides the background from $D^0 \to K^- e^+ \nu_e$, the other significant background comes from random combinations of pions and electrons. We parametrize the shape for this combinatoric background using a wrong-sign sample consisting of $\pi_f^- e^+ \pi_s^-$, $\pi_f^+ e^+ \pi_s^-$, and $\pi_f^+ e^+ \pi_s^+$ combinations, plus charge conjugates. A detailed study of the major components of the backgrounds in the $D^0 \to K^- e^+ \nu_e$ analysis [8] showed that this wrong-sign sample gives a good representation of the smooth shape in the two-dimensional space. The wrong-sign sample is not used to normalize the background, however. It is important to understand whether there are any significant backgrounds from D^0 decays other than $K^- e^+ \nu_e$ that would peak in the kinematic region of the signal but would not show up in the wrong-sign data. Contamination from $D^0 \to K^- \pi^+$ would lie in the critical region of the two-dimensional plot just above the upper limit for $D^0 \to K^- e^+ \nu_e$ decays. Because the $D^0 \to K^- \pi^+$ events form a narrow peak in the two-dimensional $\delta m - m(\pi_f e)$ space, we fit for this component explicitly in the data, and find 0 ± 3 events. For three-body hadronic decays of the D^0 in which one particle is missed and another particle is misidentified as an electron, the invariant mass $m(\pi_f e)$ is low enough that very few events feed into the mass region used in this analysis. We also studied the level of contamination from semileptonic decays such as $D \to K^* e \nu$ and $D \to \eta e \nu$ and found it to be negligible. There are only 10 events from the process $D^0 \to K^{*-} e^+ \nu_e$ in the final sample, and none of these are in the important band at high $m(\pi_f e)$ in which the $D^0 \to \pi^- e^+ \nu_e$ signal is measured.

TABLE I. The efficiency of the hadron identification cuts for pions and kaons in six momentum bins. The column labeled "fraction" gives the fraction of accepted $\pi e \nu$ events that lie in each bin. The averages reported in the table are weighted with this fraction.

Momentum (GeV/c)	ε_π	ε_K	Fraction
0.5–0.7	0.683±0.026	0.080±0.009	0.06
0.7–1.0	0.556±0.019	0.048±0.006	0.15
1.0–1.2	0.583±0.024	0.135±0.012	0.12
1.2–1.5	0.480±0.018	0.177±0.011	0.13
1.5–2.0	0.610±0.016	0.250±0.010	0.27
2.0–···	0.607±0.011	0.145±0.005	0.27
Ave.	0.595 ±0.016	0.176±0.008	

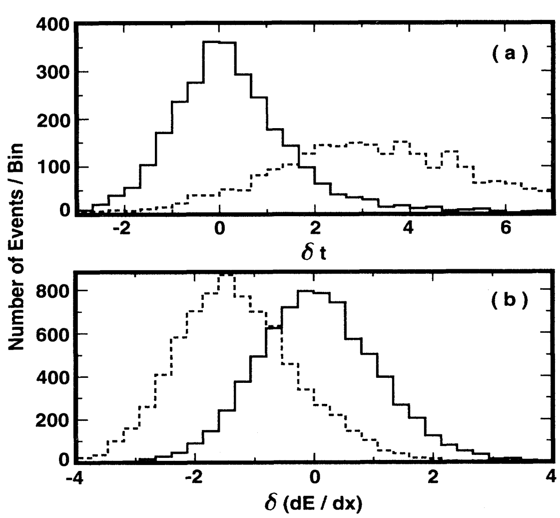

FIG. 2. The distributions of (a) δt for pions and kaon with momentum between 0.5 and 1.2 GeV/c and (b) $\delta(dE/dx)$ for pions and kaons with momentum above 1.5 GeV/c. The variables are defined in the text. In each plot, the pion distribution is the solid histogram, the kaon distribution is the dotted.

To extract the size of the $D^0 \to \pi^- e^+ \nu_e$ signal, we fit the two-dimensional distribution in $[\delta m, m(\pi_f e)]$ with three components:

$$n[\delta m, m(\pi_f e)] = N_\pi f_\pi + N_K f_K + N_{\rm bg} f_{\rm bg}. \qquad (4)$$

The N_i represent the number of events in each component, and the values are varied in the fit; the f_i are fixed shapes for each component. The three components are $D^0 \to \pi^- e^+ \nu_e, D^0 \to K^- e^+ \nu_e$, and combinatoric background. The shapes for the two semileptonic decays are taken from Monte Carlo samples weighted by the measured particle identification efficiency. The shape of the combinatoric background is parametrized using the wrong-sign sample. The binned likelihood fit yields $N_\pi = 87 \pm 33$, $N_K = 227 \pm 36$, and $N_{\rm bg} = 259 \pm 20$. The χ^2 of the fit is 305 for 297 degrees of freedom, corresponding to a confidence level of 70%. We have checked the

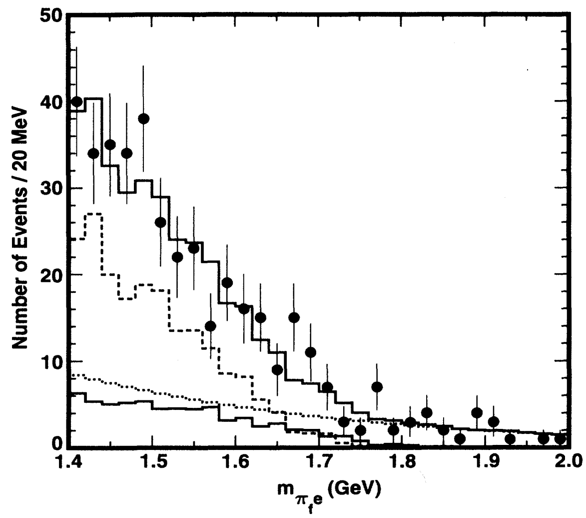

FIG. 3. The result of the two-dimensional fit projected on the $m(\pi_f e)$ axis for events with $\delta m < 0.16$. The data are shown with error bars, the fit in the upper solid histogram. The components of the fit are also shown: $D^0 \to \pi^- e^+ \nu_e$ (solid), $D^0 \to K^- e^+ \nu_e$ (dashed), and other background (dotted).

quality of the fit by comparing its likelihood with that of a set of test samples, and get a comparable confidence level. The amount of $\pi e \nu$ signal is determined mostly by the excess of events above background in the critical region near the maximum allowed value of $m(\pi_f e)$ for a given δm, as shown in Fig. 1. In this band, which is about 100 MeV wide, there are about 20 $\pi^- e + \nu_e$ events, 26 $K^- e^+ \nu_e$ events, and 20 background events. Figure 3 shows the result of the two-dimensional fit projected on the $m(\pi_f e)$ axis for events with $\delta m < 0.16$. About 100 of the background events have $\delta m < 0.16$ and are therefore included in this plot. Such a plot does not display all of the information used by the fit to separate the components, but it gives some idea of the quality of the fit.

We use the yield for $D^0 \to K^- e^+ \nu_e$ from Ref. [8] to normalize the branching ratio, correcting for the ratio of luminosities. The yield for $D^0 \to K^- e^+ \nu_e$ from the present analysis is less precisely measured, since the particle identification cuts are designed to suppress it. The ratio of branching ratios is therefore

$$R_0 = \frac{N_\pi/\epsilon_\pi}{N_K/\epsilon_K} = \frac{(4484 \pm 1700)}{(43505 \pm 1045)} = (10.3 \pm 3.9)\%. \quad (5)$$

By normalizing to this mode we minimize our systematic errors, since the tracking and electron identification efficiencies almost cancel. Only the errors on the kaon and pion identification are effectively uncorrelated, and they are 4.5% and 2.7%, respectively. The systematic errors on the fit include the statistical error on the Monte Carlo samples used for the shape of the semileptonic components (7.5%), the uncertainty in the background function (5%), the uncertainty in the q^2 dependence of the form factor for the signal (6%), and the uncertainty in the $D^0 \to K^- \pi^+$ component (5%). We estimate the error due to the uncertainty in the number of lepton fakes to be less than 1%. Combining these errors in quadrature we assign a total systematic error of $\pm 13\%$. The final result is

TABLE II. Theoretical predictions for R_0.

Technique	Group	R_0 (%)
Quark models	Wirbel *et al.* [3]	8.8
	Isgur *et al.* [4]	5.3
QCD sum rules	Dominguez and Paver [5]	9.3
	Narison [6]	8.3
Lattice QCD	Lubicz *et al.* [7]	8.6

$$R_0 = (10.3 \pm 3.9 \pm 1.3)\%. \quad (6)$$

To evaluate the ratio $C_{\pi K}$ defined in Eq. (3), we assume that each form factor factor has a pole shape, $f_+(q^2) = f_+(0)/(1 - q^2/m_V^2)$, where m_V, the mass of the vector pole, is taken as the mass of the $D^{*+}(D_s^{*+})$ for the $\pi e \nu (K e \nu)$ decay. Using the result $C_{\pi K} = 1.97$ from this calculation and the measured value of R_0, we get $\left|\frac{V_{cd}}{V_{cs}}\right|^2 \left|\frac{f_+^\pi(0)}{f_+^K(0)}\right|^2 = 0.052 \pm 0.020 \pm 0.007$. Unitarity constraints on the CKM matrix yield a value of 0.051 ± 0.001 for $\left|\frac{V_{cd}}{V_{cs}}\right|^2$ [11]; using this value we obtain $\left|\frac{f_+^\pi(0)}{f_+^K(0)}\right| = 1.01 \pm 0.20 \pm 0.07$.

In conclusion, we have measured the branching ratio of the Cabibbo-suppressed decay $D^0 \to \pi^- e^+ \nu_e$ relative to the Cabibbo-favored decay $D^0 \to K^- e^+ \nu_e$ to be $(10.3 \pm 3.9 \pm 1.3)\%$, corresponding to an upper limit of 15.6% at the 90% confidence level. This result agrees well with the theoretical predictions listed in Table II. It also agrees with the Mark III measurement, but has a somewhat smaller error. It has a lower central value than that implied by the CLEO $D^{*+} \to \pi^0 D^+$, $D^+ \to \pi^0 \ell^+ \nu_e$ measurement, but is consistent at the 1σ level. We calculate the world average of all three measurements to be $(12.1 \pm 2.9)\%$.

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