Measurement of the Branching Fractions for $D^0 \to \pi^- e^+ \nu_e$ and $D^0 \to K^- e^+ \nu_e$ and Determination of $|V_{cd}/V_{cs}|^2$

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(Received 30 December 1988)

Measurements of the exclusive branching fractions $B(D^0 \to \pi^- e^+ \nu_e)$ and $B(D^0 \to K^- e^+ \nu_e)$, using data collected at the $\psi(3770)$ with the Mark III detector at the SLAC e^+e^- storage ring SPEAR, are used to determine the ratio of Kobayashi-Maskawa matrix elements $|V_{cd}/V_{cs}|^2 = 0.057^{+0.038}_{-0.015} \pm 0.005$.

PACS numbers: 13.20.Fc, 12.15.Ff, 14.40.Jz

Present knowledge of the Kobayashi-Maskawa (KM) matrix element V_{cd} has been derived from a measurement of neutrino-induced charm production.[1] This determination, however, depends on the production cross sections for D^0, D^+, and to a lesser degree, other charmed particles. It also depends on the semimuonic branching ratio and fragmentation function of each particle type. While determinations of $|V_{cd}|$ using hadronic decays of D mesons are free from uncertainties in the production mechanism, they suffer from the effects of interference and final-state interactions.[2] In contrast, semileptonic decays are free of these complications. We report herein measurements of the branching fractions $B(D^0 \to \pi^- e^+ \nu_e)$ and $B(D^0 \to K^- e^+ \nu_e)$ and use their ratio to determine $|V_{cd}/V_{cs}|^2$.[3]

The data were collected with the Mark III detector[4] at the SLAC e^+e^- storage ring SPEAR near the peak of the $\psi(3770)$, which decays predominantly to $D\bar{D}$. The data contain about 27700 produced $D^0\bar{D}^0$ events.[5] Candidate events are selected by first reconstructing a $\bar{D}^0$, called a tag, in the following modes: $K^+\pi^-$, $K^+\pi^-\pi^+\pi^-$, $K_S^0\pi^+\pi^-$, and $K^+\pi^-\pi^0$. The absolute branching fractions $B(D^0 \to \pi^- e^+ \nu_e)$ and $B(D^0 \to K^- e^+ \nu_e)$ are then measured by reconstructing these decay modes in the system recoiling from the tagged $\bar{D}^0$.[6]

Tagged events are selected by using the beam-constrained mass, $(E_{\text{beam}}^2 - p_{\bar{D}^0}^2)^{1/2}$, where $p_{\bar{D}^0}$ is the measured $\bar{D}^0$ momentum. All events with a beam-constrained mass greater than 1.8 GeV/c^2 are retained. A signal region is defined from 1.854 to 1.874 GeV/c^2; events in a sideband from 1.830 to 1.850 GeV/c^2 are used to evaluate the background under the peak. 80% of events in the signal region have a unique tag; the remainder contain an average of 2.5 tags per event. Multiple tags are most often found in the $K^+\pi^-\pi^0$ mode; they arise from the use of photon candidates whose source is hadronic showers or charged-kaon decays. To determine the total number of events with at least one tag, we plot in Fig. 1(a) the beam-constrained mass of the tag from the mode having the least background per event, starting with the lowest-multiplicity decay, $K^+\pi^-$, and continuing through $K^+\pi^-\pi^+\pi^-$, $K_S^0\pi^+\pi^-$, and $K^+\pi^-\pi^0$. Multiple $K^+\pi^-\pi^+\pi^-$ or $K_S^0\pi^+\pi^-$ tags are resolved by selecting the tag whose lowest-momentum track has the largest momentum. The preferred $K^+\pi^-\pi^0$ tag is selected by means of a constrained fit of the photons to the π^0 mass. Figure 1(a), which shows the results of this procedure, contains a single entry per event. There are $3636 \pm 54 \pm 195$ events (N_{tag}) above background.

A $D^0 \to \pi^- e^+ \nu_e$ or $D^0 \to K^- e^+ \nu_e$ decay candidate recoiling against a tag is required to contain two oppositely charged tracks, one of which is identified as an electron. The sign of the charge of the lepton must be opposite the charm of the tag.[7] Electrons are identified

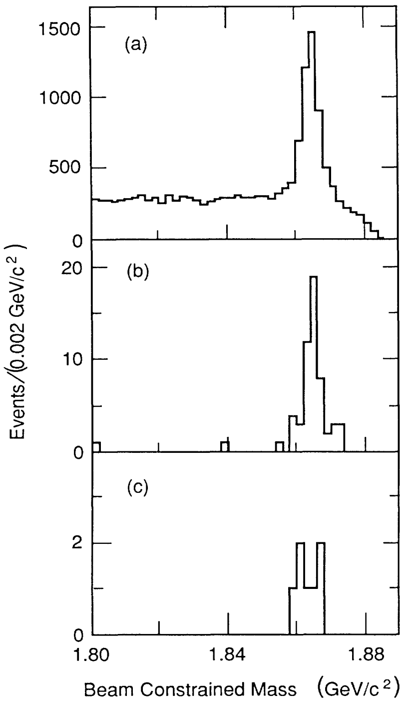

FIG. 1. (a) Beam-constrained mass of $\bar{D}^0$ hadronic tags. (b) Beam-constrained mass of $\bar{D}^0$ hadronic tags for $K^-e^+\nu_e$ events. (c) Beam-constrained mass of $\bar{D}^0$ hadronic tags for $\pi^-e^+\nu_e$ events.

using information from the time-of-flight (TOF) counters and the barrel electromagnetic calorimeter. For momenta below 0.3 GeV/c, TOF alone is used. Above 0.4 GeV/c, an algorithm using shower energy and shower shape[8] is used to distinguish electrons from pions. Between 0.3 and 0.4 GeV/c, electrons identified by either technique are accepted. Electron candidates with a kaon TOF identification are rejected. In this analysis, 75% of electrons are correctly identified; 7% of muons and 5% of pions are misidentified as electrons.

Two independent methods are used to identify the recoiling hadron. The kinematics of a fully reconstructed semileptonic decay permit the identification of the hadron as either a pion or kaon. The quantity $U \equiv E_{\text{missing}} - |\mathbf{P}_{\text{missing}}|$, calculated for both the pion and kaon hypotheses, is expected to be zero for the correct choice since a single massless particle is undetected. For events with multiple tags, U is calculated separately for each. Monte Carlo studies indicate that the choice of the correct assignment has the minimum $|U|$. The hypothesis with the smallest value of $|U|$ is accepted, and then only if the kinematic identification agrees with the TOF identification.[9] For the $K^-e^+\nu_e$ analysis, we also accept kinematically identified kaons even when no TOF information is present. These may be tracks which do not enter the TOF system, tracks which have decayed before reaching the TOF counters, or tracks which enter a counter close to the position of another track. For the $\pi^-e^+\nu_e$ analysis, we require that the pion be identified *both* kinematically and by TOF.

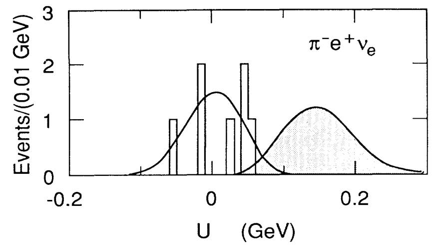

FIG. 2. Distribution of U ($D^0 \rightarrow \pi^-e^+\nu_e$ hypothesis) calculated for $D^0 \rightarrow \pi^-e^+\nu_e$ candidates (histogram), for reconstructed Monte Carlo $D^0 \rightarrow \pi^-e^+\nu_e$ decays (solid curve), and for the principle background, $D^0 \rightarrow K^-e^+\nu_e$ decays interpreted as $D^0 \rightarrow \pi^-e^+\nu_e$ (shaded). The curves are not normalized to the data.

Next, backgrounds from hadronic and other semileptonic decays of the recoil D^0 must be suppressed. The decay $D^0 \rightarrow K^-\pi^+$ is removed by requiring that the invariant mass calculated by interpreting the hadron and electron as a kaon and pion be less than 1.7 GeV/c^2. Less than 5% of $K^-e^+\nu_e$ events fail to meet this requirement. Recoiling decays with neutral pions (e.g., $D^0 \rightarrow K^-\pi^0 l^+\nu_l$) are suppressed by rejecting events with photons other than those used in the hadronic tag. A visual scan is performed to prevent the elimination of events with showers caused by hadronic interactions or hadronic decays: Six additional $K^-e^+\nu_e$ events containing hadronic showers classified as photons are recovered.[10] No additional $\pi^-e^+\nu_e$ events are recovered by the scan.

Seven $\pi^-e^+\nu_e$ candidates[11] and 56 $K^-e^+\nu_e$ candidates are retained, and their U distributions are shown in Figs. 2 and 3, respectively. Monte Carlo simulations are used to predict signal and background U distributions. The solid curves in Figs. 2 and 3 are the expected distributions for reconstructed signal events. The shaded area in Fig. 2 shows the expected distribution for D^0

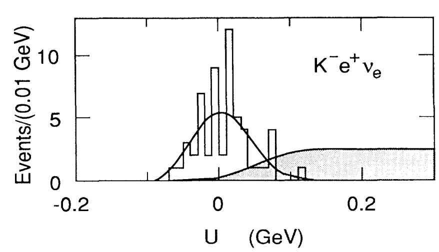

FIG. 3. Distribution of U ($D^0 \rightarrow K^-e^+\nu_e$ hypothesis) calculated for $D^0 \rightarrow K^-e^+\nu_e$ candidates (histogram), for reconstructed Monte Carlo $D^0 \rightarrow K^-e^+\nu_e$ decays (solid curve, normalized to the data), and for the background ($\times 100$) from $D^0 \rightarrow K^-\pi^0e^+\nu_e$ decays (shaded).

$\rightarrow K^- e^+ \nu_e$ events, where each event is interpreted incorrectly as $D^0 \rightarrow \pi^- e^+ \nu_e$. The shaded area in Fig. 3 shows the expected feed-down of $K^- \pi^0 e^+ \nu_e$ events with an undetected π^0 into the $K^- e^+ \nu_e$ sample. The requirement $|U| < 0.1$ GeV is imposed to reduce these backgrounds and other backgrounds with undetected massive neutral particles. One $K^- e^+ \nu_e$ candidate is rejected by this cut.

The beam-constrained mass distributions for $K^- e^+ \nu_e$ and $\pi^- e^+ \nu_e$ events passing the particle identification and background rejection requirements are shown in Figs. 1(b) and 1(c). Events in the sideband region are used to evaluate the background due to incorrectly reconstructed tags. A Monte Carlo simulation incorporating a complete model of D^0 decays[5,12] is used to evaluate backgrounds occurring with a correct tag. Backgrounds are enumerated in Table I. The efficiencies for reconstructing semielectronic decays in the recoil to a tag are $\epsilon_{\pi^- e^+ \nu_e} = 0.38$ and $\epsilon_{K^- e^+ \nu_e} = 0.37$. The efficiencies for reconstructing semimuonic decays as their corresponding semielectronic decays are $\epsilon_{\pi^- \mu^+ \nu_\mu} = 0.050$ and $\epsilon_{K^- \mu^+ \nu_\mu} = 0.052$. Lepton universality implies nearly identical semielectronic and semimuonic branching fractions; semimuonic events need not, therefore, be subtracted as a background. Instead, acceptance and background corrections are made using the expression

TABLE I. Number of background and observed events.

Decay	$N_{\pi^- e^+ \nu_e}$	$N_{K^- e^+ \nu_e}$
$K^- e^+ \nu_e$	0.44	N.A.
$K^- \mu^+ \nu_\mu$	0.03	N.A.
$\pi^- e^+ \nu_e$	N.A.	0.06
$\pi^- \mu^+ \nu_\mu$	N.A.	0.02
$\pi^+ \pi^- \pi^0$	0.03	$\cdots$
$K^- \pi^+$	0.04	0.05
$K^{*-} e^+ \nu_e$	$\cdots$	0.13
$K^- \rho^+$	$\cdots$	0.19
$K^{*-} \pi^+$	$\cdots$	0.06
Sideband	0	1
$N_{\text{background}}$	0.53	1.51
N_{observed}	7	55

$$B(D^0 \rightarrow X^- e^+ \nu_e) = \frac{N_{\text{observed}} - N_{\text{background}}}{(\epsilon_{X^- e^+ \nu_e} + \epsilon_{X^- \mu^+ \nu_\mu}) N_{\text{tag}}} \left[1 - \frac{\bar{\epsilon}_{\text{tag}} \sum B(D^0 \rightarrow \text{tag modes})}{2} \right],$$

where X is a π or K and ϵ_{tag} is the average tag reconstruction efficiency. We find

$$B(D^0 \rightarrow \pi^- e^+ \nu_e) = (0.39^{+0.23}_{-0.11} \pm 0.04)\%$$

(Ref. 13) and

$$B(D^0 \rightarrow K^- e^+ \nu_e) = (3.4 \pm 0.5 \pm 0.4)\%.$$

Systematic errors arise from uncertainties in the simulation of backgrounds (50% of the subtracted background), determination of the number of tags (5.3%), electron identification efficiency (2%), photon reconstruction efficiency (5%), visual scan efficiency (5%), track reconstruction efficiency (2%), and TOF identification of hadrons (5%). These errors are added in quadrature. The technique of tagging with hadronic $\bar{D}^0$ decays eliminates any dependence on the charm production cross section or the integrated luminosity.

The ratio $|V_{cd}/V_{cs}|^2$ is obtained from $B(D^0 \rightarrow \pi^- e^+ \nu_e)$ and

$$\left| \frac{V_{cd}}{V_{cs}} \right|^2 = \left(\frac{f_+^K(0)}{f_+^\pi(0)} \right)^2 \left(\frac{\int [m_{D_S^*}^2/(m_{D_S^*}^2 - t)]^2 (E_K^2 - m_K^2)^{3/2} dt}{\int [m_{D^*}^2/(m_{D^*}^2 - t)]^2 (E_\pi^2 - m_\pi^2)^{3/2} dt} \right) \left(\frac{B(D^0 \rightarrow \pi^- e^+ \nu_e)}{B(D^0 \rightarrow K^- e^+ \nu_e)} \right),$$

under the assumption that the t dependence of the vector form factor is described by a single pole.[8,14] The ratio of the integrals is 0.507. While the individual form factors $f_+^K(0)$ and $f_+^\pi(0)$ are expected to deviate substantially from unity due to SU(4) symmetry breaking, the ratio $f_+^K(0)/f_+^\pi(0)$ is expected to deviate from unity[15] by only ~10% due to SU(3) symmetry breaking. Nevertheless, taking $f_+^K(0)/f_+^\pi(0)$ to be unity, the ratio of the KM matrix elements is $|V_{cd}/V_{cs}|^2 = 0.057^{+0.038}_{-0.015} \pm 0.005$, where no systematic error is included for the uncertainty in $f_+^K(0)/f_+^\pi(0)$, and the statistical error is a two-sided 68.3% likelihood interval.[16] The systematic error for $|V_{cd}/V_{cs}|^2$ is independent of the detection efficiency and the number of tags; only the background subtraction and the visual scan contribute.

We gratefully acknowledge the dedicated efforts of the SPEAR storage ring and linear accelerator operating staffs, and the continued support of the Directorate of the Stanford Linear Accelerator Center for the SPEAR high-energy physics program. This work was supported in part by the Department of Energy, under Contracts No. DE-AC03-76SF00515, No. DE-AC02-76ER01195, No. DE-AC03-81ER40050, No. DE-AM03-

76SF00034, and No. DE-AC02-87ER40318, and by the National Science Foundation.

[(a)]Deceased.

[1]H. Abramowicz *et al.*, Z. Phys. C **15**, 19 (1982); K. Kleinknecht and B. Renk, Z. Phys. C **34**, 209 (1987). The papers are based on analyses of the same data. The first finds $|V_{cd}|=0.24\pm0.03$ using an average semimuonic branching fraction of $(7.1\pm1.3)\%$. The second finds $|V_{cd}|=0.21\pm0.03$ using an updated estimate for the average semimuonic branching fraction of $(9.3\pm1.0)\%$.

[2]B. Guberina *et al.*, Phys. Lett. **89B**, 111 (1979); I. I. Bigi, SLAC Report No. SLAC-PUB-4455, 1987 (unpublished).

[3]Reference to a state shall henceforth also imply reference to its charge conjugate.

[4]D. Bernstein *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **226**, 301 (1984).

[5]J. Adler *et al.*, Phys. Rev. Lett. **60**, 89 (1988).

[6]As the four-momentum of the semileptonic decay candidate is known, the event can be reconstructed with no kinematic ambiguity, in spite of the undetected neutrino.

[7]A $K_S^0\pi^+\pi^-$ can come either from the decay of a D^0 or a $\bar{D}^0$; hence both electron signs are accepted.

[8]D. M. Coffman, Ph.D. thesis, California Institute of Technology, 1986 (unpublished).

[9]J. S. Brown *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **221**, 503 (1984). The TOF alone provides more than 2.0σ π-K separation over the entire kinematic range.

[10]Showers that start in the first three radiation lengths of the calorimeter and deposit more than 0.1 GeV are classified as photons if they are further than 18° from the nearest charged track.

[11]If the TOF criteria are removed, one additional $\pi^-e^+\nu_e$ candidate is accepted.

[12]J. Adler *et al.*, Phys. Lett. B **196**, 107 (1987); R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **56**, 2136 (1986); R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **55**, 150 (1985); R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **54**, 1976 (1986).

[13]The statistical probability that 0.53 event (the expected background) would produce 7 or more observed events is 1.5×10^{-6}.

[14]J. C. Anjos *et al.*, Phys. Rev. Lett. **62**, 1587 (1989). They measure $\Gamma(D^0\to K^-e^+\nu_e)/\Gamma(D^0\to K^-\pi^+)=0.91\pm0.07\pm0.11$.

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[16]A. G. Frodesen, O. Skjeggestad, and H. Tøfte, *Probability and Statistics in Particle Physics* (Universitetsforlaget, Bergen, 1979). The marginal likelihood function for $|V_{cd}/V_{cs}|^2$ is obtained from the joint likelihood function for $B(D^0\to\pi^-e^+\nu_e)$ and $B(D^0\to K^-e^+\nu_e)$. Our point estimate for $|V_{cd}/V_{cs}|^2$ is the value which maximizes the marginal likelihood function.