Measurement of the $B \to D\ell\nu$ Branching Fractions and Form Factor

J. Bartelt,[1] S. E. Csorna,[1] K. W. McLean,[1] S. Marka,[1] Z. Xu,[1] R. Godang,[2] K. Kinoshita,[2,*] I. C. Lai,[2] P. Pomianowski,[2] S. Schrenk,[2] G. Bonvicini,[3] D. Cinabro,[3] R. Greene,[3] L. P. Perera,[3] G. J. Zhou,[3] S. Chan,[4] G. Eigen,[4] E. Lipeles,[4] J. S. Miller,[4] M. Schmidtler,[4] A. Shapiro,[4] W. M. Sun,[4] J. Urheim,[4] A. J. Weinstein,[4] F. Würthwein,[4] D. E. Jaffe,[5] G. Masek,[5] H. P. Paar,[5] E. M. Potter,[5] S. Prell,[5] V. Sharma,[5] D. M. Asner,[6] J. Gronberg,[6] T. S. Hill,[6] D. J. Lange,[6] R. J. Morrison,[6] H. N. Nelson,[6] T. K. Nelson,[6] D. Roberts,[6] B. H. Behrens,[7] W. T. Ford,[7] A. Gritsan,[7] H. Krieg,[7] J. Roy,[7] J. G. Smith,[7] J. P. Alexander,[8] R. Baker,[8] C. Bebek,[8] B. E. Berger,[8] K. Berkelman,[8] V. Boisvert,[8] D. G. Cassel,[8] D. S. Crowcroft,[8] M. Dickson,[8] S. von Dombrowski,[8] P. S. Drell,[8] K. M. Ecklund,[8] R. Ehrlich,[8] A. D. Foland,[8] P. Gaidarev,[8] L. Gibbons,[8] B. Gittelman,[8] S. W. Gray,[8] D. L. Hartill,[8] B. K. Heltsley,[8] P. I. Hopman,[8] J. Kandaswamy,[8] D. L. Kreinick,[8] T. Lee,[8] Y. Liu,[8] N. B. Mistry,[8] C. R. Ng,[8] E. Nordberg,[8] M. Ogg,[8,†] J. R. Patterson,[8] D. Peterson,[8] D. Riley,[8] A. Soffer,[8] B. Valant-Spaight,[8] A. Warburton,[8] C. Ward,[8] M. Athanas,[9] P. Avery,[9] C. D. Jones,[9] M. Lohner,[9] C. Prescott,[9] A. I. Rubiera,[9] J. Yelton,[9] J. Zheng,[9] G. Brandenburg,[10] R. A. Briere,[10] A. Ershov,[10] Y. S. Gao,[10] D. Y.-J. Kim,[10] R. Wilson,[10] H. Yamamoto,[10] T. E. Browder,[11] Y. Li,[11] J. L. Rodriguez,[11] S. K. Sahu,[11] T. Bergfeld,[12] B. I. Eisenstein,[12] J. Ernst,[12] G. E. Gladding,[12] G. D. Gollin,[12] R. M. Hans,[12] E. Johnson,[12] I. Karliner,[12] M. A. Marsh,[12] M. Palmer,[12] M. Selen,[12] J. J. Thaler,[12] K. W. Edwards,[13] A. Bellerive,[14] R. Janicek,[14] P. M. Patel,[14] A. J. Sadoff,[15] R. Ammar,[16] P. Baringer,[16] A. Bean,[16] D. Besson,[16] D. Coppage,[16] C. Darling,[16] R. Davis,[16] S. Kotov,[16] I. Kravchenko,[16] N. Kwak,[16] L. Zhou,[16] S. Anderson,[17] Y. Kubota,[17] S. J. Lee,[17] R. Mahapatra,[17] J. J. O'Neill,[17] R. Poling,[17] T. Riehle,[17] A. Smith,[17] M. S. Alam,[18] S. B. Athar,[18] Z. Ling,[18] A. H. Mahmood,[18] S. Timm,[18] F. Wappler,[18] A. Anastassov,[19] J. E. Duboscq,[19] K. K. Gan,[19] T. Hart,[19] K. Honscheid,[19] H. Kagan,[19] R. Kass,[19] J. Lee,[19] H. Schwarthoff,[19] A. Wolf,[19] M. M. Zoeller,[19] S. J. Richichi,[20] H. Severini,[20] P. Skubic,[20] A. Undrus,[20] M. Bishai,[21] S. Chen,[21] J. Fast,[21] J. W. Hinson,[21] N. Menon,[21] D. H. Miller,[21] E. I. Shibata,[21] I. P. J. Shipsey,[21] S. Glenn,[22] Y. Kwon,[22,‡] A. L. Lyon,[22] S. Roberts,[22] E. H. Thorndike,[22] C. P. Jessop,[23] K. Lingel,[23] H. Marsiske,[23] M. L. Perl,[23] V. Savinov,[23] D. Ugolini,[23] X. Zhou,[23] T. E. Coan,[24] V. Fadeyev,[24] I. Korolkov,[24] Y. Maravin,[24] I. Narsky,[24] R. Stroynowski,[24] J. Ye,[24] T. Wlodek,[24] M. Artuso,[25] E. Dambasuren,[25] S. Kopp,[25] G. C. Moneti,[25] R. Mountain,[25] S. Schuh,[25] T. Skwarnicki,[25] S. Stone,[25] A. Titov,[25] G. Viehhauser,[25] and J. C. Wang[25]

(CLEO Collaboration)

[1] *Vanderbilt University, Nashville, Tennessee 37235*
[2] *Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[3] *Wayne State University, Detroit, Michigan 48202*
[4] *California Institute of Technology, Pasadena, California 91125*
[5] *University of California, San Diego, La Jolla, California 92093*
[6] *University of California, Santa Barbara, California 93106*
[7] *University of Colorado, Boulder, Colorado 80309-0390*
[8] *Cornell University, Ithaca, New York 14853*
[9] *University of Florida, Gainesville, Florida 32611*
[10] *Harvard University, Cambridge, Massachusetts 02138*
[11] *University of Hawaii at Manoa, Honolulu, Hawaii 96822*
[12] *University of Illinois, Urbana-Champaign, Illinois 61801*
[13] *Carleton University, Ottawa, Ontario, Canada K1S 5B6 and the Institute of Particle Physics, Canada*
[14] *McGill University, Montréal, Québec, Canada H3A 2T8 and the Institute of Particle Physics, Canada*
[15] *Ithaca College, Ithaca, New York 14850*
[16] *University of Kansas, Lawrence, Kansas 66045*
[17] *University of Minnesota, Minneapolis, Minnesota 55455*
[18] *State University of New York at Albany, Albany, New York 12222*
[19] *Ohio State University, Columbus, Ohio 43210*
[20] *University of Oklahoma, Norman, Oklahoma 73019*
[21] *Purdue University, West Lafayette, Indiana 47907*
[22] *University of Rochester, Rochester, New York 14627*
[23] *Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*
[24] *Southern Methodist University, Dallas, Texas 75275*
[25] *Syracuse University, Syracuse, New York 13244*

(Received 25 November 1998)

 0031-9007/99/82(19)/3746(5)$15.00

Using a sample of 3.3×10^6 B-meson decays collected with the CLEO detector at the Cornell Electron Storage Ring, we have studied $B^- \to D^0 \ell^- \bar{\nu}$ and $\bar{B}^0 \to D^+ \ell^- \bar{\nu}$ decays, where ℓ^- can be either e^- or μ^-. We distinguish $B \to D\ell\nu$ from other B semileptonic decays by examining the net momentum and energy of the particles recoiling against $D - \ell$ pairs. We find $\Gamma(B \to D\ell\nu) = (14.1 \pm 1.0 \pm 1.2)\ \mathrm{ns}^{-1}$ and derive branching fractions for $B^- \to D^0 \ell^- \bar{\nu}$ and $\bar{B}^0 \to D^+ \ell^- \bar{\nu}$ of $(2.32 \pm 0.17 \pm 0.20)\%$ and $(2.20 \pm 0.16 \pm 0.19)\%$, respectively, where the uncertainties are statistical and systematic. We also investigate the $B \to D\ell\nu$ form factor and the implication of the result for $|V_{cb}|$. [S0031-9007(99)09093-6]

PACS numbers: 13.20.He, 12.15.Hh, 12.39.Hg, 14.40.Nd

The semileptonic decays of the B-meson play important roles in heavy quark physics. They provide our best information on the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements V_{cb} and V_{ub} [1] and reveal the dynamics of heavy quark decay in their form factors. Heavy quark effective theory (HQET) [2] suggests a reliable method for extracting $|V_{cb}|$ by predicting that quantum chromodynamics (QCD) effects are small when the final-state meson is at rest relative to the initial meson (zero recoil). Most studies of the form factors and $|V_{cb}|$ [3] have used the $B \to D^*\ell\nu$ decay because its differential rate near zero recoil is large and the QCD effects have been calculated to the highest accuracy [4]. There have been two recent studies of the mode $B \to D\ell\nu$ [5,6]. Here we present a new, more precise study of $B \to D\ell\nu$ using a different analysis method.

We select the B semileptonic decays $B \to D\ell\nu$, $B \to D^*\ell\nu$, $B \to D^{**}\ell\nu$, and $B \to D^{(*)}\pi\ell\nu$ by identifying events with a D (D^0 or D^+ and their charge conjugates) and a lepton (e or μ). We then separate $B \to D\ell\nu$ from the other semileptonic modes using the net energy and momentum of the particle or particles recoiling against the $D - \ell$ pair. Information on the partial width and differential decay rate is obtained from the $B^- \to D^0 \ell^- \bar{\nu}$ and $\bar{B}^0 \to D^+ \ell^- \bar{\nu}$ yields as a function of the HQET variable $w = (M_B^2 + m_D^2 - q^2)/2M_B m_D$, where q^2 is the squared invariant mass of the virtual W, and M_B and m_D are the B- and D-meson masses.

Data were obtained using the CLEO detector [7] at the Cornell Electron Storage Ring (CESR). The data consist of 3.1 fb^{-1} (3.3×10^6 $B\bar{B}$ events) collected at the $\Upsilon(4S)$ resonance and 1.6 fb^{-1} collected 60 MeV below resonance to evaluate the background from the $e^+e^- \to q\bar{q}$ continuum. The CLEO drift chamber system, immersed in a 1.5 T magnetic field, provides the trajectories and momenta of charged particles. In addition, the main drift chamber provides their specific ionization (dE/dx), and scintillation counters surrounding the drift chamber provide their time of flight (TOF). A CsI electromagnetic calorimeter aids electron identification, and counters embedded in the steel surrounding the magnet provide muon identification.

This analysis uses events with at least five charged tracks and, to suppress non-$B\bar{B}$ events, the ratio of Fox-Wolfram moments [8] $H_2/H_0 < 0.45$. We reconstruct D^0 and D^+ candidates in the decay modes $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$, respectively. To select K's and π's, we require $P_i > 0.01$ and $P_i/(P_K + P_\pi) > 0.3$, where P_i $(i = \pi, K)$ is an integrated χ^2 probability that combines dE/dx and TOF. The candidate mass must be within $1.835 < m_{K\pi} < 1.893$ GeV for D^0 and $1.846 < m_{K\pi\pi} < 1.890$ GeV for D^+ decays. To suppress D mesons produced in $e^+e^- \to c\bar{c}$ events, we require $|\mathbf{p}_D| < 2.5$ GeV/c.

Electrons are identified using dE/dx, the shape of the shower in the CsI calorimeter, and E/p, the ratio of the particle's energy deposit in the CsI to its momentum. Electrons are required to have momenta between 0.8 and 2.4 GeV/c. Muons, which must penetrate at least five interaction lengths of material, have momentum above about 1.4 GeV/c. The lepton must have the same charge as the K. We require that the D and ℓ lie in opposite hemispheres; because the B is nearly at rest (the average momentum is 300 MeV/c), this is the case for about 90% of the $D\ell\nu$ decays.

For events satisfying these criteria, we compute $\cos\theta_{B-D\ell}$, the cosine of the angle between the $D\ell$ momentum $\mathbf{p}_{D\ell} = \mathbf{p}_D + \mathbf{p}_\ell$ and the B momentum $\mathbf{p}_B$, assuming that the decay is $B \to D\ell\nu$ and that the only missing particle is the massless neutrino, that is,

$$\cos\theta_{B-D\ell} = \frac{2E_B E_{D\ell} - M_B^2 - M_{D\ell}^2}{2|\mathbf{p}_B|\,|\mathbf{p}_{D\ell}|}. \tag{1}$$

For $B \to D\ell\nu$ decays, $-1 < \cos\theta_{B-D\ell} \le 1$. When final-state particles are missing, in addition to the ν, as is the case for the other B semileptonic decay modes, $\cos\theta_{B-D\ell}$ can be smaller. We use the distribution of $\cos\theta_{B-D\ell}$ to separate $B \to D\ell\nu$ from the other B semileptonic decays after subtracting backgrounds.

The backgrounds come from several sources: random $K\pi(\pi)$ combinations, D mesons matched with a lepton from the other B decay (uncorrelated), D mesons combined with a lepton that is a granddaughter of the same B (correlated), hadrons misidentified as leptons (fake lepton), and $e^+e^- \to q\bar{q}$ events.

To assess the contribution from random combinations we use events in the mass regions above and below the D peak (sideband). Monte Carlo simulated B decays indicate that within small uncertainties the sidebands have the correct $\cos\theta_{B-D\ell}$ distribution and normalization.

When the D and ℓ arise from the decays of different B mesons, the angular distribution between them is nearly uniform. We take advantage of this uniformity: For each event in which the D and ℓ are in the same hemisphere we reverse the lepton's direction and compute $\cos\theta_{B-D\ell}$, thereby constructing this distribution for the uncorrelated background.

The $e^+e^- \to q\bar{q}$ continuum background is determined from off-resonance data. The correlated background arises from modes such as $B \to D_s D$ followed by $D_s \to X\ell\nu$ and $B \to DX\tau\nu$ followed by $\tau \to \ell\nu\bar{\nu}$. We estimate these small contributions using a Monte Carlo simulation. Fake lepton background is assessed by repeating the analysis using hadrons in place of leptons and then scaling the yield by the momentum-dependent electron and muon misidentification probabilities. Table I summarizes the yield and backgrounds.

After subtracting the backgrounds, we are left with $B \to D^0X\ell\nu$ and $B \to D^+X\ell\nu$ decays, where X stands for zero or more pions or photons (from $D^* \to D\gamma$). We then extract the $D^0\ell^-\bar{\nu}$ and $D^+\ell^-\bar{\nu}$ yields in bins of $\tilde{w}$ by fitting the $\cos\theta_{B-D\ell}$ distribution in each, as shown in Fig. 1. Here $\tilde{w}$ is the reconstructed value of w, and is smeared by the detector resolution and motion of the B. We use ten equal $\tilde{w}$ bins over the range $1.0 \le \tilde{w} < 1.6$. In the fits, we assume $\cos\theta_{B-D\ell}$ distributions for $D\ell\nu$, $D^*\ell\nu$, and the sum of $D^{**}\ell\nu$ and $D^{(*)}\pi\ell\nu$ provided by a GEANT-based [9] Monte Carlo simulation that uses the model by ISGW2 [10] for $D\ell\nu$ and $D^{**}\ell\nu$, the form factors measured by CLEO [11] for $B \to D^*\ell\nu$, and the results of Goity and Roberts [12] for nonresonant $D^{(*)}\pi$ decays. The fits constrain the ratio of $B \to D^*\ell\nu$ to $B \to D\ell\nu$ decay rates to be the same for B^+ and B^0 decays. The sum of the $D^0\ell^-\bar{\nu}$ and $D^+\ell^-\bar{\nu}$ results are displayed in Fig. 2.

To obtain information on $|V_{cb}|$ and the form factor $F_D(w)$, we fit the differential decay width [4],

$$\frac{d\Gamma}{dw} = \frac{G_F^2|V_{cb}|^2}{48\pi^3}(M_B + m_D)^2 m_D^3 (w^2 - 1)^{3/2} F_D(w)^2, \tag{2}$$

TABLE I. The $D^0X\ell\nu$ and $D^+X\ell\nu$ yields and backgrounds. Uncertainties are statistical only.

	$D^0\ell$	$D^+\ell$
Total Yield	12 595 ± 112	18 087 ± 134
Random $K\pi(\pi)$ combinations	5083 ± 50	13 502 ± 70
Uncorrelated	948 ± 63	761 ± 75
Continuum	452 ± 84	432 ± 104
Correlated	119 ± 16	119 ± 23
Fake lepton	71 ± 19	26 ± 25
Background-subtracted Yield	5922 ± 163	3247 ± 201

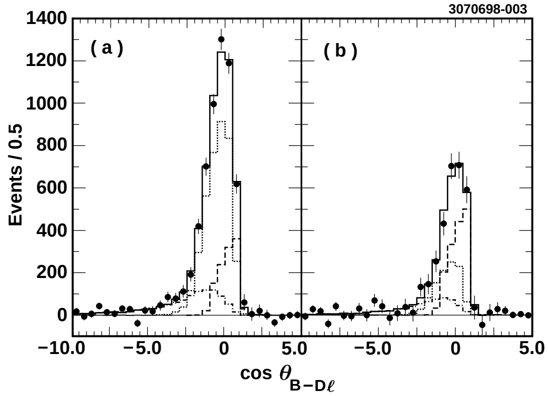

FIG. 1. The $\cos\theta_{B-D\ell}$ distribution for (a) $B \to D^0X\ell\nu$ and (b) $B \to D^+X\ell\nu$ for data (solid circle), simulated $B \to D\ell\nu$ (dashed histogram), $B \to D^*\ell\nu$ (dotted histogram), and $B \to D^{**}\ell\nu + D^{(*)}\pi\ell\nu$ decays (dash-dotted histogram), and their total (solid histogram). The normalizations of the simulated samples are provided by the fit.

to the $\tilde{w}$ distributions of the data in the region $\tilde{w} > 1.12$. (For $\tilde{w} < 1.12$, the rate is low and backgrounds are large.) Here G_F is the weak coupling constant. The fit minimizes $\chi^2 = \chi^2_{D^0\ell^-\bar{\nu}} + \chi^2_{D^+\ell^-\bar{\nu}}$, where

$$\chi^2_{D^0\ell^-\bar{\nu}} = \sum_{i=3}^{10} \frac{[N_i^{\rm obs} - \sum_{j=1}^{10}\epsilon_{ij}N_j]^2}{\sigma^2_{N_i^{\rm obs}} + \sum_{j=1}^{10}\sigma^2_{\epsilon_{ij}}N_j^2}, \tag{3}$$

$N_i^{\rm obs}$ is the yield in the ith $\tilde{w}$ bin, N_j is the number of decays in the jth w bin, and the matrix ϵ_{ij} accounts for the reconstruction efficiency and the smearing in $\tilde{w}$. The fraction of $D^0\ell^-\bar{\nu}$ decays in each w bin that is reconstructed is 17% to 21% and the average $\tilde{w}$ resolution is 0.026, about one-half the bin width. The small statistical uncertainty in ϵ_{ij} is represented by $\sigma^2_{\epsilon_{ij}}$. Explicitly,

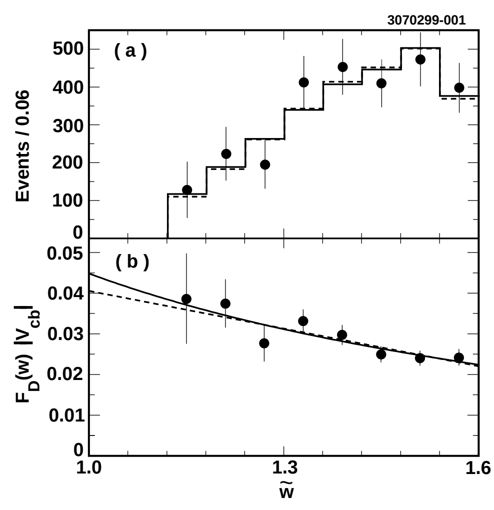

FIG. 2. The sum of $D^0\ell^-\bar{\nu}$ and $D^+\ell^-\bar{\nu}$ (a) yields and (b) $F_D(w)|V_{cb}|$ as a function of $\tilde{w}$ for the data (solid circles), a linear form factor (dashed histogram), and the form factor of Boyd *et al.* (solid histogram). Plot (b) is partially corrected for the smearing in $\tilde{w}$.

$N_j = 4f_{+-}N_{\Upsilon(4S)}\mathcal{B}_{K\pi}\tau_{B^-}\int_{w_j} dw\, d\Gamma/dw$, where τ_{B^-} is the B^- lifetime [13], $\mathcal{B}_{K\pi}$ is the $D^0 \to K^-\pi^+$ branching fraction [14], $N_{\Upsilon(4S)}$ is the number of $\Upsilon(4S)$ events in the sample, and f_{+-} is the $\Upsilon(4S) \to B^+B^-$ branching fraction. We form $\chi^2_{D^+\ell^-\bar{\nu}}$ analogously. The fit varies $|V_{cb}|F_D(1)$, the parameters describing $F_D(w)/F_D(1)$, and f_{+-}.

Our results for several parametrizations of the form factor are summarized in Table II. We first consider the common expansion $F_D(w)/F_D(1) = 1 - \rho_D^2(w-1) + c_D(w-1)^2$. The result when c_D is constrained to be zero is shown in Fig. 2. Separate fits to the $D^0\ell^-\bar{\nu}$ and $D^+\ell^-\bar{\nu}$ samples give consistent values of ρ_D^2 as expected; in the quoted results they are constrained to be the same. We also assume that $f_{+-} + f_{00} = 1$, i.e., that B^+B^- and $B^0\bar{B}^0$ together saturate $\Upsilon(4S)$ decays. We find $f_{+-} = 0.49 \pm 0.04$, consistent with previous measurements [15]. The correlation coefficients for this fit, which is representative, are $\rho[|V_{cb}|F_D(1), \rho_D^2] = 0.95$, $\rho[|V_{cb}|F_D(1), f_{+-}] = 0.12$, and $\rho(f_{+-}, \rho_D^2) = 0.03$. When c_D is allowed to vary, we find that it is consistent with zero within large errors; that is, our data allow substantial curvature but do not require it. The values obtained for ρ_D^2 and c_D are completely correlated because our data are precise only at large values of w.

Dispersion relations constrain the form factor. Boyd *et al.* [16] expand the form factor of the variable $z = (\sqrt{w+1} - \sqrt{2N})/(\sqrt{w+1} + \sqrt{2N})$. Because z is small, this expansion converges more rapidly than does one in $w - 1$. Fitting for the linear coefficient a_1 with $N = 1.108$, we find $a_1 = -0.043 \pm 0.027$. Expanding this form factor in powers of $w - 1$ yields $\rho_D^2 = 1.30 \pm 0.27$ and $c_D = 1.21 \pm 0.31$ plus higher order terms. Caprini *et al.* [17] have also used dispersion relations to constrain the form factors. Their parametrization leads to similar results.

To obtain the $B \to D\ell\nu$ decay rate, we use the form factor parameters provided by the fits and integrate $d\Gamma/dw$ over w. The fit using the form factor of Boyd *et al.* [16] gives $\Gamma = (14.1 \pm 1.0)\ \mathrm{ns}^{-1}$. This result is insensitive to f_{+-}.

The systematic uncertainties are given in Table III. The uncertainties in the B-meson momentum and mass dominate because they, respectively, affect the width and mean of the $\cos\theta_{B-D\ell}$ distributions and therefore the $D^0\ell^-\bar{\nu}$ and $D^+\ell^-\bar{\nu}$ yields extracted in each $\tilde{w}$ bin. We have tuned our simulation to reproduce the B momentum distribution of fully reconstructed B decays; however, a 6 MeV/c uncertainty in the mean leads to fractional systematic uncertainties of 5% for ρ_D^2, 4% for $|V_{cb}|F_D(1)$, and 3% for Γ. The 1.8 MeV [13] uncertainty in the B mass generates uncertainties of 7% for ρ_D^2, 4% for $|V_{cb}|F_D(1)$, and 3% for Γ.

The other large systematic error arises from uncertainty in the $\cos\theta_{B-D\ell}$ distribution of the combined $B \to D^{**}\ell\nu$ and $B \to D^{(*)}\pi\ell\nu$ backgrounds. This distribution depends mainly on the number of final-state pions that are not reconstructed. We therefore separate it into two components: one in which the final-state D is accompanied by one π and the other in which it is accompanied by two, and vary their relative proportions from 1:4 to 2:3 [18] to evaluate the systematic uncertainty.

All $D\ell\nu$ form factor fits give the same decay width within 0.8%. The $D\ell\nu$ form factor can affect the efficiency matrix and the $\cos\theta_{B-D\ell}$ distribution used to obtain the $D^0\ell^-\bar{\nu}$ and $D^+\ell^-\bar{\nu}$ yields in each $\tilde{w}$ bin. Each of these effects is less than 1%.

Our final result is

$$\Gamma(B \to D\ell\nu) = (14.1 \pm 1.0 \pm 1.2)\ \mathrm{ns}^{-1}. \qquad (4)$$

Multiplying this by the measured B-meson lifetimes gives the branching fractions

$$\mathcal{B}(B^- \to D^0\ell^-\bar{\nu}) = (2.32 \pm 0.17 \pm 0.20)\% \qquad (5)$$

and

$$\mathcal{B}(\bar{B}^0 \to D^+\ell^-\bar{\nu}) = (2.20 \pm 0.16 \pm 0.19)\%, \qquad (6)$$

where the first errors are statistical and the second are systematic. This result is consistent with previous measurements but is more precise. Combining it with the previous CLEO result [5], taking into account correlations, gives

$$\Gamma(B \to D\ell\nu) = (13.4 \pm 0.8 \pm 1.2)\ \mathrm{ns}^{-1}, \qquad (7)$$

$$\mathcal{B}(B^- \to D^0\ell^-\bar{\nu}) = (2.21 \pm 0.13 \pm 0.19)\%, \qquad (8)$$

and

$$\mathcal{B}(\bar{B}^0 \to D^+\ell^-\bar{\nu}) = (2.09 \pm 0.13 \pm 0.18)\%. \qquad (9)$$

TABLE II. Summary of the $B \to D\ell\nu$ form factor fits. Errors are statistical only.

Form factor	ρ_D^2	c_D	$10^2\lvert V_{cb}\rvert F_D(1)$	χ^2/dof
Linear	0.76 ± 0.16	$\cdots$	4.05 ± 0.45	8.8/13
Parabolic	$0.77^{+1.18}_{-2.83}$	$0.01^{+1.70}_{-3.96}$	$4.05^{+1.51}_{-1.63}$	8.8/12
Boyd *et al.* [a,b]	1.30 ± 0.27	1.21 ± 0.31	4.48 ± 0.61	8.9/13
Caprini *et al.* [b]	1.27 ± 0.25	1.18 ± 0.26	4.44 ± 0.58	8.9/13

[a] We find $a_1 = -0.043 \pm 0.027$ for $N = 1.108$.
[b] Also has terms of order $(w-1)^3$ and higher.

TABLE III. The fractional systematic uncertainties.

Source	ρ_D^2	$\lvert V_{cb}\rvert F_D(1)$	$\Gamma(B \to D\ell\nu)$
Track-finding	$\cdots$	0.02	0.035
Lepton ID	$\cdots$	0.01	0.020
K and π ID	0.02	0.01	0.022
Backgrounds	0.06	0.04	0.018
$\lvert \mathbf{p}_B\rvert$ and M_B	0.08	0.05	0.042
Luminosity	$\cdots$	0.01	0.018
$D\ell\nu$ form factor	0.01	0.01	0.010
$D^*\ell\nu$ form factors	0.01	0.01	0.005
$D^{**}\ell\nu$ model	0.04	0.03	0.026
D branching fractions	$\cdots$	0.02	0.036
τ_B	$\cdots$	0.02	0.026
Total	0.11	0.08	0.085

Since we obtain both branching fractions from the decay width, their errors are completely correlated.

Our studies of the form factor give $\rho_D^2 = 0.76 \pm 0.16 \pm 0.08$ (linear fit), and $\rho_D^2 = 1.30 \pm 0.27 \pm 0.14$ and $c_D = 1.21 \pm 0.31 \pm 0.15$ plus higher order terms (dispersion relations). The latter gives $|V_{cb}|F_D(1) = 0.0448 \pm 0.0061 \pm 0.0037$. Combining this with the previous CLEO result, we obtain

$$|V_{cb}|F_D(1) = 0.0416 \pm 0.0047 \pm 0.0037\,. \qquad (10)$$

Various authors have found $F_D(1) = 0.98 \pm 0.07$ [19], 1.04 [10], and 1.069 ± 0.029 (preliminary) [20]. Using $F_D(1) = 1.0$, we find $|V_{cb}| = 0.042 \pm 0.005 \pm 0.004 \pm 0.004$, where the last uncertainty covers all of these values of $F_D(1)$. This value of $|V_{cb}|$ is consistent with that from $B \to D^*\ell\nu$ decays (0.0387 ± 0.0031) [3], though its uncertainty is larger. The linear form factor, used in most previous studies of $B \to D^*\ell\nu$, gives a value of $|V_{cb}|$ that is reduced by about 10%. Use of the linear form factor is likely to have a smaller, but nevertheless important, effect on the $|V_{cb}|$ extracted from $B \to D^*\ell\nu$ decays.

We thank C. Glenn Boyd and Matthias Neubert for useful discussions. We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the National Science Foundation, the U.S. Department of Energy, Research Corporation, the Natural Sciences and Engineering Council of Canada, the A. P. Sloan Foundation, the Swiss National Science Foundation, and the Alexander von Humboldt Stiftung.

*Permanent address: University of Cincinnati, Cincinnati, OH 45221.

†Permanent address: University of Texas, Austin, TX 78712.

‡Permanent address: Yonsie University, Seoul 120-749, Korea.

[1] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[2] N. Isgur and M. B. Wise, Phys. Lett. B **232**, 113 (1989); N. Isgur and M. B. Wise, Phys. Lett. B **237**, 527 (1990); M. Neubert, Phys. Rep. **245**, 259 (1994).

[3] P. Drell, in *Proceedings of the 18th International Symposium on Lepton-Photon Interactions, Hamburg, Germany, 1997* (World Scientific, Singapore, 1998).

[4] M. Neubert, Phys. Lett. B **264**, 455 (1991).

[5] M. Athanas *et al.*, Phys. Rev. Lett. **79**, 2208 (1997).

[6] D. Buskulic *et al.*, Phys. Lett. B **395**, 373 (1997).

[7] Y. Kubota *et al.*, Nucl. Instrum. Methods. Phys. Res., Sect. A **320**, 66 (1992).

[8] G. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).

[9] T. Brun *et al.*, GEANT 3.15, CERN Report DD/EE/84-1.

[10] D. Scora and N. Isgur, Phys. Rev. D **52**, 2783 (1995); N. Isgur *et al.*, Phys. Rev. D **39**, 799 (1989).

[11] J. E. Duboscq *et al.*, Phys. Rev. Lett. **76**, 3898 (1996).

[12] J. L. Goity and W. Roberts, Phys. Rev. D **51**, 3459 (1995).

[13] Particle Data Group, C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998). We use $\tau_{B^-} = (1.65 \pm 0.04)$ ps and $\tau_{\bar{B}^0} = (1.56 \pm 0.04)$ ps.

[14] Particle Data Group, C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998). We use $\mathcal{B}(D \to K\pi) = 0.0385 \pm 0.0009$ and $\mathcal{B}(D \to K\pi\pi) = 0.090 \pm 0.006$.

[15] C. S. Jessop *et al.*, Phys. Rev. Lett. **79**, 4533 (1997).

[16] C. G. Boyd, B. Grinstein, and R. F. Lebed, Phys. Rev. D **56**, 6895 (1997).

[17] I. Caprini, L. Lellouch, and M. Neubert, Nucl. Phys. **B530**, 153 (1998).

[18] ALEPH Collaboration, D. Buskulic *et al.*, Z. Phys. C **73**, 601 (1997).

[19] I. Caprini and M. Neubert, Phys. Lett. B **380**, 376 (1996).

[20] S. Hashimoto, in Proceedings of the Sixteenth International Symposium on Lattice Field Theory (Lattice '98), Boulder, Colorado, 1998 (to be published).