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ARTICLES

Exclusive and inclusive semileptonic decays of B mesons to D mesons

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We report new measurements of the branching fractions $B(B^-\to D^0 l^- \bar{\nu})$, $B(\bar{B}^0\to D^+ l^- \bar{\nu})$, and $B(B^-\to D^{*0} l^- \bar{\nu})$. Combining these results with our previous measurement of $B(\bar{B}^0\to D^{*+} l^- \bar{\nu})$, we find that the ratio of semileptonic widths for final states with a vector meson and pseudoscalar meson is $(2.6^{+1.1+1.0}_{-0.6-0.8})$ and the ratio of charged- to neutral-B-meson lifetimes is $(0.89\pm0.19\pm0.13)(f_{00}/f_{+-})$ where (f_{00}/f_{+-}) is the ratio of neutral- to charged-B-meson production at the $\Upsilon(4S)$. From the $\bar{B}\to D l^- \bar{\nu}$ branching fraction, we calculate $|V_{cb}|=0.040\pm0.006$ ±0.006, where the first error is statistical and the second is systematic and dominated by the uncertainty in the B-meson lifetime.

I. INTRODUCTION

In the standard model, semileptonic decays are easier to describe than hadronic decays. Values of the Kobayashi-Maskawa[1] matrix elements V_{cs} and V_{us}, for example, have been extracted reliably from the exclusive semileptonic decays of spinless hadrons in which theoretical models have been used to calculate the relevant hadronic form factors.[2] Similarly, measurement of $\Gamma(\bar{B}\to D l \bar{\nu})$ would lead to a value of V_{cb} that is less subject to theoretical uncertainties than estimates based on inclusive semileptonic decays.[2] Furthermore, measurements of exclusive semileptonic channels provide constraints on theoretical models[3-5] of semileptonic B decay.

At present, the experimental information available on semileptonic B decay consists of the average semileptonic branching fraction for B mesons,[6] the branching fraction in two exclusive channels, $\bar{B}^0 \to D^+ l^- \bar{\nu}$ (Ref. 7) and $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$,[8,9] the polarization of the D^{*+} in the latter decay, and the fraction of D^0, D^+, and D^{*+} production in inclusive semileptonic B decays.[10] In this paper we present the first measurement of the exclusive branching fractions $B(B^- \to D^0 l^- \bar{\nu})$ and $B(B^- \to D^{*0} l^- \bar{\nu})$, a new measurement of $B(\bar{B}^0 \to D^+ l^- \bar{\nu})$, and a new measurement of inclusive charm production in semileptonic B decays. We use our previously published branching fraction[8] $B(\bar{B}^0 \to D^{*+} l^- \bar{\nu})$ along with these measurements to extract the lifetime ratio of charged to neutral B mesons, and show that these four exclusive processes are insufficient to completely account for the inclusive semileptonic rate.

II. THE DATA SAMPLE AND SELECTION PROCEDURES

The data used in this analysis were collected with the improved CLEO detector at the Cornell Electron Storage Ring (CESR). The data sample consists of an integrated luminosity of 212 pb^{-1} on the $\Upsilon(4S)$ and 102 pb^{-1} of e^+e^- annihilation data taken at an energy below the threshold of $B\bar{B}$ production (referred to as the continuum data sample). The continuum data are only used to estimate and subtract any contribution to the resonance data from $e^+e^- \to q\bar{q}$ production. The data sample contains approximately 480 000 B-meson decays. The CLEO detector and the recent modifications to its central tracking system are described in detail elsewhere.[6,11,12] The detector feature most important to this analysis is the charged-particle tracking system which measures both momentum and specific ionization energy loss (dE/dx) used for particle identification. The overall momentum resolution of the central tracking system is $(\delta p/p)^2 = (0.23\% p)^2 + (0.7\%)^2$, where p is in GeV/c. The dE/dx is measured in the main tracking chamber to an accuracy of 6.5%, and provides K/π separation for momenta up to 700 MeV/c.

All events under consideration in this analysis pass our hadronic event-selection criteria.[13] Briefly, for this analysis there are four primary requirements.

(i) The ratio of the number of bad track candidates (those with no z fit or high residuals and those which do not point to the interaction region) to the number of good tracks is required to be less than 1.15.

(ii) A minimum value for visible energy (charged tracks plus energy deposits in the calorimeter not matched to charged tracks) of 30% of the center-of-mass energy is demanded.

(iii) The total energy deposited in the electromagnetic calorimeter is required to be between 0.5 and 7.0 GeV.

(iv) Since the momentum imbalance in most hadronic events is small, the ratio R_1 of Fox-Wolfram moments[14] is required to be less than 0.45.

The overall efficiency of these hadronic event-selection cuts for $B\bar{B}$ events is 96%.

For all analyses discussed in this paper, we require the ratio of the Fox-Wolfram moments[14] R_2 to be less than 0.4. This requirement selects "spherical" events as opposed to "jetlike" events and thus reduces the background from continuum e^+e^- annihilation. With this cut, we lose less than 5% of the $B\bar{B}$ events while rejecting about 55% of the continuum events.

We require that all charged particles used for D^0, D^+, or lepton candidates be well measured by our central tracking system. For reconstructed charged-track candidates with momenta above 500 MeV/c, we require that (1) the track not belong to a reconstructed K_S^0, Λ, or converted γ vertex, (2) the closest approach of the trajectory of the track to the nominal beam position be within 3 mm in the plane perpendicular to the beam line ($r-\phi$) and 4 cm in the direction along the beam axis (z), (3) the rms deviation of the fitted track from measured wire hits be no more than 1.3 mm in $r-\phi$, and (4) the $K^\pm$ ($\pi^\pm$) track candidate have a dE/dx measurement consistent with a $K^\pm$ ($\pi^\pm$) mass hypothesis. Reconstructed charged-track candidates with momenta below 500 MeV/c are subject to a looser requirement on the closest approach of the track trajectory to the nominal beam position on $r-\phi$. We relax the limit linearly with decreasing track momentum from ≤ 3 mm at 500 MeV/c to ≤ 1 cm in the limit of $p=0$.

Lepton identification with CLEO is described elsewhere.[6,15] For this analysis, the candidate leptons are required to have a momentum p_l between 1.4 and 2.4 GeV/c. The upper momentum limit is close to the maximum kinematically allowed momentum for leptons from B decays to charm. The lower-momentum limit suppresses leptons that are not primary B decay products; we estimate that $(1.9 \pm 1.0)\%$ of the leptons surviving the momentum cut are from semileptonic decays of D mesons which are produced in B-meson decay ("cascade" leptons). We eliminate leptons originating from the process $B \to \psi X, \psi \to l^+ l^-$ by discarding lepton candidates which, when combined with any track of opposite charge,[16] have an invariant mass within 60 MeV/c^2 (2.5 standard deviations) of the ψ mass. After subtracting the continuum contribution, there are $16\,527 \pm 227$ electron candidates and $10\,335 \pm 173$ muon candidates in this momentum range. Misidentified hadrons ("fakes") account for $(2.4 \pm 0.5)\%$ of the electrons and $(3.4 \pm 0.7)\%$ of the muons.

III. CHARM CONTENT OF SEMILEPTONIC B DECAYS

Before examining the exclusive semileptonic decay rates of B's, we consider the inclusive production of charmed mesons associated with leptons in B decay. In this analysis we reconstruct D^0 or D^+ decays in leptonic events. We search for D^0 by observing its decay into $K^-\pi^+$, and for D^+ via its decay to $K^-\pi^+\pi^+$. We also search for the charge-conjugate decays, which is implicit throughout the remainder of this report. We require the laboratory momentum of D candidates to be less than 2.5 GeV/c. This limit is near the maximum kinematically allowed momentum for D's produced in B-meson decays at the $\Upsilon(4S)$.

Decays of the $\Upsilon(4S)$ produce $B\bar{B}$ meson pairs. It is possible that one $\bar{B}$ will decay to a D while the other decays to a lepton.[17] However, we are interested in decays where both the D and lepton are produced from a single $\bar{B}$ meson, i.e., $\bar{B}\to DXl^-\bar{\nu}$. Here the D contains the c-flavor quark and the lepton has a negative sign. In both $D^0\to K^-\pi^+$ and $D^+\to K^-\pi^+\pi^+$, the negative kaon charge indicates the flavor of the parent D. Thus the charge of the daughter kaon matches the charge of the lepton in real $\bar{B}\to DXl^-\bar{\nu}$ events. We refer hereafter to $K^\pm l^\pm$ (or Dl^-) combinations as "right sign," while $K^\pm l^\mp$ (Dl^+) are called "wrong sign."

The invariant-mass distributions for D^0 and D^+ candidates in events with an identified lepton of the right sign are shown in Fig. 1. We fit the distributions with a polynomial background plus a function representing the D signal. In the fit to the D^0 mass distribution, we exclude the invariant-mass region populated by $D^0\to K^-\pi^+\pi^0$ decays. We find, after subtraction of the continuum contribution, 445±37 D^0l^- events and 273±43 D^+l^- events. We also extract the size of the D signals in the wrong-sign (Dl^+) events. We find 275±34 D^0l^+ events, and 177±36 D^+l^- events after continuum subtraction.

Because the dE/dx measurement can separate the K from the π in only a limited momentum range, some events with $\bar{D}^0l^-$ combinations, where $\bar{D}^0\to\pi^-K^+$, can be misidentified as D^0l^-, where $D^0\to K^-\pi^+$.[18] This effect gives rise to a peak at the D^0 mass in the observed $K^-\pi^+$ mass spectrum [Fig. 1(a)].[19] Fortunately the peak due to misidentified $\bar{D}^0$'s is much wider than that due to correctly identified D^0's.[20] To extract the number of real D^0 events in the peak we fit the observed distribution to a shape found by Monte Carlo simulation, representing D^0 decays with right and wrong particle assignments. Since this procedure for fitting the $K\pi$ mass spectrum explicitly accounts for misidentification we will not discuss this contribution to our $Dl^\pm$ yields hereafter.

Table I lists the observed number of $Dl^\pm$ pairs, single leptons, and D mesons, as well as the results of our calculation of fake and cascade lepton yields. Using this information we calculate the inclusive charm production rate in semileptonic B decays. The number of D's per semileptonic B decay (R_{Dl^-}) is given by (see Appendix)

$$R_{Dl}\equiv\frac{B(\bar{B}\to DXl^-\bar{\nu})}{B(\bar{B}\to Xl^-\bar{\nu})}$$

$$=\left[\frac{N_{Dl^\pm}-N_{Df^\pm}-(N_D/N_B)(N_l-N_F)(\epsilon_{Dl}/\epsilon_D)}{N_l-N_F-N_C}\right]\times\frac{1}{\epsilon_{Dl}}\ , \qquad (1)$$

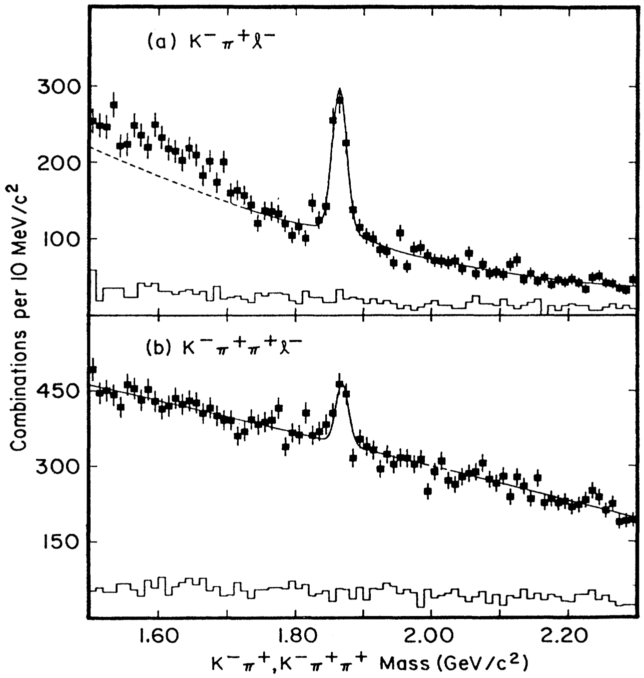

FIG. 1. Invariant-mass distribution for D candidates in events containing identified leptons. The histograms show scaled continuum data. The solid lines are the fits to the spectra.

TABLE I. Numbers of observed events related to the inclusive semileptonic branching fractions. Continuum-subtracted yields of leptons and D mesons. Errors in yields include our statistical and systematic errors combined in quadrature. The first error in R_{Dl} is our combined statistical and systematic error and the second error is the systematic error due to the uncertainty in the D branching fractions.

Leptons	Symbol	e	μ
Lepton candidates	N_l	16 527±227	10 335±173
Tracks into fiducial volume		90 055±1164	73 981±1092
Fake-subtracted leptons	N_l-N_F	16 186±232	9983±187
Cascade leptons	N_C	307±162	190±100
D mesons		D^0	D^+
D's	N_D	6093±257	3916±429
D + fake $l^\pm$	$N_{Df^\pm}$	19±5	8±4
D-l^-	N_{Dl^-}	445±37	273±43
D-l^+	N_{Dl^+}	275±34	177±36
D's per semileptonic B decay	R_{Dl}	0.67±0.09±0.10	0.26±0.07±0.04

where $N_{Dl^\pm}$, N_D, N_B, and N_l are the observed numbers of D-lepton pairs (of either sign correlation), D mesons, B mesons, and leptons, respectively, from the $\Upsilon(4S)$. The parameter N_F (N_C) is the total number of fake leptons (cascade leptons) of either sign in our sample, and $N_{Df^\pm}$ is the number of $Dl^\pm$ candidates in our sample due to lepton fakes. The parameter ϵ_{Dl} is the efficiency for finding a D in an event with an identified lepton whose momentum is greater than 1.4 GeV/c, while ϵ_D is the efficiency for finding a D in a $\bar{B}\to DX$ event; both include the relevant D branching fractions. We use $B(D^0\to K^-\pi^+)=(4.2\pm0.4\pm0.4)\%$ and $B(D^+\to K^-\pi^+\pi^+)=(9.1\pm1.3\pm0.4)\%$ as measured by the Mark III Collaboration[21] to obtain $\epsilon_{Dl}=0.0221$ for D^0 and 0.0353 for D^+, and $\epsilon_D=0.0230$ for D^0 and 0.0368 for D^+. By summing the Dl^- and Dl^+ yields together, we obtain the ratio R_{Dl^-} (the number of D's per semileptonic B decay) which is independent of the level of B^0-$\bar{B}^0$ mixing and other mechanisms for producing right-sign Dl^- pairs from different B's (for example, $W^-\to\bar{c}s$ production of $\bar{D}$ mesons).

Adding the D^0l^- and D^+l^- fractions gives $(0.93\pm0.11\pm0.11)$ D's per semileptonic B decay. Here the first error is the quadratically combined statistical and systematic uncertainty of our experiment alone, and the second is due solely to the uncertainty in the D branching fractions. This result is consistent with decays to D^0X and D^+X final states accounting for all of the semileptonic B decays with $1.4<p_l<2.4$ GeV/c.

IV. RECONSTRUCTION OF EXCLUSIVE SEMILEPTONIC B DECAYS

We now turn to extracting exclusive semileptonic B decay rates. We have reported[8] a measurement of the exclusive rate $B(\bar{B}^0\to D^{*+}l^-\bar{\nu})$, in which we identified the exclusive final state by examining the spectrum of invariant missing-mass (M_m^2) values in events containing a D^{*+} and an identified lepton. The missing mass squared recoiling against the $D^{*+}l^-$ pair is given by

$$M_m^2=(E_B-E_{D^*}-E_l)^2-(\mathbf{p}_B-\mathbf{p}_{D^*}-\mathbf{p}_l)^2 . \quad (2)$$

Although we know $|\mathbf{p}_B|\approx330$ MeV/c at the $\Upsilon(4S)$, the B direction is unknown, and our best estimate of M_m^2 results from setting $|\mathbf{p}_B|=0$. The width of the resulting missing-mass distribution is dominated by the intrinsic uncertainty in the B direction.

In this analysis we use the same technique but reconstruct only the D^0 or D^+ in leptonic events, where the D^0 and D^+ are selected as described in Sec. III.

Some of the physical processes that could result in the observation of a Dl^- final state are as follows.

(a) Direct $\bar{B}\to Dl^-\bar{\nu}$ semileptonic decay.

(b) D coming from D^* decays, where the pion (or photon) is not detected: $\bar{B}\to D^*l^-\bar{\nu}$, $D^*\to D\pi$, or $D^*\to D\gamma$.

(c) D coming from D^{**} decays, with one or more undetected particles: $\bar{B}\to D^{**}l^-\bar{\nu}$; $D^{**}\to DX$, where D^{**} is a bound state of a charmed and a light (u,d) quark in a relative $l=1$ state, as observed by ARGUS,[22] CLEO,[23] and E691.[24]

(d) The process $\bar{B}\to(Dn\pi)_{nr}l^-\bar{\nu}$, where $(Dn\pi)_{nr}$ indicates nonresonant production of extra pions.

(e) D from one B and l^- from the other: e.g., $B\to DX$, $\bar{B}\to Yl^-\bar{\nu}$.

(f) Fake leptons.

(g) Nonresonant e^+e^- annihilation (continuum).

The processes contributing to (e) are events where (1) an initial B^0 mixes to $\bar{B}^0$, (2) a $\bar{D}^0$ final state is misidentified as D^0, (3) the lepton is the result of the cascade $B\to\bar{D}\to Yl^-\bar{\nu}$, or (4) the D is produced from the fragmentation of the virtual W^+ emitted by the $\bar{b}$ quark in the spectator process $\bar{b}\to\bar{c}W^+, W^+\to c\bar{s}$. As noted in our analysis of inclusive semileptonic decays above, the background due to D^0 misidentification is explicitly taken into account in the fits to the $K\pi$ mass spectra discussed below and is not included in our background calculations.

To reduce the background from process (e), we require that the angle between the D and l^-, θ_{Dl}, satisfy $\cos\theta_{Dl}<0$. Since the angle between an uncorrelated Dl^- pair is random, the $\cos\theta_{Dl}$ cut eliminates half of this background. But the requirement of a high-momentum lepton favors Dl^- combinations from the same B traveling in roughly opposite directions; a Monte Carlo simulation of B decays using the Isgur-Scora-Grinstein-Wise[4] (ISGW) model, including the effects of our detection efficiency, shows that 1% (5%) of real $\bar{B}\to Dl^-\bar{\nu}$ ($\bar{B}\to D^*l^-\bar{\nu}$) decays are eliminated by this cut. The Monte Carlo distributions of $\cos\theta_{Dl}$ from semileptonic B decay and the background process $B\to D(D^*)X,\bar{B}\to Yl^-\bar{\nu}$ are shown in Fig. 2, along with the distribution observed in the D mass peak in our data.

There is a large combinatorial background in the D^+ sample ($D^+\to K^-\pi^+\pi^+$). To reduce this, we require the laboratory momentum of D^+ candidates to be greater than 1.5 GeV/c. Since combinatorial background in the D^0 candidate spectrum is much smaller than that of the D^+'s, we do not use this requirement in the D^0 analysis. The D momentum spectra predicted by models of semileptonic B decay[3-5] are shown in Fig. 3. The momentum cut is efficient for the decay $\bar{B}\to Dl^-\bar{\nu}$ since theories predict relatively few low-momentum D's from $\bar{B}\to Dl^-\bar{\nu}$. Furthermore, this cut will discriminate against $\bar{B}\to D^*l^-\bar{\nu}$, $D^*\to DX$ decays.[25] Therefore, since we have already measured the $\bar{B}^0\to D^{*+}l^-\bar{\nu}$ branching fraction, the momentum cut in the D^+l^- sample will enhance the signal for the decay $\bar{B}^0\to D^+l^-\bar{\nu}$ relative to the contribution from the "background" decay $\bar{B}^0\to D^{*+}l^-\bar{\nu}$. The same momentum cut in the D^0l^- sample would also reduce the $\bar{B}\to D^*l^-\bar{\nu}$ contribution. However, since the $B^-\to D^{*0}l^-\bar{\nu}$ branching fraction has not been measured and we can improve its measurement by including low-momentum D^0 sample in the analysis, this momentum cut is not applied to the D^0l^- candidates.

We extract the missing-mass-squared spectra of the Dl combinations by performing fits to the $K\pi$ and $K\pi\pi$ mass spectra over a range of missing-mass-squared values, and finding the area of the D peak in fifteen missing-mass-squared bins from $-4.5 < M_m^2 < 3.0$ GeV$^2/c^4$. The fits are performed in the same manner as the inclusive analysis described above. The continuum data taken below the $\Upsilon(4S)$ resonance [process (g)] are subtracted directly from the data taken on the $\Upsilon(4S)$ before the fit is performed, after scaling the continuum data by a factor of 2.09, which is the ratio of luminosity divided by energy squared for data taken at the $\Upsilon(4S)$ to that of the continuum. The missing-mass-squared spectra generated from the D yields in the $K\pi(\pi)$ mass spectra are shown in Fig. 4. In Tables II and III, the total number of observed Dl^- candidate events on the $\Upsilon(4S)$ are listed together with the number of these having a missing mass squared between -1.0 and 3.0 GeV$^2/c^4$ (the "signal" region).

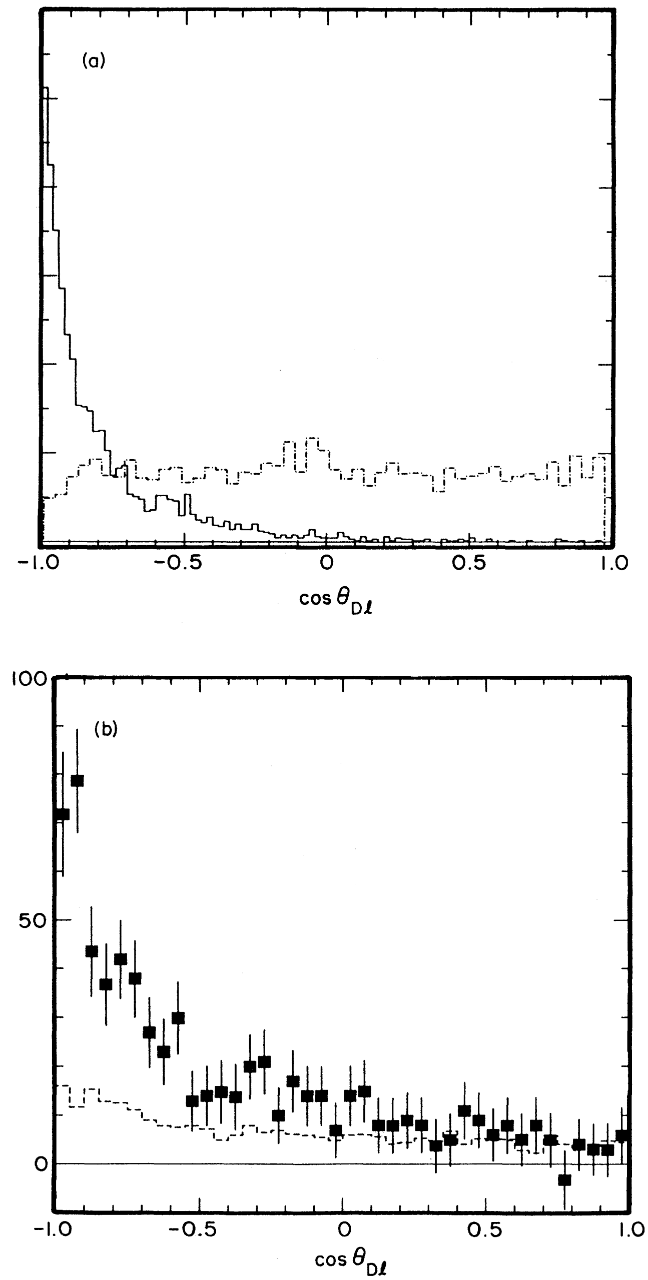

FIG. 2. (a) Monte Carlo distributions of the cosine of the angle between the D and l^-, $\cos\theta_{Dl}$, for both the semileptonic decay $\bar{B} \to Dl^-\bar{\nu}$ (solid line), and the background process $B \to D(D^*)X, \bar{B} \to Yl^-\bar{\nu}$ (dotted line). The distributions have been normalized to the same area. (b) Distribution of $\cos\theta_{Dl}$ in data, both in the D peak (data points) and in the D sidebands, properly normalized (dotted line). The peak region is defined as $1.85 < M_{K\pi} < 1.88$ GeV$/c^2$ and the sidebands $1.7 < M_{K\pi} < 1.8$ GeV$/c^2$ and $1.9 < M_{K\pi} < 2.0$ GeV$/c^2$.

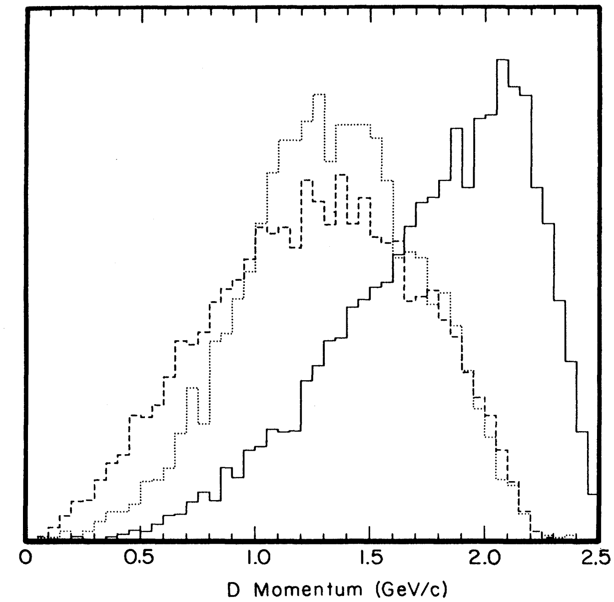

FIG. 3. Momentum spectra of final-state pseudoscalar D mesons in semileptonic B decay, as predicted by the ISGW model (Ref. 4) and the CLEO detector simulation; other models produce similar spectra. The decay modes shown are $\bar{B} \to Dl^-\bar{\nu}$ (solid line), $\bar{B} \to D^*l^-\bar{\nu}$, $D^* \to DX$ (dashed line), $\bar{B} \to D^{**}l^-\bar{\nu}$, $D^{**} \to D(D^*)X$ (dotted line).

We now consider contributions to the M_m^2 spectra from background sources; these include fake leptons and Dl^- combinations from different B's.

The contribution to the missing-mass spectrum from events with fake leptons is calculated using the mass distribution of D candidates in each missing-mass-squared interval. For each event with a D candidate we require that there is also a track in the lepton fiducial volume with momentum greater than 1.4 GeV/c, and that the track not be identified as a lepton. Each combination (D plus track) is weighted by the probability that the track will be misidentified as a lepton. This fake probability varies with track momentum and is determined from our data taken on the lepton-poor $\Upsilon(1S)$ resonance and a sample of identified hadrons in the $\Upsilon(4S)$ data.[6] The resulting fake contributions are also listed in Table II and III.

The contribution to the missing-mass-squared spectra from process (e), where the D comes from one B and the lepton from the other, is estimated by studying the missing-mass-squared distribution of "wrong-sign" Dl^+

events. The yield of Dl^+ events provides the normalization for this background [see Appendix, Eq. (A3)] and the shape of the missing-mass-squared spectrum in these events is determined from a Monte Carlo simulation. This spectrum is shown in Fig. 5, and it agrees well with the measured missing-mass-squared spectrum of Dl^+ events. From the Monte Carlo distribution, we conclude that 56% of all events in which the D and lepton come from different B's will have a missing mass squared in the region of the peak ($-1 < M_m^2 < 3$ GeV$^2/c^4$).

B^0-$\bar{B}^0$ mixing is the largest source of Dl^- events where the D and the l^- arise from different B's. From a measurement of the mixing parameter[26] r we can calculate the expected number of such Dl^- events from this process. The published values $r=0.18\pm0.05$ assume that the charged- and neutral-B semileptonic branching fractions are equal, which we do not wish to assume *a priori.* Furthermore, we do not know the relative numbers of $B^0\bar{B}^0$ and B^+B^- states coming from the $\Upsilon(4S)$. We take into account these uncertainties by setting $r=0.2^{+0.2}_{-0.1}$, and including this uncertainty in r in our systematic error. We find the number of D^0l^- (D^+l^-) events due to mixing with $\cos\theta_{Dl}<0$ to be 14^{+19}_{-8} (3^{+3}_{-1}) with 8^{+10}_{-5} (1 ± 1) of these in the signal missing-mass-squared range.

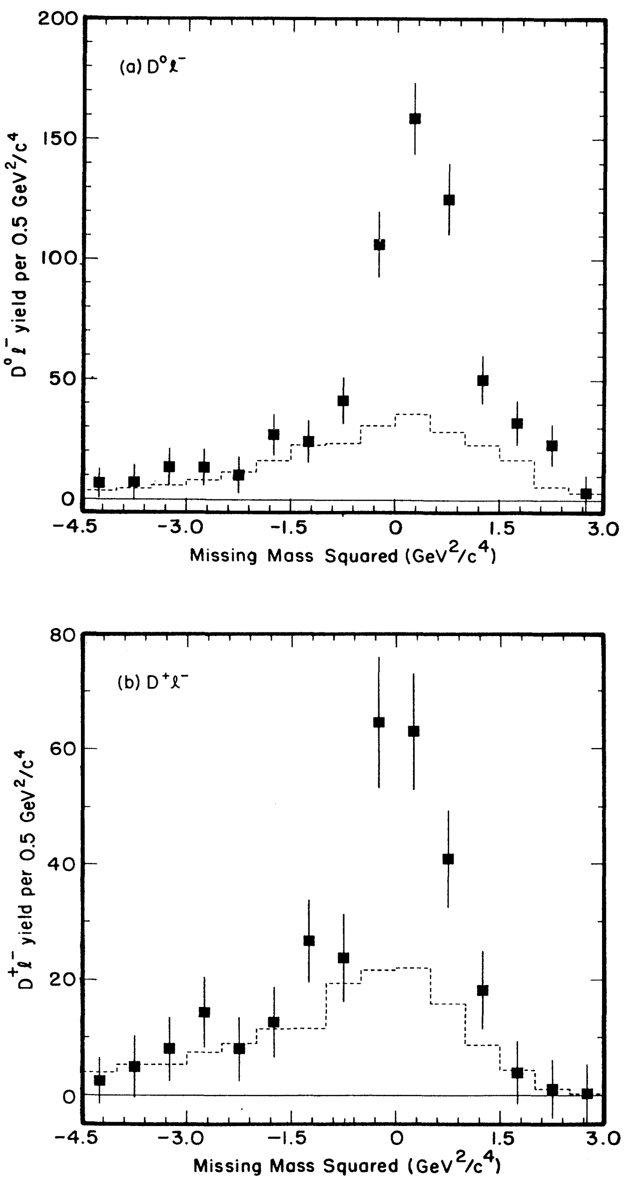

FIG. 4. Missing-mass-squared distributions from fits to $K\pi(\pi)$ mass spectra. Data points show the fitted D yield in right-sign combinations $[K^-\pi^+(\pi^+)l^-]$ in each M_m^2 bin, and the histogram shows the ones in wrong-sign combinations $[K^-\pi^+(\pi^+)l^+]$.

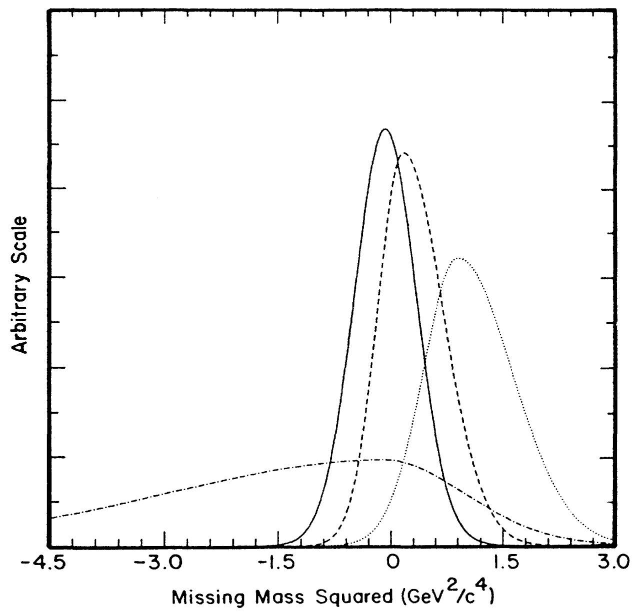

FIG. 5. Missing-mass-squared distributions generated from the CLEO Monte Carlo distribution: $B\to Dl^-\bar{\nu}$ (solid line), $B\to D^*l^-\bar{\nu}$ (dashed line), $B\to D^{**}l^-\bar{\nu}$ (dotted line), $B\to D(D^*)X, \bar{B}\to Yl^-\bar{\nu}$ (dot-dashed line). All curves have been normalized to the same area for display purposes.

Contamination from cascade leptons is estimated to be 3 ± 1 events for D^0l^- combinations and <1 for D^+l^-; W^+ fragmentation is estimated to be roughly an order of magnitude smaller than the mixing background. After subtracting off contributions from the background processes discussed above, we conclude that the total number of D^0l^- events coming from B decays is 375^{+39}_{-42}, with 356^{+32}_{-36} of these in the missing-mass-squared peak. The corresponding number for D^+l^- events are 141 ± 26, with 120 ± 22 in the peak.

In Fig. 6 the missing-mass-squared spectra of D^0l^- and D^+l^- events are plotted after subtraction of continuum contributions, fake leptons, and Dl^- events coming from opposite B's. The contributions from $\bar{B}\to Dl^-\bar{\nu}$, $\bar{B}\to D^*l^-\bar{\nu}$, and $\bar{B}\to D^{**}l^-\bar{\nu}$ are derived by fitting the missing-mass-squared spectra shown in Fig. 6 to the function

$$F(M_m^2)=A_DF_D(M_m^2)+A_{D^*}F_{D^*}(M_m^2)+A_{D^{**}}F_{D^{**}}(M_m^2)\ . \quad (3)$$

TABLE II. Number of events containing a D^0 and a right-sign lepton. Total D^0l^- events and backgrounds with $\cos\theta_{Dl}<0$. Error in number of candidates is quadratic sum of errors in each M_m^2 bin. The M_m^2 "peak" is defined as $-1<M_m^2<3$ GeV$^2/c^4$.

	Total number of events	Number of events in missing-mass-squared peak
D^0 candidates	403 ± 38	374 ± 32
Fake leptons	10 ± 3	8 ± 2
D^--l from opposite B's [process (e)]:		
(e1) Mixing produces $\bar{B}^0\bar{B}^0$	14^{+19}_{-8}	8^{+10}_{-5}
(e2) Lepton comes from cascade decay	3 ± 1	2 ± 1
(e3) D^0 is produced by W^+ fragmentation	1 ± 1	<1
D^0-l events from B decay	375^{+39}_{-42}	356^{+32}_{-36}

The amplitudes A_D, A_{D^*}, and $A_{D^{**}}$ are determined by our fit. The functions $F_D(M_m^2)$, $F_{D^*}(M_m^2)$, and $F_{D^{**}}(M_m^2)$ are determined using our Monte Carlo generator of semileptonic B decay,[27] and are each normalized such that an integral over M_m^2 gives unity. These functions are shown in Fig. 5. We have tested the accuracy of our simulation by comparing the function $F_{D^*}(M_m^2)$ to data from identified $\bar{B}^0\to D^{*+}l^-\bar{\nu}$ decays[8] in which we reconstruct the D^{*+} via the decay $D^{*+}\to D^0\pi^+$, $D^0\to K^-\pi^+$, or $D^0\to K^-\pi^+\pi^+\pi^-$, select events which have a M_m^2 recoiling against the $D^{*+}l^-$ satisfying $|M_m^2(D^{*+}l^-)|<1$ GeV$^2/c^4$, and then recalculate the missing mass for only the D^0l^- combinations. The data and the fit curve are shown in Fig. 7. The data are well described by the Monte Carlo–generated function.

For the D^{**} state [process (c)], we have investigated the missing-mass-squared distributions for a range of assumptions concerning the D^{**} mass, width, and spin parity. We find the distributions are similar in all cases. For process (d) we considered nonresonant production of only one or two extra pions. The $D\pi(\pi)$ momentum vectors are assumed to be distributed according to phase space, and the resulting missing-mass-squared distribution is indistinguishable from that for the D^{**} state.[28] Thus $A_{D^{**}}$ measures the magnitude of the sum of processes (c) and (d).

In our fits to the Dl^- spectra, we fix the contribution from $\bar{B}^0\to D^{*+}l^-\bar{\nu}$ with the D^{*+} feeding down to a D^+ or a D^0 using our measurement[8] of $B(\bar{B}^0\to D^{*+}l^-\bar{\nu})=(4.6\pm0.5\pm0.7)\%$ and the measurement of the D and D^{*+} branching fractions by the Mark III experiment $[B(D^{*+}\to D^0\pi^+)=0.57\pm0.04\pm0.04$ and $B(D^{*+}\to D^+X)=0.43\pm0.04\pm0.04]$.[21,29] We calculate $A_{D^{*+}}(D^0)=87\pm9$ and $A_{D^{*+}}(D^+)=37\pm12$, where the errors are due to uncertainties in the input branching fractions and are treated as systematic errors in our analysis. The relative error in $A_{D^{*+}}(D^0)$ is much smaller because the relevant D branching fractions cancel in the calculation.

In our fits to the D^0l^- spectra, we further constrain our result by using additional information about the D^0 momentum spectra. We divide our D^0 data into two momentum bins: 0 GeV/$c<p_{D^0}<1.5$ GeV/c and 1.5 GeV/$c<p_{D^0}<2.5$ GeV/c. We find 263 ± 29 D^0l^- events

TABLE III. Number of events containing a D^+ and a right-sign lepton. Total D^+l^- events and backgrounds with $\cos\theta_{Dl}<0$ and D^+ momentum <1.5 GeV/c. Error in number of candidates is quadratic sum of errors in each M_m^2 bin. The M_m^2 "peak" is defined as $-1<M_m^2<3$ GeV$^2/c^4$.

	Total number of events	Number of events in mixing-mass-squared peaks
D^+ candidates	147 ± 26	123 ± 22
Fake leptons	3 ± 1	2 ± 1
D^+-l from opposite B's [process (e)}:		
(e1) Mixing produces $\bar{B}^0\bar{B}^0$	3^{+3}_{-1}	1 ± 1
(e2) Lepton comes from cascade decay	<1	<1
(e3) D^+ is produced by W^+ fragmentation	<1	<1
D^+-l events from B decay	141 ± 26	120 ± 22

in the lower-momentum bin and 140±24 in the higher-momentum bin. Theoretical models of semileptonic B decay predict the daughter D momentum spectra (as seen in Fig. 3) and thus the relative population of these two bins for each of the decay processes. We use this information to constrain the relative areas of individual fit components in the two different momentum bins, which we fit simultaneously. The models all predict similar D momentum spectra, so this procedure is essentially model independent. Fitting the D^0 data only yields

$$\begin{aligned} A_{D^0} &= 42\pm 14 \ , \\ A_{D^*}(D^0) &= 218\pm 35 \ , \\ A_{D^{**}}(D^0) &= 79\pm 29 \ , \end{aligned} \tag{4}$$

while fitting the D^+ data gives

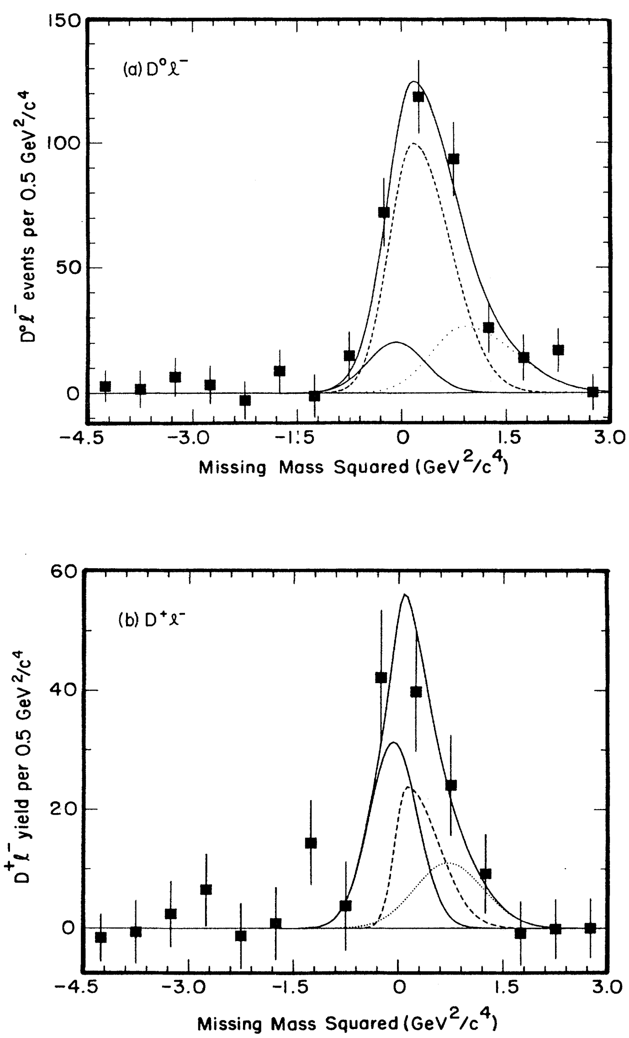

FIG. 6. Missing-mass-squared distributions from data with fit. Contributions from fake leptons and Dl^- events from different B's have been subtracted. The fit to the distribution and the various components are displayed separately, using the same symbols as in Fig. 5.

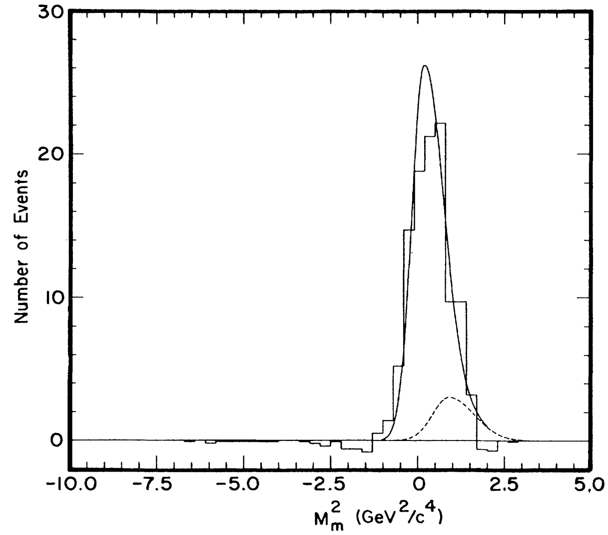

FIG. 7. Missing-mass-squared (M_m^2) distributions from data (histogram) and Monte Carlo distribution (solid curve) for the processes $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$, $D^{*+} \to D^0 \pi^+$ and $B \to D^{**} l^- \bar{\nu}$, $D^{**} \to D^{*+} X, D^{*+} \to D^0 \pi^+$. The dashed line shows the assumed contribution from the latter process. The missing mass is calculated using only the D^0 and l^- and so the distribution is centered at small positive values of M_m^2.

$$A_{D^+} = 54\pm 18, \quad A_{D^{**}}(D^+) = 27\pm 17 \ . \tag{5}$$

We make a second fit to the $D^0 l^-$ and $D^+ l^-$ missing-mass-squared spectra in which we impose the constraint that the ratio of the semileptonic widths into vector versus pseudoscalar final states must be the same for charged and neutral B mesons, which follows from isospin symmetry:

$$\frac{\Gamma(\bar{B}^0 \to D^{*+} l^- \bar{\nu})}{\Gamma(\bar{B}^0 \to D^+ l^- \bar{\nu})} = \frac{\Gamma(B^- \to D^{*0} l^- \bar{\nu})}{\Gamma(B^- \to D^0 l^- \bar{\nu})} \ . \tag{6}$$

Our fit to the $D^0 l^-$ spectrum alone yields $2.4^{+2.2}_{-1.2}$ for this ratio while fitting the $D^+ l^-$ spectrum gives $2.6^{+1.3}_{-0.7}$. The combined fit to the $D^0 l^-$ and $D^+ l^-$ spectra yields

$$\begin{aligned} & V/P = 2.6^{+1.1}_{-0.6}, \quad A_{D^*}(D^0) = 220\pm 25 \ , \\ & A_{D^{**}}(D^0) = 79\pm 28, \quad A_{D^{**}}(D^+) = 27\pm 16 \ , \end{aligned} \tag{7}$$

where V/P is the ratio of widths for decays into vector vs pseudoscalar mesons. Using these results and the D^{*+} magnitudes $A_{D^{*+}}(D^+)$ and $A_{D^{*+}}(D^0)$ given above we find

$$A_{D^0} = 39\pm 14, \quad A_{D^+} = 54\pm 18 \ , \tag{8}$$

with $\chi^2/N_{\rm DF} = 0.5$ for 20 degrees of freedom. We note that setting $A_{D^{**}} = 0$ gives a poorer fit ($\chi^2/N_{\rm DF} = 1.0$) due to the excess of events at large missing-mass-squared values, which must be due to extra particles which do not come from D^*'s.[30]

The results of the fits to the Dl^- missing-mass-squared

TABLE IV. Results of fitting the Dl^- missing-squared spectra.

	$A_i(D^0)$	$A_i(D^+)$
(a) The D^0l^- and D^+l^- spectra are fit independently		
$\bar{B}\to Dl^-\bar{\nu}$	42±14	54±18
$\bar{B}\to D^*l^-\bar{\nu}$	218±35	(37)
$\bar{B}\to D^{**}l^-\bar{\nu}$ and $\bar{B}\to D(n\pi)l^-\bar{\nu}$	79±29	27±17
(b) The D^0l^- and D^+l^- spectra are fit simultaneously, with the ratio of vector to pseudoscalar widths constrained to be the same in both fits		
$\bar{B}\to Dl^-\bar{\nu}$	39±14	54±18
$\bar{B}\to D^*l^-\bar{\nu}$	220±25	(37)
$\bar{B}\to D^{**}l^-\bar{\nu}$ and $\bar{B}\to D(n\pi)l^-\bar{\nu}$	79±28	27±16

spectra are summarized in Table IV.

The branching fractions $B(B^-\to D^0l^-\bar{\nu})$ and $B(\bar{B}^0\to D^+l^-\bar{\nu})$ are given by

$$B(B^-\to D^0l^-\bar{\nu})=\frac{A_{D^0}}{2N_{4S}f_{+-}\epsilon_{D^0l}\epsilon_l\epsilon_s}\ , \tag{9}$$

$$B(\bar{B}^0\to D^+l^-\bar{\nu})=\frac{A_{D^+}}{2N_{4S}f_{00}\epsilon_{D^+l}\epsilon_x\epsilon_l\epsilon_s}\ . \tag{10}$$

Here $2N_{4S}=N_B=480\,000$ is the total number of B mesons assuming $B(\Upsilon(4S)\to B\bar{B})=1.0$, f_{+-} is the fraction of $\Upsilon(4S)$ decays to B^+B^-, f_{00} is the fraction of $\Upsilon(4S)$ decays to $B^0\bar{B}^0$, ϵ_{Dl} is the efficiency for detecting the D^0 or D^+ in a semileptonic B decay as described in Sec. III (including the $\cos\theta_{Dl}$ cut, $\epsilon_{D^0l}=0.0219$ and $\epsilon_{D^+l}=0.0356$), ϵ_x is the fraction of the D^+ momentum spectrum retained by the D^+ momentum cut when the leptons are required to have a momentum 1.4 GeV/c $<p_l<2.4$ GeV/c (0.74 for D^+ and 0.33 for D^{*+} in the ISGW model[4]), ϵ_l is the efficiency for finding a lepton with momentum $p_l>1.4$ GeV/c [(62±2)% for electrons and (41±1)% for muons], and ϵ_s is the fraction of the lepton spectrum from this process in the 1.4 to 2.4 GeV/c momentum range (0.46 in the ISGW model[4]). We obtain

$$B(B^-\to D^0l^-\bar{\nu})=(1.6\pm0.6\pm0.3)(0.5/f_{+-})\%\ , \tag{11}$$

$$B(\bar{B}^0\to D^+l^-\bar{\nu})=(1.8\pm0.6\pm0.3)(0.5/f_{00})\%\ . \tag{12}$$

The latter result agrees well with the value reported by the ARGUS Collaboration of $(1.6\pm0.5\pm0.5)\times(0.5/f_{00})\%$.[7] Our first error is statistical. The second error is systematic and includes contributions due to the uncertainty in the magnitude of the feeddown from D^{*+} [process (b)], the uncertainties in the fitting procedure,[31] and the uncertainty in the D branching fractions. Here, and hereafter, we combine the statistical and systematic errors in the D branching fractions in quadrature and treat the result as a contribution to our systematic error.

From $A_{D^*}(D^0)$ we obtain the branching fraction $B(B^-\to D^{*0}l^-\bar{\nu})$ using a similar procedure. Because of the constraints we impose in fitting the spectrum this result is not independent of those quoted above. First we subtract the contribution to $A_{D^*}(D^0)$ from $B(\bar{B}^0\to D^{*+}l^-\bar{\nu})$ decays; thus the D^{*0} component of A_{D^*} is 133±25 events. Using an equation analogous to Eq. (9), where $\epsilon_{Dl}=0.0209$ and $\epsilon_s=0.63$ for D^*'s from the ISGW model, we find

$$B(B^-\to D^{*0}l^-\bar{\nu})=(4.1\pm0.8^{+0.8}_{-0.9})(0.5/f_{+-})\%\ . \tag{13}$$

V. RESULTS AND CONCLUSIONS

As noted above, from our simultaneous fit to the D^0l^- and D^+l^- spectra we extract the ratio of vector-to-pseudoscalar decay widths in semileptonic B decay. We find

$$\frac{\Gamma(\bar{B}\to D^*l^-\bar{\nu})}{\Gamma(\bar{B}\to Dl^-\nu)}=2.6^{+1.1+1.0}_{-0.6-0.8}\ , \tag{14}$$

TABLE V. Model predictions for semileptonic B decay.

Models	$\frac{\Gamma_{SL}(D^*)}{\Gamma_{SL}(D)}$	$\Gamma(\bar{B}\to Dl^-\bar{\nu})$ (10^{12} sec^{-1})	$\Gamma(\bar{B}\to D^*l^-\bar{\nu})$ (10^{12} sec^{-1})
ISGW (Ref. 4)	2.3	$11.2\ \lvert V_{cb}\rvert^2$	$25.2\lvert V_{cb}\rvert^2$
KS (Ref. 5)	3.1	$8.3\lvert V_{cb}\rvert^2$	$25.7\lvert V_{cb}\rvert^2$
WBS (Ref. 3)	2.7	$8.1\lvert V_{cb}\rvert^2$	$21.9\lvert V_{cb}\rvert^2\rvert$

where we have required $\Gamma_{SL}(D^{*+})/\Gamma_{SL}(D^+) = \Gamma_{SL}(D^{*0})/\Gamma_{SL}(D^0)$.[32] This result is independent of the values of f_{00} and f_{+-} and is compatible with theoretical predictions, as shown in Table V.[33] The result is also consistent with the value previously found by the ARGUS Collaboration[7] of $3.3^{+3.7}_{-1.1}$.

Isospin symmetry implies $\Gamma(\bar{B}^0 \to D^{*+} l^- \bar{\nu}) = \Gamma(B^- \to D^{*0} l^- \bar{\nu})$.[34] Therefore the lifetime ratio of charged to neutral B mesons can be calculated from the ratio of semileptonic branching fractions:

$$\frac{\tau(B^-)}{\tau(B^0)} = \frac{B(B^- \to D^{*0} l^- \bar{\nu})}{B(\bar{B}^0 \to D^{*+} l^- \bar{\nu})} = \frac{B(B^- \to D^0 l^- \bar{\nu})}{B(\bar{B}^0 \to D^+ l^- \bar{\nu})}$$
$$= (0.89 \pm 0.19 \pm 0.13)(f_{00}/f_{+-}) , \quad (15)$$

where our use of an isospin symmetry constraint in our fits [see Eq. (6)] imposes the second equality on our results. Here the first error is statistical. The second error is a systematic error and includes the uncertainty in the magnitude of the D^{*+} contribution, the uncertainties in the fitting procedure,[31] and the uncertainty in the branching fraction $B(D^{*+} \to D^0 \pi^+)$.[29] This measurement of the lifetime ratio of B mesons is consistent with our previously published limits,[35] and a recent indirect measurement by ARGUS.[36] Theoretical predictions for this ratio require it to be greater than unity, with typical values in the range of 1.0 to 1.2.[37] Note that here the result for the ratio $\tau(B^-)/\tau(B^0)$ is directly proportional to the ratio of neutral to charged B mesons produced at the $\Upsilon(4S)$, f_{00}/f_{+-}, so a possible decrease in this ratio would result in a similar decrease in the lifetime ratio.

In principle, the best way to measure V_{cb} is to measure $\Gamma(\bar{B} \to D l^- \bar{\nu})$. Previous measurements of V_{cb} have relied on measurement of the average B-meson lifetime, $\tau_B = 1.18 \pm 0.11$ psec,[38] and either the inclusive semileptonic branching fraction or the exclusive branching fraction $B(\bar{B}^0 \to D^{*+} l^- \bar{\nu})$. The inclusive procedure results in an estimate of $|V_{cb}|$ in the range 0.03 to 0.06.[39] The uncertainty here is large because the expression for the inclusive rate includes the fifth power of the poorly estimated b-quark mass. The uncertainty in the theoretical calculations of the exclusive semileptonic widths is contained in the hadronic form factors involved. For $\bar{B} \to D^* l^- \bar{\nu}$ there are three form factors whereas only one enters into the calculation of $\bar{B} \to D l^- \bar{\nu}$. The predictions of several theoretical models for the exclusive semileptonic width $\Gamma(\bar{B} \to D l^- \bar{\nu})$ in terms of $|V_{cb}|^2$ are shown in Table V.

We use the relation $\Gamma(\bar{B} \to D l^- \bar{\nu}) = B(\bar{B} \to D l^- \bar{\nu})/\tau(\bar{B})$ to find the exclusive widths. However, we do not know the individual lifetimes of charged and neutral B mesons, as only the average B lifetime τ_B is measured. In addition, τ_B is measured on the continuum above the $\Upsilon(4S)$ and includes not only B^0 and B^- mesons but also an unknown admixture of other bottom-flavored hadrons. We assume $\tau(B^0) = \tau(B^-) = \tau_B$ and assign an additional 20% systematic error to τ_B to account for this uncertainty. Then

$$\Gamma(\bar{B} \to D l^- \bar{\nu}) = \left[\frac{1}{2\tau_B}\right][B(B^- \to D^0 l^- \bar{\nu}) + B(\bar{B}^0 \to D^+ l^- \bar{\nu})]$$
$$= (1.5 \pm 0.4 \pm 0.4) \times 10^{10} \text{ sec}^{-1} , \quad (16)$$

where we have used $f_{00} = f_{+-} = 0.5$. Thus result implies $|V_{cb}| = 0.037 \pm 0.005$ in the ISGW model and $|V_{cb}| = 0.043 \pm 0.006$ in the Wirbel-Stech-Bauer (WSB) and Körner-Schuler (KS) models, with the errors being statistical only. The results are only weakly dependent on the individual values of f_{00} and f_{+-}. If we naively average these results and treat the model dependence as a systematic error, we obtain $|V_{cb}| = 0.040 \pm 0.006 \pm 0.006$. The systematic error here is dominated by the systematic error we assigned to τ_B. This value of $|V_{cb}|$ is consistent with previous estimates using the average semileptonic branching fraction of B mesons, and using the branching fraction $B(\bar{B}^0 \to D^{*+} l^- \bar{\nu})$.[8,9]

Finally, it is interesting to compare the sum of the semileptonic branching fractions for the exclusive charmed modes to our results for the inclusive semileptonic branching fractions to charm discussed in Sec. III. There we found that

$$\frac{B(\bar{B} \to (D^0 + D^+) X l^- \bar{\nu})}{B(\bar{B} \to X l^- \bar{\nu})}$$

was $0.93 \pm 0.11 \pm 0.11$. Using our new measurement,[6]

$$B(B \to X l^- \bar{\nu}) = (10.2 \pm 0.2 \pm 0.4)\% , \quad (17)$$

we find $B(\bar{B} \to (D^0 + D^+) X l^- \bar{\nu}) = (9.5 \pm 1.2 \pm 1.2)\%$. To make the appropriate comparison we must average over the exclusive branching fractions of charged and neutral B's:

$$\left\langle \sum_{X'=D,D^*} B(B \to X' l^- \bar{\nu}) \right\rangle = f_{00}[B(\bar{B}^0 \to D^+ l^- \bar{\nu}) + B(\bar{B}^0 \to D^{*+} l^- \bar{\nu})] + f_{+-}[B(B^- \to D^0 l^- \bar{\nu}) + B(B^- \to D^{*0} l^- \bar{\nu})]$$
$$= (6.1 \pm 0.6 \pm 1.1)\% . \quad (18)$$

Taking the ratio of this number to the inclusive semileptonic charm branching fraction above we find that only $(64 \pm 10)\%$ of the total is accounted for by the D and D^* final states.[40] The comparison is summarized in Table VI. This result is somewhat lower than theoretical predictions of Isgur *et al.*[4] which expected $\approx 87\%$ of the inclusive rate accounted for by the lowest-lying states.[41] It also indicates that B decays do not respect the Shifman-Voloshin limit[42] in which decays to the lowest-lying vector and pseudoscalar mesons account for all of the semileptonic decay width. We note that adding contributions from other [D^{**},$(D\pi)_{nr}$, or $(D\pi\pi)_{nr}$] final states could ac-

TABLE VI. Comparison of exclusive and inclusive semileptonic branching fractions. We have used $f_{00}=f_{+-}=0.5$ to make the entries in the table; however, the f's drop out when one takes the appropriate average over charged and neutral B's (see text). The first errors in all quantities are statistical only and the second are systematic and dominated by the uncertainties in the D branching fractions. These largely cancel out when the ratio of exclusive to inclusive branching fractions is taken.

	B^0 exclusive (%)	B^+ exclusive (%)		Average B (%)
$B(B\to Dl^-\bar{\nu})$	$1.8\pm0.6\pm0.3$	$1.6\pm0.6\pm0.3$	$B(B\to D^+Xl^-\bar{\nu})$	$2.7\pm0.6\pm0.4$
$B(B\to D^*l^-\bar{\nu})$	$4.6\pm0.5\pm0.7$	$4.1\pm0.8^{+0.8}_{-0.9}$	$B(B\to D^0Xl^-\bar{\nu})$	$6.9\pm0.9\pm1.0$
$\sum_{X'=D,D^*} B(B\to X'l^-\bar{\nu})$	$6.4\pm0.8\pm1.0$	$5.7\pm1.0\pm1.1$	$\sum_{D=D^0,D^+} B(B\to DXl^-\bar{\nu})$	$9.5\pm1.2\pm1.2$

Average

$$\left\langle \sum_{X'=D,D^*} B(B\to X'l^-\bar{\nu})\right\rangle=(6.1\pm0.6\pm1.1)\%$$

Fraction of exclusive decays to lowest-lying states in inclusive $B\to DXl^-\bar{\nu}$:

$$\left\langle \sum_{X'=D,D^*} B(B\to X'l^-\bar{\nu})\right\rangle \Big/ \sum_{D=D^0,D^+} B(B\to DXl^-\bar{\nu})=0.64\pm0.10\pm0.06$$

count for the remainder of the inclusive semileptonic rate, consistent with our result for inclusive semileptonic charm production discussed in Sec. III above. The presence of such states is clearly indicated by the data as a shoulder on the high side of the invariant missing-mass-squared peak. The shoulder is most pronounced when the D's have low momentum (<1.5 GeV/c) as one would expect from decays of excited D systems or nonresonant production of extra particles.

We have assumed throughout this analysis that the Dl events we observe on the $\Upsilon(4S)$ come from B mesons (since the contribution from $e^+e^-\to q\bar{q}$ events is directly subtracted). It is possible that a significant fraction of $\Upsilon(4S)$ decays do not proceed through the $B\bar{B}$ channel.[43] Then $f_{00}+f_{+-}<1$ and the total number of B's in our data sample, N_B, is smaller than we have assumed. The exclusive branching fractions we quote would need to be scaled by the correct values of f_{00} or f_{+-}. The value of $|V_{cb}|$ determined from the exclusive branching fractions would also increase. If the non-$B\bar{B}$ decays of the $\Upsilon(4S)$ produce D's and leptons within our momentum cuts, then our results for inclusive semileptonic B decays are in error due to this background. Since the exclusive modes are less likely to include background from non-$B\bar{B}$ decays, the sum of the exclusive branching fractions would increase relative to the inclusive semileptonic branching fraction to charm. In any case, the value for the ratio of vector-to-pseudoscalar widths $\Gamma_{SL}(D^*)/\Gamma_{SL}(D)$ would be unchanged, as would the lifetime ratio of charged to neutral B mesons $\tau(B^-)/\tau(B^0)$.

In conclusion we have made the first measurements of the exclusive semileptonic branching fractions of B^- mesons to the charmed final states D^0 and D^0:

$$B(B^-\to D^{*0}l^-\bar{\nu})=(4.1\pm0.8^{+0.8}_{-0.9})(0.5/f_{+-})\% ,$$

$$B(B^-\to D^0(l^-\bar{\nu})=(1.6\pm0.6\pm0.3)(0.5/f_{+-})\% .$$

We confirm the observation of the decay $\bar{B}^0\to D^+l^-\bar{\nu}$ and measure the branching fraction:

$$B(\bar{B}^0\to D^+l^-\bar{\nu})=(1.8\pm0.6\pm0.3)(0.5/f_{00})\% .$$

These results yield the ratio of vector-to-pseudoscalar widths

$$\Gamma_{SL}(D^*)/\Gamma_{SL}(D)=2.6^{+1.1+1.0}_{-0.6-0.8} .$$

We find the lifetime ratio for charged to neutral B mesons $\tau(B^-)/\tau(B^0)$ to be

$$(0.89\pm0.19\pm0.13)(f_{00}/f_{+-}) .$$

Using theoretical models, we extract a measurement of $|V_{cb}|=0.040\pm0.006\pm0.006$. The sum of the exclusive semileptonic branching fractions to pseudoscalar- and vector-meson final states only accounts for $(64\pm10)\%$ of the total semileptonic branching fraction to charmed final states.

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APPENDIX

Our goal is to extract the rate of $\bar{B}\to DXl^-\bar{\nu}$ in our sample of B decays, using only our measured D and lepton yields and lepton fake rates. We begin by expressing our yield of Dl pairs in terms of the contributing physical processes:

$$N_{Dl^-}=N_{SL}+f_{mis}(1-f_{mix})N_{opp}+f_{mix}N_{opp} + N_{Wcs}+N_{cas}+N_{Df^-} , \quad (A1)$$

$$N_{Dl^+}=(1-f_{mix})N_{opp}+f_{mis}N_{SL}+N_{Df^+} , \quad (A2)$$

where

$$N_{\rm SL}=N_B B(\bar{B}\to DXl^-\bar{\nu})\epsilon_{Dl}\text{-}\epsilon_l \ ,$$

$$N_{\rm opp}=N_B B(\bar{B}\to DX)B(\bar{B}\to X'l^-\bar{\nu})\epsilon_{Dl}\text{-}\epsilon_l \ ,$$

$$N_{Wcs}=N_B B(B\to DX)B(\bar{B}\to X'l^-\bar{\nu})\epsilon_{Dl}\text{-}\epsilon_l \ ,$$

$$N_{\rm cas}=N_B B(B\to \bar{D}X)B(\bar{D}\to Yl^-\bar{\nu})B(\bar{B}\to DX)\epsilon_{Dl}\text{-}\epsilon_l' \ ,$$

and $N_{Df^{\pm}}$ is the number of $D+(l^{\pm}$ fake) events passing all cuts. The efficiencies are ϵ_{Dl}, the efficiency for finding a D in an event containing a lepton with momentum $p_l > 1.4$ GeV/c,[44] including D branching fractions, and ϵ_l (ϵ_l'), the efficiency for finding a lepton from a primary B decay (cascade D decay) with momentum greater than 1.4 GeV/c. The parameter $f_{\rm mix}$ is the fraction of all B decays which are mixed and is given approximately by $f_{\rm mix}\approx f_{00}r\approx 0.1$, where f_{00} is the fraction of $B^0\bar{B}^0$ pairs produced at the $\Upsilon(4S)$ and r is the mixing parameter.[26] The parameter $f_{\rm mis}$ is the fraction of $D^0\to K^-\pi^+$ events misidentified as $\bar{D}^0\to K^+\pi^-$, as discussed in the text. Since misidentified events have a broader peak than correctly identified D^0's, we can account for them directly as a background in our fits to the $K\pi$ mass spectrum, and thus we will drop them from our expressions hereafter. It should be noted that the inclusive branching fractions listed are averages of those of B^0 and B^+ mesons, weighted by their production cross sections at the $\Upsilon(4S)$. Finally we note that charge conjugation is implied throughout, so that N_B is the number of B and $\bar{B}$ mesons produced at the $\Upsilon(4S)$.

As an aside, we note that we can now rearrange Eq. (A2) to read

$$N_{\rm opp}=\frac{N_{Dl^+}-N_{Df^+}}{1-f_{\rm mix}} \ , \qquad \text{(A3)}$$

which fixes the number of events rising from opposite B's. We make use of this result to calculate the magnitude of the misidentification and mixing backgrounds in the right-sign (Dl^-) signal.

We also note that in order-of-magnitude estimates

$$N_{\rm opp}\approx N_{\rm SL} \ ,$$

$$N_{Wcs}=\left[\frac{B(B\to DX)}{B(B\to \bar{D}X)}\right]N_{\rm opp}\lesssim 0.01N_{\rm opp} \ ,$$

$$N_{\rm casc}\approx\left[\frac{\epsilon_l'}{\epsilon_l}\right]N_{\rm opp}=0.02N_{\rm opp} \ ,$$

where we assume that $B\to DX$ arises from fragmentation of the $W^+\to c\bar{s}$ vertex. Thus all terms following $N_{\rm SL}$ in Eq. (A1) are an order of magnitude smaller than $N_{\rm SL}$ itself, and are "first-order corrections." Throughout this analysis we ignore "second-order correction" terms [e.g., this is why we have not included $f_{\rm mix}N_{\rm casc}$ in Eq. (A2)].

Adding Eq. (A1) and (A2) gives

$$N_{Dl^{\pm}}=N_{\rm SL}+N_{\rm opp}+N_{Wcs}+N_{\rm casc}+N_{Df^{\pm}} \ . \qquad \text{(A4)}$$

Now we introduce our observed number of D mesons and leptons, N_D and N_l:

$$N_D=N_B[B(\bar{B}\to DX)+B(B\to DX)]\epsilon_D \ , \qquad \text{(A5)}$$

$$\begin{aligned} N_l&=N_B B(\bar{B}\to Xl^-\bar{\nu})\epsilon_l+N_F\\ &\quad+N_B B(B\to\bar{D}X)B(\bar{D}\to Yl^-\bar{\nu})\epsilon_l'\\ &=N_B B(\bar{B}\to Xl^-\bar{\nu})\epsilon_l+N_F+N_C \ , \end{aligned} \qquad \text{(A6)}$$

where N_F is the total number of lepton fakes of both signs, N_C is the total number of cascade leptons with momenta greater than 1.4 GeV/c, and ϵ_D is the efficiency for finding a D in a $\bar{B}\to DX$ event.

Inserting these equations into (A4) to eliminate the branching fractions, and dropping terms of second order, we arrive at

$$\begin{aligned} N_{Dl^{\pm}}&=N_B B(\bar{B}\to DXl^-\bar{\nu})\epsilon_{Dl}\epsilon_l\\ &\quad+\frac{N_D}{N_B}\frac{\epsilon_{Dl}}{\epsilon_D}(N_l-N_F)+N_{Df^{\pm}} \ . \end{aligned} \qquad \text{(A7)}$$

Solving this equation for $B(\bar{B}\to DXl^-\bar{\nu})$ and (A6) for $B(\bar{B}\to Xl^-\bar{\nu})$, dividing the former by the latter yields

$$\begin{aligned} R_{Dl}&\equiv\frac{B(\bar{B}\to DXl^-\bar{\nu})}{B(\bar{B}\to Xl^-\bar{\nu})}\\ &=\left[\frac{N_{Dl^{\pm}}-N_{Df^{\pm}}-\left[\frac{N_D}{N_B}\right](N_l-N_F)\left[\frac{\epsilon_{Dl}}{\epsilon_D}\right]}{N_l-N_F-N_C}\right]\frac{1}{\epsilon_{Dl}} \ . \end{aligned} \qquad \text{(A8)}$$

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[15]R. Kowalewski, Ph.D. dissertation, Cornell University, 1988.

[16]We exclude combinations with tracks which are positively identified as nonleptonic.

[17]Hereafter, unless otherwise indicated, we will adopt the notation that D represents any pseudoscalar nonstrange charmed meson with its constituent quarks in a relative $l=0$ state. Further, B represents an average over the charged and neutral bottom mesons produced in decays of the $\Upsilon(4S)$ resonance.

[18]Similarly, $D^0 l^-$ with $D^0 \to K^- \pi^+$ contributes to the $\bar{D}^0 l^-$ distribution.

[19]A Monte Carlo simulation of our particle identification procedure indicates that $45\pm1\%$ of $\bar{D}^0$'s will be accepted as D^0's due to this effect. For a more thorough discussion, see E. Blucher, Ph.D. dissertation, Cornell University, 1988.

[20]The rms width for the D^0 in the $K^-\pi^+$ mode is 10.6 MeV/c in the CLEO detector; the rms width for $\bar{D}^0 \to K^+\pi^-$ misidentified as π^+K^- depends on the $\bar{D}^0$ momentum but averages about 45 MeV/c.

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[25]The momentum cut will, of course, discriminate against any process which produces low-momentum D^+'s in the final state, and this includes processes (c) and (d) as well as (b).

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[27]The decays $\bar{B} \to D l^- \bar{\nu}$ and $\bar{B} \to D^* l^- \bar{\nu}$ are produced using the ISGW model (Ref. 4), and current values of the relevant D branching fractions have been used. $F_{D^*}(M_m^2)$ is the Dl^- missing-mass-squared spectrum for $B^- \to D^* l^- \bar{\nu}, D^* \to DX$, where X can be a pion or photon and D can be a D^+ or a D^0. The shape of the spectrum does not depend on the final pseudoscalar state nor the initial vector state. $F_{D^{**}}(M_m^2)$ is the analogous extension for D^{**} decays.

[28]We note, however, that there are no theoretical calculations of $\Gamma(\bar{B} \to D\pi(\pi) l^- \bar{\nu})$ in the context of the form-factor models (Refs. 3–5) we are considering; thus our predictions for process (d) arise from a free-quark model calculation which may not accurately represent the c-quark fragmentation.

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[30]We find that setting $A_{D^{**}}=0$ yields $V/P=2.4^{+0.8}_{-0.5}$, $A_{D^*}(D^0)=248\pm23$.

[31]The systematic error includes contributions due to the uncertainties in the magnitudes and shapes of the missing-mass spectra of all background processes [(c)–(f)], and in the shapes of the signal processes [(a) and (b)].

[32]The errors in $\Gamma_{\rm SL}(D^{*0})/\Gamma_{\rm SL}(D^0)$ are enhanced due to the correlations between the D^0, D^{*0}, and D^{**} components of the fit. The error quoted reflects the rms spread of the resulting (non-Gaussian) distribution of values obtained for the vector-to-pseudoscalar ratio.

[33]We note that this result, combined with our previously published measurement of the D^{*+} polarization (see Ref. 8 above), restricts the free parameter J_B/J_B^0 in the model of Wirbel *et al.* (see Ref. 3 above) to be between 0.6 and 1.2 at the 90% confidence level (using only the statistical error).

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[40]We choose to normalize our results in this manner in order to avoid the systematic errors in the D branching fractions.

[41]We note that this disagreement ($\approx 2\sigma$) with the model of Isgur *et al.* may indicate that our estimate of the theoretical uncertainty ($\pm7\%$) in extracting V_{cb} from the exclusive rate $B(B \to Dl\bar{\nu})$ is too small, but at this point we cannot make a better quantitative assessment of this error.

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[44]In principle, the efficiency for finding a D from the decay $\bar{B} \to DXl^-\bar{\nu}$ can be different from that for finding a D from the process $B \to DX$, $\bar{B} \to Yl^-\bar{\nu}$; however, for D^0 and D^+ final states we find this difference to be less than 2%.