Investigation of Semileptonic B Meson Decays to p-Wave Charm Mesons

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We have studied semileptonic B meson decays with a p-wave charm meson in the final state using 3.29×10^6 $B\overline{B}$ events collected with the CLEO II detector at the Cornell Electron-Positron Storage Ring. We find a value for the exclusive semileptonic product branching fraction $\mathcal{B}(B^- \to D_1^0 \ell^- \overline{\nu}_\ell)\mathcal{B}(D_1^0 \to D^{*+}\pi^-) = (0.373 \pm 0.085 \pm 0.052 \pm 0.024)\%$ and an upper limit for $\mathcal{B}(B^- \to D_2^{*0} \ell^- \overline{\nu}_\ell)\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-) < 0.16\%$ (90% C.L.). Furthermore, we present the first measurement of the q^2 spectrum for $B^- \to D_1^0 \ell^- \overline{\nu}_\ell$. [S0031-9007(98)06078-5]

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There is general agreement among a number of measurements of the exclusive semileptonic $\overline{B}$ meson decays, $\overline{B} \to D\ell\overline{\nu}_\ell$ and $\overline{B} \to D^*\ell\overline{\nu}_\ell$. Together they account for approximately 60%–70% of the inclusive $\overline{B} \to X\ell\overline{\nu}_\ell$ branching fraction [1]. Since the branching fraction for $b \to u\ell\overline{\nu}_\ell$ is known to be small, the missing exclusive decays must be sought among $b \to c\ell\overline{\nu}_\ell$ decays to higher mass D_J states or nonresonant hadronic states with a D or D^* and other hadrons. Pioneering measurements by ARGUS [2] and CLEO [3] indicate the possible presence of resonant and nonresonant contributions from $D\pi\ell\overline{\nu}_\ell$ and $D^*\pi\ell\overline{\nu}_\ell$ in $\overline{B}$ decays. More recent measurements from the CERN Large Electron-Positron Collider experiments [4–6] confirm the presence of $D\pi$ and $D^*\pi$ states in $\overline{B}$ semileptonic decays. Exclusive measurements of $B^- \to D_1^0\ell^-\overline{\nu}_\ell$ and $B^- \to D_2^{*0}\ell^-\overline{\nu}_\ell$ have been reported previously [4,5]. In this paper we report new measurements of these two decay modes.

The D_J mesons contain one charm quark and one light quark with relative angular momentum $L = 1$. The quark spins can sum to $S = 0$ or $S = 1$, so there are four spin-parity states given by $J^P = 1^+$ or 0^+, 1^+, and 2^+. Parity and angular momentum conservation restrict the decays available to the four states. According to heavy quark effective theory (HQET), there exists an approximate spin-flavor symmetry for hadrons consisting of one heavy and one light quark [7]. In the limit of infinite heavy quark mass, such mesons are described by the total angular momentum of the light constituents $j = S_q + L$. In HQET, the D_J mesons make up two doublets, $j = 1/2$ and $j = 3/2$. The members of the $j = 3/2$ doublet are predicted to decay dominantly via d wave and to be relatively narrow. The $j = 1/2$ mesons are predicted to decay only in an s wave and to be relatively broad. In this analysis we study the semileptonic decays of the $\overline{B}$ meson to final states containing the narrow ($j = 3/2$) excited charm mesons: the ${}^jL_J = {}^{3/2}P_2$ and ${}^{3/2}P_1$, called D_2^* and D_1, respectively [8].

The data used in this analysis were collected with the CLEO II detector at the Cornell Electron-Positron Storage Ring (CESR). The CLEO II detector [9] is a multipurpose high energy physics detector incorporating excellent charged and neutral particle detection and measurement. The data sample consists of an integrated luminosity of 3.11 fb^{-1} on the $\Upsilon(4S)$ resonance (ON resonance), corresponding to 3.29×10^6 $B\overline{B}$ events, and 1.61 fb^{-1} at a center-of-mass energy ~55 MeV below the $\Upsilon(4S)$ resonance (OFF resonance).

The exclusive $B^- \to D_J^0\ell^-\overline{\nu}_\ell$ decay is studied [10] by reconstructing the decay channel $D_J^0 \to D^{*+}\pi^-$ using the decay chain $D^{*+} \to D^0\pi^+$, and $D^0 \to K^-\pi^+$ or $D^0 \to K^-\pi^+\pi^0$ [11]. Hadronic events are required to have at least one track identified as a lepton with momentum between 0.8 and 2.0 GeV/c for electrons and between 1.0 and 2.0 GeV/c for muons. Electrons are identified by matching energy deposited in the CsI calorimeter and momentum measured in the drift chamber, and by measuring their energy loss in the drift chamber gas. The muon identification relies upon penetration through layers of iron absorber to muon chambers. To reduce non-$B\overline{B}$ background [contamination of our sample by e^+e^- interactions which result in $q\overline{q}$ hadronization rather than producing an $\Upsilon(4S)$ meson], each event must satisfy a requirement on the ratio of Fox-Wolfram [12] moments, $H_2/H_0 < 0.4$. All charged tracks must originate from the vicinity of the e^+e^- interaction point. Charged kaon and pion candidates, with the exception of the slow pion from the decay of the D^{*+}, are required to have ionization losses in the drift chamber within 2.5 and 3.0 standard deviations, respectively, of those expected for the hypothesis under consideration. The invariant mass of the two photons from $\pi^0 \to \gamma\gamma$ must be within 2.0 standard deviations ($\sigma = 5$ MeV/c^2 to 8 MeV/c^2, depending on shower energies and polar angles) of the nominal π^0 mass.

The $K^-\pi^+$ and $K^-\pi^+\pi^0$ combinations are required to have an invariant mass within 16 and 25 MeV/c^2 (~2σ) of the nominal D^0 mass, respectively. In addition, we select regions of the $D^0 \to K^-\pi^+\pi^0$ Dalitz plot to take advantage of the known resonant substructure [13] and we enforce a minimum energy for the π^0. In the $D^0 \to K^-\pi^+\pi^0$ mode we require $|\mathbf{p}_D| > 0.8$ GeV/c in order to further reject fake D^0 background. We then combine D^0 candidates with π^+ candidates to form D^{*+} candidates. The slow pion used to form the D^{*+} must have a momentum of at least 65 MeV/c. The reconstructed mass difference $\delta m = M(D^0\pi^+) - M(D^0)$ is required to be within 2 MeV/c^2 of the known $D^{*+} - D^0$ mass difference [8]. The D^{*+} candidate is then combined with an additional π^- in the event to form a D_J^0 candidate. The D_J^0 candidates must have a scaled momentum $x_{D_J} = |\mathbf{p}_{D_J}|/\sqrt{E_{\rm beam}^2 - M^2(D_J)} < 0.5$, the kinematic limit from B decays.

These D_J^0 candidates are then paired with leptons selected as described above to form candidates for $B^- \to D_J^0 \ell^- \overline{\nu}_\ell$ decays. There is significant background in this analysis from real D^{*+}'s combined with pions that are not from D_J^0 mesons. To suppress this background, we select $D_J^0 \ell^-$ pairs that are consistent with $B^- \to D_J^0 \ell^- \overline{\nu}_\ell$ decays and reject $D^{*+}\ell^-$ pairs that are consistent with $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$. Thus, we require $D_J^0\ell^-$ candidates to have $|\cos\theta_{B-D_J\ell}| \leq 1$ and $\cos\theta_{B-D^*\ell} < -1$, where

$$\cos\theta_{B-D_J\ell} = \frac{|\mathbf{p}_{D_J\ell}|^2 + |\mathbf{p}_B|^2 - |\mathbf{p}_\nu|^2}{2|\mathbf{p}_B|\,|\mathbf{p}_{D_J\ell}|}, \qquad (1)$$

and

$$\cos\theta_{B-D^*\ell} = \frac{|\mathbf{p}_{D^*\ell}|^2 + |\mathbf{p}_B|^2 - |\mathbf{p}_\nu|^2}{2|\mathbf{p}_B|\,|\mathbf{p}_{D^*\ell}|}. \qquad (2)$$

Here, $\theta_{B-D_J\ell}$ ($\theta_{B-D^*\ell}$) is the angle between $\mathbf{p}_B$ and $\mathbf{p}_{D_J\ell}$ ($\mathbf{p}_{D^*\ell}$), where $|\mathbf{p}_B|$ is the known magnitude of the B momentum, and $\mathbf{p}_{D_J\ell}$ ($\mathbf{p}_{D^*\ell}$) is the momentum of the $D_J^0\ell^-$ ($D^{*+}\ell^-$) candidate. The magnitude of the neutrino momentum $|\mathbf{p}_\nu|$ is inferred from energy conservation, using the beam energy for the B meson energy E_B. When the requirements $|\cos\theta_{B-D_J\ell}| \leq 1$ and $\cos\theta_{B-D^*\ell} < -1$ are applied together, they retain 60% of the $B^- \to D_J^0\ell^-\overline{\nu}_\ell$ decays and reject 89% of the background remaining after all other cuts. To reduce uncorrelated background (background from events in which the D_J^0 comes from the $\overline{B}$ and the lepton from the B), we require the D_J^0 and the lepton to be in opposite hemispheres: $\cos\theta_{D_J\ell} < 0$, where $\theta_{D_J\ell}$ is the angle between the D_J^0 and the lepton. The remaining uncorrelated background is negligible.

The $B^- \to D_J^0\ell^-\overline{\nu}_\ell$ signal is identified using the mass difference $\delta M_J = M(D^{*+}\pi^-) - M(D^{*+})$. To avoid multiple $D_J^0\ell^-$ combinations per event, we select the best candidate based on the probability that a $D_J^0\ell^-$ combination is a signal event. The latter probability is calculated from the independent observables $M(\pi^0)$, $M(D^0)$, δm, and $M^2(\overline{\nu}_\ell) \simeq M_B^2 + M^2(D_J\ell) - 2E_B E(D_J\ell)$. In the computation of $M^2(\overline{\nu}_\ell)$, the B meson momentum $\mathbf{p}_B$ is taken to be zero, and $E(D_J\ell)$ is the energy of the $D_J^0\ell^-$ candidate.

The δM_J distribution obtained by combining the two decay modes of the D^0 meson is shown in Fig. 1. An unbinned likelihood fit is performed on the δM_J distribution. The fitting function is the sum of a threshold background function [14] plus Breit-Wigner resonance functions with the masses and widths of the two narrow D_J^0 resonances fixed [8]. Each Breit-Wigner function is convoluted with a Gaussian function that describes the detector resolution. The width of the Gaussian function is estimated by Monte Carlo simulation to be $\sigma =$

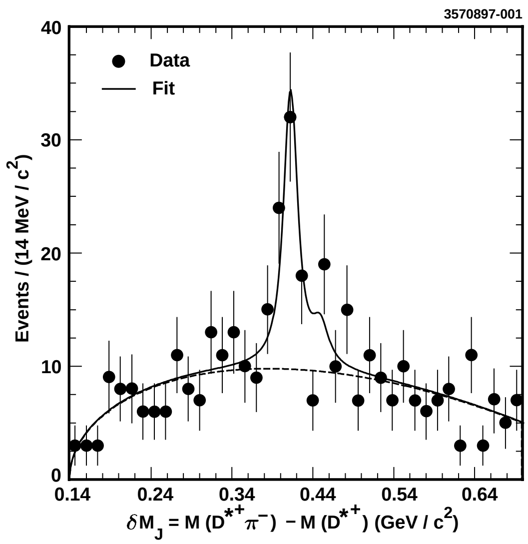

FIG. 1. The δM_J distribution from the $\Upsilon(4S)$ resonance data for $B^- \to D_1^0\ell^-\overline{\nu}_\ell$ and $B^- \to D_2^{*0}\ell^-\overline{\nu}_\ell$ ($\ell = e$ and μ) candidates obtained by combining both the $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^0$ modes. The dashed curve illustrates the background function, whereas the solid line shows the sum of the background and signal functions.

2.8 MeV$/c^2$. The D_1^0 and D_2^{*0} yields obtained from the fit are summarized in Table I.

To check that the data are consistent with the presence of a signal, we fit the δM_J distribution with only the smooth background function. The difference between the logarithm of the likelihood of the fit with the signal plus the background functions and the logarithm of the likelihood with only the background function is 18.7. Assuming Gaussian statistics, this corresponds to a 6.1σ statistical significance for the signal. If the mass and the width of the D_1^0 resonance are allowed to float, the fitted mass and width obtained are 2420 ± 4 MeV$/c^2$ and 23 ± 9 MeV$/c^2$, which are in agreement with the Particle Data Group averages [8]. The D_1^0 and D_2^{*0} yields from this fit are 62.5 ± 16.7 and 10.5 ± 9.8, respectively.

The background from non-$B\overline{B}$ events is obtained by measuring the signal yields using OFF resonance data. The results are scaled by the ratio of the luminosities and the square of the beam energies. Fake lepton background (the contribution in which a D_J^0 is paired with a hadron misidentified as a lepton) is estimated by performing the same analysis using tracks that are not leptons. The fake lepton yields are scaled by the appropriate misidentification probabilities and abundances for hadrons. The sums of these two types of backgrounds are subtracted from the ON resonance yields as indicated in Table I.

Semileptonic $\overline{B}$ decays to more highly excited charmed mesons which then decay to D_J^0 mesons are predicted to be small [15]. The smooth background function accounts for both combinatoric background and possible background from broad and nonresonant $D^{*+}\pi^-X$ states.

TABLE I. Yields and product branching fractions. The first error on the product branching fractions is statistical, the second is experimental systematic, and the third is theoretical.

	D_1^0	D_2^{*0}
ON resonance yield	56.6 ± 11.9	10.3 ± 9.4
Background yield	3.1 ± 2.8	1.5 ± 2.8
Net yield	53.5 ± 12.2	8.8 ± 9.8
$\mathcal{P}(D_J^0)$	$(0.373 \pm 0.085 \pm 0.052 \pm 0.024)\%$	$(0.059 \pm 0.066 \pm 0.010 \pm 0.004)\%$

The product branching fractions $\mathcal{P}(D_1^0) \equiv \mathcal{B}(B^- \to D_1^0 \ell^- \overline{\nu}_\ell)\mathcal{B}(D_1^0 \to D^{*+}\pi^-)$ and $\mathcal{P}(D_2^{*0}) \equiv \mathcal{B}(B^- \to D_2^{*0} \ell^- \overline{\nu}_\ell)\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-)$ are obtained by dividing the yields by the total numbers of B^- events in our data sample and the sum of the products of the efficiencies times the D^{*+} and D^0 branching fractions for the modes used. The reconstruction efficiencies (ε_{D_J}) for $B^- \to D_J^0 \ell^- \overline{\nu}_\ell$ ($\ell = e$ and μ) are $\varepsilon_{D_1}^{K\pi} = (4.37 \pm 0.09)\%$, $\varepsilon_{D_1}^{K\pi\pi^0} = (1.09 \pm 0.02)\%$, $\varepsilon_{D_2^*}^{K\pi} = (4.61 \pm 0.09)\%$, and $\varepsilon_{D_2^*}^{K\pi\pi^0} = (1.10 \pm 0.02)\%$. Our event selection efficiencies were obtained using Monte Carlo data generated according to the ISGW2 model [15]. The quoted errors on the efficiencies are statistical only. We assume that the branching fractions of $\Upsilon(4S)$ to charged and neutral $B\overline{B}$ pairs are each 50%. The values of the D^{*+} and D^0 branching fractions are taken from Ref. [8]. The contributions of the systematic uncertainties are listed in Table II. Details on the estimation of the systematic uncertainties can be found elsewhere [10]. The theoretical uncertainties associated with the model dependence of the efficiency is obtained by varying the parameters and the form factors used in the ISGW2 model. We choose to quote the product of branching fractions because the branching fractions for $D_J^0 \to D^{*+}\pi^-$ have not been measured. We find

$$\mathcal{P}(D_1^0) = (0.373 \pm 0.085 \pm 0.052 \pm 0.024)\%\,, \quad (3)$$

$$\mathcal{P}(D_2^{*0}) = (0.059 \pm 0.066 \pm 0.010 \pm 0.004)\% < 0.16\% \text{ (90\% C.L.)}\,, \quad (4)$$

where the errors are statistical, systematic, and theoretical, respectively. For the quoted upper limit, we add the experimental systematic and the theoretical uncertainties in quadrature, and add the result to the upper limit computed with the statistical error only.

TABLE II. Experimental systematic errors on the product branching fractions. Tracking uncertainties are for all charged particles other than the slow π.

Source of systematic error	$\mathcal{P}(D_1^0)$	$\mathcal{P}(D_2^{*0})$
M_{D_J}	1.0%	1.1%
Γ_{D_J}	10.0%	14.0%
Background function	4.0%	5.0%
Uncorrelated background	0.5%	0.4%
Lepton fake	1.0%	1.0%
Lepton ID	1.3%	1.3%
Monte Carlo statistics	1.5%	1.5%
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	2.0%	2.0%
$\mathcal{B}[D^0 \to K^-\pi^+(\pi^0)]$	3.5%	3.5%
Slow π efficiency	5.0%	5.0%
Tracking efficiency	4.0%	4.0%
π^0 reconstruction	2.4%	2.4%
Dalitz weight	1.9%	1.9%
Multiple counting	1.4%	1.4%
Particle identification	1.0%	1.0%
Luminosity	2.0%	2.0%
Total	14.0%	17.3%

In order to estimate the contribution of these decays to the total semileptonic $\overline{B}$ meson branching fraction, we need to make some assumptions about the branching fractions of the D_J^0 mesons. Isospin conservation and CLEO measurements [16] of the decays of the D_J^0 mesons suggest that $\mathcal{B}(D_1^0 \to D^{*+}\pi^-) = 67\%$ and $\mathcal{B}(D_2^{*0} \to D^{*+}\pi^-) = 20\%$. Using these estimates, we find

$$\mathcal{B}(B^- \to D_1^0 \ell^- \overline{\nu}_\ell) = (0.56 \pm 0.13 \pm 0.08 \pm 0.04)\%\,, \quad (5)$$

$$\mathcal{B}(B^- \to D_2^{*0} \ell^- \overline{\nu}_\ell) < 0.8\% \text{ (90\% C.L.)}\,. \quad (6)$$

This leads to an upper limit of

$$\mathcal{R} = \frac{\mathcal{B}(B^- \to D_2^{*0} \ell^- \overline{\nu}_\ell)}{\mathcal{B}(B^- \to D_1^0 \ell^- \overline{\nu}_\ell)} < 1.5 \text{ (90\% C.L.)}\,. \quad (7)$$

A clear picture of the exclusive modes which make up the 30%–40% of the $\overline{B}$ semileptonic decays that are not $D\ell\overline{\nu}_\ell$ and $D^*\ell\overline{\nu}_\ell$ has not yet emerged. However, it appears that no more than half of the excess can be due to exclusive semileptonic decays to $D_1^0(2420)$ and $D_2^{*0}(2460)$. It should be noted that this interpretation holds under specific assumptions: we assume the contribution of three body, ρ, and η decays of the narrow D_J to be negligible.

Several theoretical models make predictions for the decay rate of exclusive semileptonic decays of the B meson to excited charm mesons [15,17–21]. Our measurements seem to disfavor all of the theoretical predictions that advocate small $\Lambda_{\rm QCD}/m_Q$ corrections for semileptonic decays of the B meson to p-wave charm mesons in the framework of HQET.

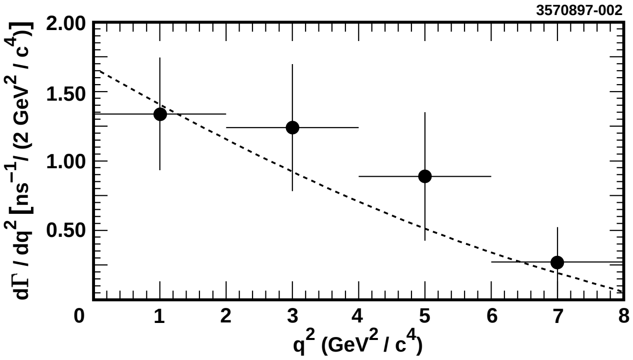

FIG. 2. The q^2 spectrum for $B^- \to D_1^0 \ell^- \overline{\nu}_\ell$ data after background subtraction and efficiency correction. The error bar on each data point is statistical only. The dashed line is the prediction from the ISGW2 model.

Despite the fact that this analysis is statistically limited, we are nevertheless able to study the q^2 spectrum for $B^- \to D_1^0 \ell^- \overline{\nu}_\ell$. The q^2 spectrum is extracted by fitting the δM_J distribution in four bins of q^2, keeping the mass and width of the D_1^0 fixed. In each bin, the appropriate non-$B\overline{B}$ and fake lepton yields are subtracted from the fitted yield. The final or net yield $n_{D_1}(q^2)$ is then corrected by the reconstruction efficiency $\varepsilon_{D_1}(q^2)$, which was computed for the same q^2 bin. The q^2 spectrum is then the differential decay rate:

$$\frac{d\Gamma}{dq^2} = \frac{n_{D_1}(q^2)/\varepsilon_{D_1}(q^2)}{2\tau_{B^-} N_{\Upsilon(4S)} \mathcal{B}(D_1^0 \to D^{*+}\pi^-) \mathcal{B}_{D^{*+}} \mathcal{B}_{D^0}} . \quad (8)$$

The B^- lifetime is taken to be $\tau_{B^-} = (1.62 \pm 0.06)$ ps [8]. We assume $\mathcal{B}(D_1^0 \to D^{*+}\pi^-) = 67\%$. The D^{*+} and D^0 branching fractions are $\mathcal{B}_{D^{*+}}$ and $\mathcal{B}_{D^0}$, respectively [8]. The resulting q^2 spectrum is shown in Fig. 2.

In summary, we have studied exclusive semileptonic decays of the B mesons to p-wave charm mesons. We measured a branching fraction for $\mathcal{B}(B^- \to D_1^0 \ell^- \overline{\nu}_\ell)$ and an upper limit for $\mathcal{B}(B^- \to D_2^{*0} \ell^- \overline{\nu}_\ell)$. These results indicate that a substantial fraction ($\gtrsim 18\%$) of the inclusive $\overline{B}$ semileptonic rate is from modes other than $D\ell\overline{\nu}_\ell$, $D^*\ell\overline{\nu}_\ell$, $D_1\ell\overline{\nu}_\ell$, and $D_2^*\ell\overline{\nu}_\ell$. Our measurements are consistent with ALEPH [4] and OPAL [5]. We also presented the first measurement of the q^2 spectrum for $B^- \to D_1^0 \ell^- \overline{\nu}_\ell$.

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