

Study of the Decay $\bar{B}^0 \rightarrow D^{*+} l^- \bar{\nu}$

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Using a sample of 484000 B mesons collected with the CLEO detector at the Cornell Electron Storage Ring, we have measured $B(\bar{B}^0 \rightarrow D^{*+} l^- \bar{\nu})$ and found that the polarization of the D^{*+} is small. These results are compared with models of semileptonic B decay.

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Semileptonic decays of B mesons are among the simplest B decays that can be described theoretically. Predictions for rates of exclusive channels containing D and D^* and for D^* polarization are available.¹⁻⁴ Here we present a detailed study of $D^{*+} l^- \bar{\nu}$ and we consider $D^* \pi l^- \bar{\nu}$ final states.⁵

The data sample used in this study was collected with the improved CLEO detector at the Cornell Electron Storage Ring (CESR). It consists of 212 pb⁻¹ at the $\Upsilon(4S)$ resonance, which contain 242000 $B\bar{B}$ pairs and 102 pb⁻¹ at energies just below the $B\bar{B}$ threshold.

The tracking system⁶ achieves a momentum resolution given by $(\delta p/p)^2 = (0.23\%p)^2 + (0.7\%)^2$, where p is in GeV/c. Lepton identification criteria in CLEO have been described in detail elsewhere.⁷ The candidate lepton is required to have momentum p_l between 1.4 and 2.4 GeV/c. The lower momentum cut suppresses leptons that are not primary B -decay products. The upper momentum cut is close to the kinematic limit for B decay into charmed particles. To suppress leptons from B

$\rightarrow \psi X$, a lepton candidate is rejected if it forms an invariant mass between 3.06 and 3.14 GeV with any oppositely charged track in the event, unless the other track has positively been identified as nonleptonic. After these cuts, we obtain a sample of $16738 \pm 218 e^\pm$ candidates and $10160 \pm 162 \mu^\pm$ candidates from B decays.

We identify D^{*+} in the decay mode $D^0 \pi^+$ with $D^0 \rightarrow K^- \pi^+$ or $K^- \pi^+ \pi^- \pi^+$. Throughout this paper charge-conjugate modes are implied. We require K and π candidates to have dE/dx within 2σ of the expected value. To select D^{*+} candidates we compute

$$\chi_{D^{*+}}^2 = (\delta M / \sigma_{\delta M})^2 + [\Delta M(D^0) / \sigma_{\Delta M, D^0}]^2,$$

where δM is the mass difference between the D^{*+} and the D^0 candidates minus the known value of 145.45 MeV and $\Delta M(D^0)$ is the mass difference between the calculated $K^- \pi^+$ or $K^- \pi^+ \pi^- \pi^+$ invariant mass and the D^0 mass (1.864 GeV). The ΔM resolution $\sigma_{\delta M}$ is 0.8 MeV while the $\Delta M(D^0)$ resolution $\sigma_{\Delta M, D^0}$ is 12 MeV for the $K^- \pi^+$ mode and 9 MeV for the $K^- \pi^+ \pi^- \pi^+$ mode.

The resolutions are determined from high-statistics samples of inclusive D^{*+} 's. A good D^{*+} candidate is required to have $\chi^2_{D^{*+}} \leq 4.6$. For events with more than one candidate, the solution with the smallest χ^2 is kept.⁸ Candidates are also required to have momentum less than 2.5 GeV/c to suppress D^{*+} from continuum events. In order to suppress the background produced by random combinations with low momentum pions, we require $\cos\theta_K \leq 0.95$ for D^{*+} candidates in the $D^0 \rightarrow K^- \pi^+$ mode, where θ_K is the angle of the direction of the K^- in the D^0 rest frame with respect to the D^0 direction in the laboratory frame.

To identify $D^{*+}l\bar{\nu}$ candidates, we calculate the missing mass square,

$$MM^2 = [E_{\text{beam}} - (E_{D^*} + E_l)]^2 - [\mathbf{p}_B - (\mathbf{p}_{D^*} + \mathbf{p}_l)]^2, \quad (1)$$

where we set \mathbf{p}_B equal to 0 and use the fact that the beam energy E_{beam} is equal to the B energy. The MM^2 distributions for $D^{*+}l^-$ (right sign) and $D^{*+}l^+$ (wrong sign) are shown in Figs. 1(a) and 1(b), respectively. The prominent peak at $MM^2 \approx 0$ in the right-sign combination is evidence for $\bar{B}^0 \rightarrow D^{*+}l^- \bar{\nu}$. The width of the MM^2 distribution (FWHM = 0.8 GeV²) arises from set-

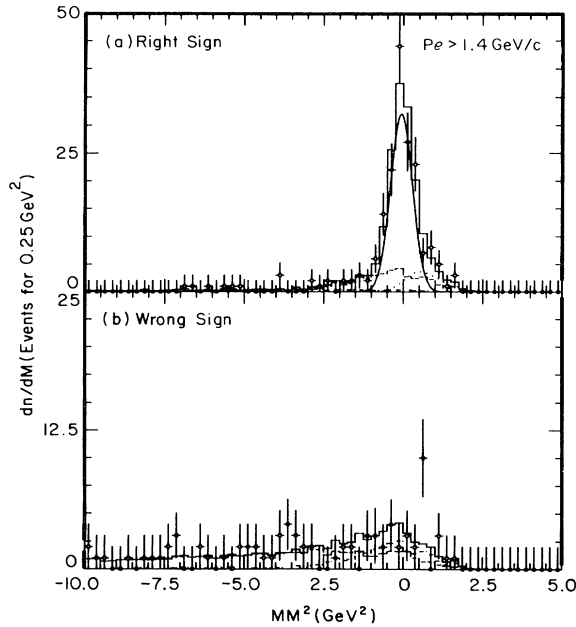


FIG. 1. Missing-mass-squared distribution for (a) $\bar{B}^0 \rightarrow D^{*+}l^- \bar{\nu}$ (right sign); the circles are the data points, the solid histogram is the result of the fit with a Gaussian for the signal and a background. The signal is the solid curve; the background due to mixing and cascades is the dot-dashed histogram, the background due to fake D^{*} 's is the dashed histogram, and the background due to excited D^{*} 's is the dotted line. (b) $\bar{B}^0 \rightarrow D^{*+}l^+ \bar{\nu}$ (wrong sign); the circles are the data points, the solid histogram is the result of the fit that contains the contribution from fake D^{*} 's (dashed histogram) and mixed events and cascades (dot-dashed line).

TABLE I. $\bar{B}^0 \rightarrow D^{*+}l^- \bar{\nu}$ signal and backgrounds for $|MM^2| < 1 \text{ GeV}^2$.

	D^0 decay mode	
	$K^- \pi^+$	$K^- \pi^+ \pi^- \pi^+$
Signal events	46 ± 8	62 ± 9
Continuum events	3 ± 2	3.2 ± 2
Fake leptons	0.5 ± 0.1	1.7 ± 0.3
Fake D^{*+} 's	0.7 ± 0.2	7.6 ± 0.4
Mixed events and cascades	0.6 ± 0.3	0.5 ± 0.3
$D^*(2420)$	12.6 ± 3.8	2.0 ± 1.8

ting \mathbf{p}_B equal to 0.

Non-negligible sources of background in the missing-mass-squared distribution of the right-sign events include nonresonant e^+e^- annihilation, fake leptons, fake D^{*+} , mixed events in which $\bar{B}^0 \rightarrow D^{*+}X$ and $B^0 \rightarrow \bar{B}^0 \rightarrow Xl^- \bar{\nu}$, and the decays $B \rightarrow D^*(2420)l^- \bar{\nu}$ where $D^*(2420) \rightarrow D^{*+}\pi$ and other resonant or nonresonant $B \rightarrow D^{*+}\pi l^- \bar{\nu}$ and cascades in which lepton come from D decay. These contributions are presented in Table I.

The continuum contribution to the background is determined from data taken at energies just below the $\Upsilon(4S)$. The magnitude and the shape of the background due to lepton fakes is obtained by computing the MM^2 distribution of all D^{*+} candidates and opposite-sign tracks not identified as leptons, within the lepton fiducial volume. This distribution is then weighted by the fake probability. The background due to D^{*+} fakes is para-

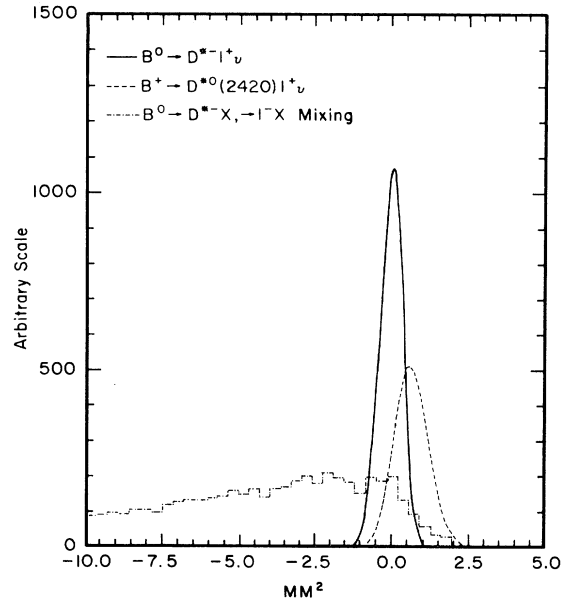


FIG. 2. MM^2 generated by the CLEO Monte Carlo simulation for $\bar{B}^0 \rightarrow D^{*+}l^- \bar{\nu}$ (solid line); $B^- \rightarrow D^{*0}(2420)l^- \bar{\nu}$ (dotted line); mixed events in which $\bar{B}^0 \rightarrow D^{*+}X$, $B^0 \rightarrow \bar{B}^0 \rightarrow l^- X \bar{\nu}$ and cascade leptons (dot-dashed line).

metrized using the MM^2 distribution obtained from D^0 sidebands.

In Fig. 2 we compare the MM^2 distributions expected from the other background contributions with the one for $\bar{B}^0 \rightarrow D^{*+}l^- \bar{\nu}$. The signal (solid line) is well described by a Gaussian function. The $D^*(2420)$ or $\bar{B}^0 \rightarrow D^{*+}\pi l^- \bar{\nu}$ background (dashed line) gives rise to a structure peaking at a small positive value of MM^2 that is well described by a skewed Gaussian.⁹ The MM^2 distribution for nonresonant $D^{*+}\pi^-$ is very similar to that for $D^*(2420)$ in models which have the $D^{*+}\pi^-$ arising from the fragmentation of the c -quark spectator anti-quark vertex; we do not distinguish between the $D^*(2420)$ and $D^{*+}\pi$ contributions. The wide background structure due to mixing is the dot-dashed line. The background due to cascade leptons is similar, so we use the mixing shape to parametrize both backgrounds.¹⁰

We fit the MM^2 distribution with a Gaussian signal, a mixed event background, and a skewed Gaussian to account for $D^*\pi$ states. The contribution due to fake leptons, fake D^{*+} , and continuum events is fixed in size. The result of the fit is shown in Fig. 1(a). The number of $\bar{B}^0 \rightarrow D^{*+}l^- \bar{\nu}$ events is 108 ± 12 , in the region $|MM^2| < 1$ GeV². The excited D^* component, presumably due to $D^{*+}(2420)$, $D^{*0}(2420)$, and other resonant and nonresonant $D^{*+}\pi$, is 18 ± 10 events. The contribution in the signal region is 14.6 events. A direct search for the decay $B^- \rightarrow D^{*0}(2420)l^- \bar{\nu}$ gives an upper limit of 9 events at 90% C.L. and a product branching ratio

$$\frac{B(B^- \rightarrow D^{*0}(2420)l^- \bar{\nu})B(D^{*0}(2420) \rightarrow D^{*+}\pi^-)}{B(B^- \rightarrow D^{*+}l^- \bar{\nu})} < 15\% \text{ (90\% C.L.)}$$

consistent with the fit result, especially since it contains both $D^{*+}(2420)$ and $D^{*0}(2420)$ components. The background due to mixed events and cascades is small under the signal. In Fig. 1(b) we show a fit to the MM^2 distribution for the wrong-sign combinations with the background shape for mixed events plus the background due to fake D^{*+} . The data and the Monte Carlo simulation are in good agreement.

We determine the branching ratio $B(\bar{B}^0 \rightarrow D^{*+}l^- \bar{\nu})$ using the following formula:

$$B(\bar{B}^0 \rightarrow D^{*+}l^- \bar{\nu}) = \frac{N(D^{*+}l^- \bar{\nu})}{\epsilon_{(D^{*+}l^-)}\epsilon_l\epsilon_b\epsilon_s f_{00}N_B},$$

where $N(D^{*+}l^- \bar{\nu})$ is the number of candidate events, N_B is the number of B mesons in the data sample, f_{00} is the fraction of neutral B mesons produced at the $Y(4S)$, ϵ_l is the efficiency to detect a lepton with $p_l > 1.4$ GeV/ c (0.62 ± 0.02 for electrons and 0.41 ± 0.01 for muons), ϵ_s is the fraction of the leptons with $p_l > 1.4$ GeV/ c [0.63 in the Isgur-Scora-Grinstein-Wise (ISGW) model¹], $\epsilon_{(D^{*+}l^-)}$ is the efficiency to reconstruct a D^{*+} when a lepton is found, and ϵ_b is a correction for the charm-

decay branching fractions. We determine $N(D^{*+}l^- \bar{\nu})$ by subtracting from the number of events found by the fitting procedure the contribution due to continuum and lepton fakes given in Table I. The efficiencies are estimated using the ISGW model¹ and the CLEO Monte Carlo simulation. The efficiency $\epsilon_{(D^{*+}l^-)}$ depends upon the lepton species and the D^0 -decay mode considered.¹¹ The factor ϵ_b is calculated from $B(D^{*+} \rightarrow D^0\pi^+) = (57 \pm 4 \pm 4)\%$, $B(D^0 \rightarrow K^-\pi^+) = (4.2 \pm 0.4 \pm 0.4)\%$, and $B(D^0 \rightarrow K^-\pi^+\pi^-\pi^+) = (9.1 \pm 1.3 \pm 0.4)\%$.¹² Assuming that f_{00} is 50% we obtain $B(\bar{B}^0 \rightarrow D^{*+}l^- \bar{\nu}) = (4.6 \pm 0.5 \pm 0.7)\%$ where the first error is statistical and the second systematic. The systematic error includes uncertainties of 13% and 10% for the D and D^{*+} branching ratios, respectively. The observed branching ratio is in agreement with the ARGUS result.^{5,13} The models¹⁻⁴ predict $\Gamma(\bar{B}^0 \rightarrow D^{*+}l^- \bar{\nu}) = K|V_{cb}|^2 \times 10^{12}$ s⁻¹, where K varies between 22 and 26. Taking the world average $\tau_B = 1.18 \pm 0.14$ ps,¹⁴ we find $|V_{cb}| = 0.039 \pm 0.004$ in the ISGW model¹ where $K = 25.2$.

We have also calculated the fraction R of the total semileptonic branching ratio due to $D^{*+}l^- \bar{\nu}$ using the formula

$$R = \frac{B(\bar{B}^0 \rightarrow D^{*+}l^- \bar{\nu})}{B(\bar{B}^0 \rightarrow Xl^- \bar{\nu})} = \frac{N(D^{*+}l^- \bar{\nu})}{N(l)f_{00}\epsilon_{(D^{*+}l^-)}\epsilon_f\epsilon_b}.$$

Here ϵ_f is the relative fraction of leptons with $p_l > 1.4$ GeV/ c from $\bar{B}^0 \rightarrow D^{*+}l^- \bar{\nu}$ with respect to $B \rightarrow Xl^- \bar{\nu}$ (1.17 in the ISGW model), and N_l is the number of leptons with $p_l > 1.4$ GeV/ c . We find $R = 0.46 \pm 0.05 \pm 0.07$. Assuming that the lifetime of the neutral charged B are equal we can compare the value of R with the prediction of theory. In the ISGW model the total semileptonic rate of B to charm is calculated as a sum over the exclusive semileptonic rate into D , D^* , and higher-spin D states. Our measurement is barely in agreement with the ISGW prediction $R = 0.60$.

We can also find the fraction R^* due to semileptonic decay $\bar{B}^0 \rightarrow D^*(2429)l^- \bar{\nu}$ and nonresonant $\bar{B}^0 \rightarrow D^{*+}\pi l^- \bar{\nu}$. Assuming equal rates for $D^{*+}\pi^- l^- \bar{\nu}$ and $D^{*+}\pi^0 l^- \bar{\nu}$ and using the value of $\epsilon_f = 0.46$ from ISGW we obtain $R^* = 0.20 \pm 0.12$.¹⁵ This is somewhat higher than the upper limit on R^* quoted by ARGUS.⁵ The prediction of $B(B^- \rightarrow D^*(2420)l^- \bar{\nu})/B(B^- \rightarrow Xl^- \bar{\nu})$ in the ISGW model is 0.1. Our result is higher but our measurement can also contain some nonresonant component and the error is large.

The helicity structure in the decay $\bar{B}^0 \rightarrow D^{*+}l^- \bar{\nu}$ can be studied using the $D^{*+} \rightarrow D^0\pi^+$ decay angular distribution, usually parametrized as

$$W(\cos\Theta^*) = \frac{3}{6+2\alpha}(1 + \alpha \cos^2\Theta^*), \quad (2)$$

where Θ^* is the angle of the D^0 in the D^{*+} rest frame with respect to the D^{*+} direction in the laboratory frame. For $\alpha = -1$ W is proportional to $\sin^2\Theta^*$, and for large α it is proportional to $\cos^2\Theta^*$. We select D^{*+} can-

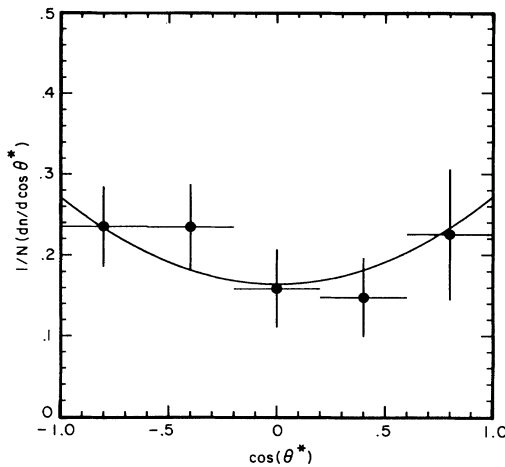


FIG. 3. Angular distribution of $\cos\Theta^*$ from D^{*+} mesons with $|\text{MM}^2| < 1 \text{ GeV}^2$ and $p_l > 1.4 \text{ GeV}/c$. The solid line is the result of the fit by Eq. (2) of the text.

didate events that satisfy $|\delta M| < 1.5 \text{ MeV}$ and $|\text{MM}^2| < 1 \text{ GeV}^2$. The number of D^{*+} in each $\cos\Theta^*$ bin is extracted by fitting the D^0 invariant-mass spectrum with mean, width, and efficiency determined by the Monte Carlo simulation. The resulting distribution, shown in Fig. 3, is fitted by the function in Eq. (2) and gives $\alpha = 0.65 \pm 0.66 \pm 0.25$ for $p_l > 1.4 \text{ GeV}/c$. The systematic error has been determined assuming that all the D^* from the decay $B \rightarrow D^*(2420)l\nu$ are completely polarized with either a $\cos^2\Theta^*$ or a $\sin^2\Theta^*$ distribution. The small value of α confirms the ARGUS measurement.⁵ Our result agrees with the Körner and Schuler² model and with the ISGW model¹ that predict $\alpha = 0.32$ and 0.28 , respectively, for $p_l > 1.4 \text{ GeV}/c$. In the recent model by Bauer and Wirbel³ there is a free parameter J_B/J_B^0 which represents their inability to calculate some coefficients of the form factors. We constrain $J_B/J_B^0 > 0.6$ at 90% C.L.

In conclusion, we have measured $B(\bar{B}^0 \rightarrow D^{*+}l^-\bar{\nu}) = (4.6 \pm 0.5 \pm 0.7)\%$ and found the D^{*+} polarization¹⁶ to be $\alpha = 0.65 \pm 0.66 \pm 0.25$ for $p_l > 1.4 \text{ GeV}/c$. Model predictions are too similar for our data to discriminate between them.

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⁸In our $D^{*+}l^-$ sample we have three events with more than one D^{*+} candidate in the $K^-\pi^+$ mode and sixteen in the $K^-\pi^+\pi^-\pi^+$ mode.

⁹A skewed Gaussian has one mean and different widths for the left and right sides.

¹⁰This procedure differs from the one adopted by ARGUS (Ref. 5). They assume that the background can be described by $D^{*+}\pi^-$ combinations.

¹¹The value of $\epsilon_{(D^{*+}e^-)}$ is 0.291 ± 0.010 for the $K^-\pi^+$ channel and 0.147 ± 0.008 for the $K^-\pi^+\pi^-\pi^+$ channel, while the corresponding values of $\epsilon_{(D^{*+}\mu^-)}$ are 0.233 ± 0.009 and 0.119 ± 0.007 , respectively.

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¹³The ARGUS measurement (Ref. 5) is $B(\bar{B}^0 \rightarrow D^{*+}l^-\bar{\nu}) = (7.0 \pm 1.2 \pm 1.9)\%$ which becomes $(5.4 \pm 0.8 \pm 1.3)\%$ taking into account that we use $B(D^{*+} \rightarrow D^0\pi^+) = (57 \pm 4 \pm 4)\%$ (Ref. 12) and $f_{00} = 0.50$ while ARGUS uses $B(D^{*+} \rightarrow D^0\pi^+) = (49 \pm 7 \pm 7)\%$ and $f_{00} = 0.45$.

¹⁴S. L. Wu, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, West Germany, 1987*, edited by R. Rückl and W. Bartel (North-Holland, Amsterdam, 1987), p. 39.

¹⁵Note that if we fit the MM^2 distribution [Fig. 1(a)] without allowing a $D^*(2420)$ component we find that $R = 0.53 \pm 0.06 \pm 0.08$. However, the fit has 53%-confidence level (C.L.) to be compared with the 83% C.L. we find by allowing the $D^*(2420)$ component.

¹⁶These results supercede the unpublished CLEO results in the Cornell report [Report No. CLNS 87/118, 1987 (to be published)] which used a flawed partial reconstruction technique.