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Lepton asymmetry measurements in $\bar{B} \to D^* l^- \bar{\nu}_l$ and implications for $V-A$ and the form factors

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We present a measurement of the lepton decay asymmetry $A_{\rm fb}$ in the reaction $\bar{B} \to D^* l^- \bar{\nu}_l$ using data collected with the CLEO II detector at the Cornell Electron Storage Ring (CESR). The value of $A_{\rm fb}$ confirms that the chirality of the weak interaction is predominantly left-handed in $b \to c$ transitions as expected in the standard model, if it is assumed that the lepton current is also left-handed. Using $A_{\rm fb}$ and the previously determined branching ratio, q^2 distribution, and D^* polarization, we obtain the first measurement of the form-factor ratios that are used to describe this semileptonic decay.

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I. INTRODUCTION

Previous information about the reaction $\bar{B}^0 \rightarrow D^{*+} l^- \bar{\nu}_l$ [1,2] consists of the branching ratio, the study of the decay angular distribution of the D^{*+} meson, and measurement of the q^2 distribution, where q^2 is the four-momentum transfer squared between the $\bar{B}$ and the D^*. These data agree with theoretical models but have limited precision. Complete checking of the models requires measurement of the three form factors which describe the decay. Furthermore, the chirality of b-quark decay has not been tested experimentally.

Here we present the first experimental study of the decay angle, Θ, of the lepton in the $(l^- \bar{\nu}_l)$ rest frame for the reaction $\bar{B} \rightarrow D^* l^- \bar{\nu}_l$. Körner and Schuler (KS) have shown that measurement of this angle provides information on the left-handedness of the charged current $b \rightarrow c$ transition [3]. Other methods and difficulties associated with checking the left-handedness of the $b \rightarrow c$ current have been discussed by Gronau and Wakaizumi [4]. Even though the standard model of electroweak interactions has been extremely successful in describing the data, the left-handed chirality of the charged current has been experimentally demonstrated only for purely leptonic currents [5] and for weak transitions of quarks belonging to the first two families [6]. Furthermore, in combination with previous measurements, the lepton decay asymmetry can be used to put significant constraints on the three form factors that describe this decay.

In the standard model, the weak decay of a b quark into a c quark through the $V-A$ interaction imparts a predominantly left-handed helicity to the c quark. Since the spectator antiquark has an equal mixture of both helicity states, it is expected that the left-handedness will be preserved when the c-antiquark system forms a D^*. Note that when a D rather than a D^* is formed all helicity information is lost. Thus, we study the two isospin-related reactions, $\bar{B}^0 \rightarrow D^{*+} l^- \bar{\nu}_l$ and $B^- \rightarrow D^{*0} l^- \bar{\nu}_l$ and their charge conjugates, where $D^{*+} \rightarrow D^0 \pi^+$ and $D^{*0} \rightarrow D^0 \pi^0$.

The decay width for the reaction $\bar{B} \rightarrow D^* l^- \bar{\nu}_l$ can be expressed, neglecting lepton masses, in terms of the q^2-dependent helicity amplitudes [7–10] H_0, H_+, and H_-:

$$\begin{aligned}\frac{d\Gamma(\bar{B} \rightarrow D^* l^- \bar{\nu}_l)}{dq^2 d\cos\Theta \, d\cos\Theta^* d\chi} = \frac{3G_F^2}{8(4\pi)^4} |V_{cb}|^2 \frac{Kq^2}{m_B^2} \big(& (|H_+|^2 + |H_-|^2)(1+\cos^2\Theta)\sin^2\Theta^* + 4|H_0|^2 \sin^2\Theta \cos^2\Theta^* \\ & -2\,\mathrm{Re}[H_+ H_-^*] \sin^2\Theta \sin^2\Theta^* \cos 2\chi \\ & -\mathrm{Re}[(H_+ + H_-)/H_0^*] \sin 2\Theta \sin 2\Theta^* \cos\chi \\ & +2\eta\xi \{ [-\mathrm{Re}[(H_+ - H_-)H_0^*] \sin\Theta \sin 2\Theta^* \cos\chi \\ & \quad + (|H_+|^2 - |H_-|^2) \cos\Theta \sin^2\Theta^* \} \big), \end{aligned} \tag{1}$$

where q^2 is the four-momentum transfer squared between the $\bar{B}$ and the D^*, m_B is the B mass, G_F is the Fermi coupling constant, and K, the momentum of the D^* in the $\bar{B}$ rest frame, is

$$K = \frac{1}{2m_B} [(m_B^2 - m_{D^*}^2 - q^2)^2 - 4m_{D^*}^2 q^2]^{1/2}.$$

The factor $\eta = +1$ (-1) describes $l^- \bar{\nu}_l$ $(l^+ \nu_l)$, while $\xi = +1$ (-1) describes the $V-A$ $(V+A)$ behavior of the leptonic current [11]. We use a reference system with the z quantization axis along the direction of the D^{*+} in the laboratory system. [The laboratory is a good approximation to the B rest frame, since B's produced at the $\Upsilon(4S)$ have velocity $\beta \approx 0.06$.] Then Θ and Θ^* are the polar angles of the lepton in the $(l^- \bar{\nu}_l)$ rest frame and of the D meson in the D^* rest frame, respectively, and χ is the azimuthal angle between the decay planes.

KS propose [3] that the $b \rightarrow c$ chirality can be tested by measuring the forward-backward asymmetry:

$$A_{\mathrm{fb}} = \frac{d\Gamma(\Theta) - d\Gamma(\pi - \Theta)}{d\Gamma(\Theta) + d\Gamma(\pi - \Theta)}, \quad \pi/2 \leq \Theta \leq \pi, \tag{2}$$

where the present notation implies that the numerator and denominator have been integrated over all the remaining observables, separately. The asymmetry projects out the coefficients of the last term of Eq. (1):

$$A_{\mathrm{fb}} = -\frac{3}{4}\eta\xi \frac{\int Kq^2(|H_+|^2 - |H_-|^2) dq^2 dp_l}{\int Kq^2(|H_+|^2 + |H_-|^2 + |H_0|^2) dq^2 dp_l}. \tag{3}$$

The KS test assumes that the lepton current is left-handed and therefore the coefficient ξ equals 1. Since in $\bar{B}$ decays η is 1, the sign of the asymmetry depends only on the chirality of the $b \rightarrow c$ transition.

Our procedure is first to measure the forward-backward asymmetry A_{fb}, then to extract quantitative information about the mixture of hadronic $V-A$ and $V+A$ currents allowed by the data, we compare the measured distribution of the decay angle Θ with model predictions. We discuss consistency of these results with the standard model prediction, under the assumption that the lepton current is left-handed. We then relax this condition and briefly consider the implication of this measurement in $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)$ extensions of the standard model. Finally, we use the measured asymmetry, the $d\Gamma/dq^2$ distribution, the branching ratio $\mathcal{B}(\bar{B} \rightarrow D^* l^- \bar{\nu}_l)$ and the D^{*+} polarization to obtain the first measurements of the form factors in semileptonic B decay.

II. DATA SAMPLES AND EVENT SELECTION

The data sample used in this study was collected with the CLEO II detector at the Cornell Electron Storage Ring (CESR). It consists of 923 pb^{-1} at the $\Upsilon(4S)$ resonance and 204 pb^{-1} at energies just below the $B\bar{B}$ threshold.

The CLEO II detector [12] is designed to detect both charged and neutral particles with excellent resolution and efficiency. The detector consists of a charged-particle tracking system surrounded by a time-of-flight scintillation system and an electromagnetic shower detector consisting of 7800 thallium-doped cesium iodide crystals. The tracking system, time-of-flight scintillators, and calorimeter are installed inside a 1.5 T superconducting solenoidal magnet. Immediately outside the magnet are iron and chambers for muon detection.

Photon candidates are selected from showers in the calorimeter that have a minimum energy of 30 MeV, are not matched to a charged-particle track from the drift chamber, and have a lateral energy distribution consistent with that expected for photons.

Neutral pion candidates are selected from pairs of photons with at least one photon in the barrel portion of the calorimeter, which subtends 70.7% of the solid angle. We also require the two photons invariant mass to be within 2.5 standard deviations (σ) of the known pion mass. All selected candidates are kinematically fitted to the known π^0 mass.

The tracking system [13] achieves a momentum resolution given by $(\delta p/p)^2=(0.15\%p)^2+(0.5\%)^2$, where p is in GeV/c. Muons are identified by their ability to penetrate an iron absorber and reach detection planes at a depth of at least three nuclear absorption lengths. Electron candidates are selected on the basis of the ratio of energy deposited in the electromagnetic calorimeter to the track's measured momentum, and also the specific ionization (dE/dx) as measured in the drift chamber. We use the calorimeter in the angular region $|\cos\theta|<0.91$, where θ is the angle of the electron with respect to the e^+ beam direction. The candidate lepton is required to have momentum p_l between 1.0 and 2.4 GeV/c. The lower momentum cut suppresses leptons that are not primary B decay products, while the upper momentum cut is close to the kinematic limit for B decay into a D^* meson.

We identify D^{*+} and D^{*0} in the decay modes $D^0\pi^+$ and $D^0\pi^0$, respectively. Throughout this paper charge conjugate modes are implied. The daughter D^0 meson is observed in the channel $D^0\to K^-\pi^+$. The decay $\bar{B}\to D^{*}l^{-}\bar{\nu}_l$ can be selected with good signal to background because of the small q^2 available for the decay $D^*\to D^0\pi$. We require K and π candidates to have dE/dx within 2σ of the expected value. To select D^* candidates we compute

$$\chi^2_{D^*}=\left[\frac{\delta M}{\sigma_{\delta_M}}\right]^2+\left[\frac{\Delta M}{\sigma_{\Delta M}}\right]^2,$$

where δM is the mass difference between the D^* and the D^0 candidate and the known value and ΔM is the mass difference between the calculated $K^-\pi^+$ invariant mass and the nominal D^0 mass. The δM resolution, σ_{δ_M}, is 0.8 MeV while the ΔM resolution, $\sigma_{\Delta M}$, is 8 MeV for the $K^-\pi^+$ mode. The resolutions are determined from high statistics samples of inclusive D^*'s. For about 10% of events with more than one candidate, the solution with the smallest $\chi^2_{D^*}$ is kept. Candidates are also required to have momentum less than 2.5 GeV/c to suppress D^*'s from continuum events. To reduce background from random pions, we require $\cos\theta_\pi>-0.95$ for D^0 candidates, where θ_π is the angle of the direction of the π^+ in the D^0 rest frame with respect to the D^0 direction in the laboratory frame.

To identify $D^*l^-\bar{\nu}_l$ candidates, we calculate the missing mass squared:

$$M^2_{\text{miss}}=[E_{\text{beam}}-(E_{D^*}+E_l)]^2-[\mathbf{p}_B-(\mathbf{p}_{D^*}+\mathbf{p}_l)]^2, \quad (4)$$

where we make the approximation $\mathbf{p}_B$ equals zero and use the fact that the B energy is equal to the beam energy E_{beam}. The M^2_{miss} distributions for the decay $\bar{B}^0\to D^{*+}l^-\bar{\nu}_l$ and $B^-\to D^{*0}l^-\bar{\nu}_l$ are shown in Figs. 1(a) and 1(b), respectively. The prominent peak at $M^2_{\text{miss}}\approx 0$ is evidence for semileptonic B decays into D^*. The M^2_{miss} distribution has an rms width of 0.52 GeV^2, where the dominant contribution arises from setting $\mathbf{p}_B$ equal to zero.

Sources of background in the M^2_{miss} distribution include nonresonant e^+e^- annihilation; fake leptons; mixed events in which $\bar{B}^0\to D^*X$ and $B^0\to\bar{B}^0\to Xl^-\bar{\nu}_l$; cascade events in which both B's decay hadronically as $\bar{B}\to D^*X$ and $B\to DX$ and the lepton comes from D decay; fake D^*'s; fake D's; the decay $B\to D^*(2420)l^-\bar{\nu}_l$ where $D^*(2420)\to D^*\pi$; and other resonant or nonresonant $B\to D^*\pi l^-\bar{\nu}_l$.

A detailed discussion of the shape of these backgrounds is found in our previous work [2]. The dotted line in Fig. 1 shows the background due to $B\to D^*(2420)l^-\bar{\nu}_l$ or $B\to D^*\pi l^-\bar{\nu}_l$, which peaks at a positive value of M^2_{miss}. (We denote this component by D^{**}.) We optimize the signal to background ratio by selecting events with missing mass satisfying $-1<M^2_{\text{miss}}<0$ GeV^2. The magnitudes of the backgrounds in the range $-1<M^2_{\text{miss}}<0$ GeV^2, which constitutes our signal region, are given in Table I.

We model the contribution to the $\cos\Theta$ distribution from fake D's by using D sidebands. The appropriately

TABLE I. Signal and backgrounds.

$-1<M^2_{\text{miss}}<0.0$ GeV^2	$D^{*+}l^-\bar{\nu}_l$	$D^{*0}l^-\bar{\nu}_l$
total	292±17	264±16
fake D	16±5	22±5
fake D^*	40±10	44±13
cascades	23±6	13±5
D^{**} [a]	12±4	7±4
signal	213±21	185±22

[a] Not subtracted.

normalized cosΘ distribution found for the D sidebands is subtracted bin-by-bin from the cosΘ distribution of the events in the signal region.

The background due to the combination of a real D meson with a random slow pion is studied by selecting sidebands in the δM distribution. The background due to cascade leptons and mixed events is taken into account by events with missing mass satisfying $-10 < M^2_{\text{miss}} < -2$ GeV^2 scaled by a factor given by a Monte Carlo simulation. To avoid overcounting the background from these two sources, we perform a D sideband subtraction. Then, the resulting cosΘ distribution is subtracted bin-by-bin from the cosΘ distribution of the events in the signal region. The total background due to fake D's, fake D^*'s, and cascade leptons is shown as the dashed histogram in Fig. 1.

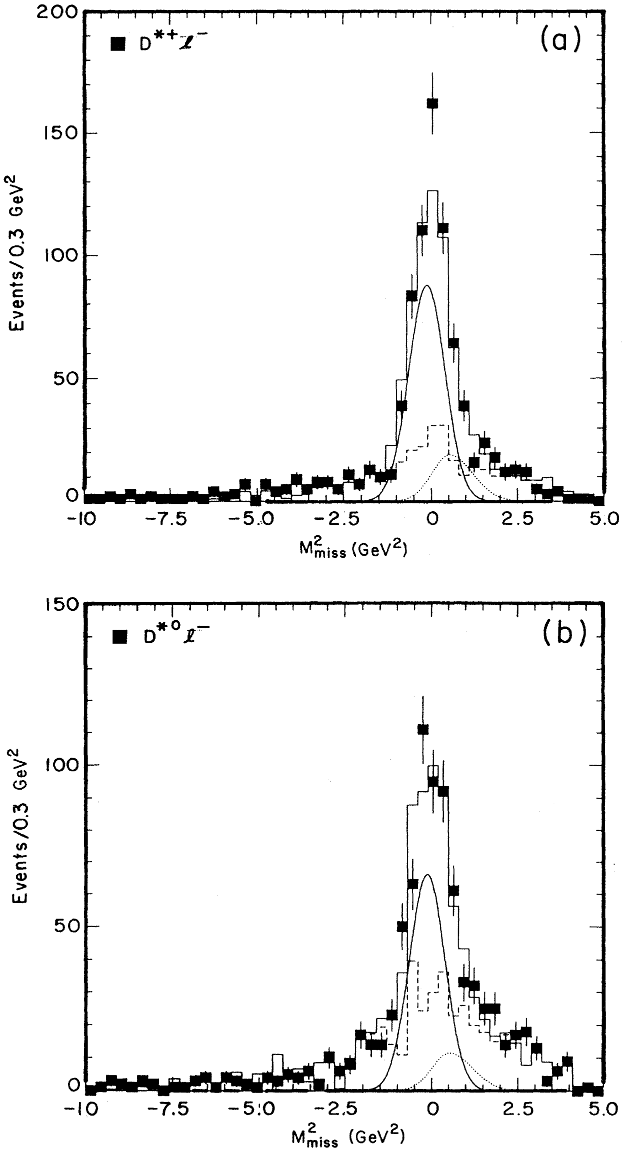

FIG. 1. Missing mass squared distribution for (a) $\bar{B}^0 \to D^{*+} l^- \bar{\nu}_l$ candidates and (b) $B^- \to D^{*0} l^- \bar{\nu}_l$ candidates. The squares are the data points; the solid histogram is the result of the fit with a Gaussian for the signal and a background. The background due to mixing, cascades, fake D^*'s, fake D's is the dashed histogram and the background due to excited D^{**}'s is the dotted line.

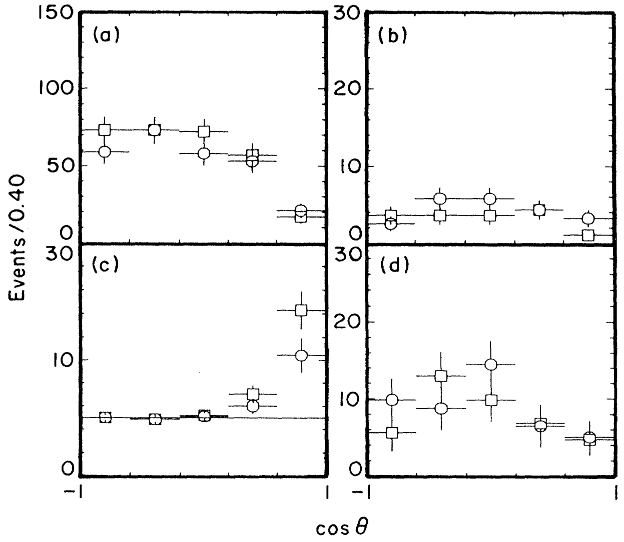

FIG. 2. cosΘ distribution for (a) all events with $-1 < M^2_{\text{miss}} < 0$, (b) fake D, (c) cascade leptons, and (d) fake D^*. The circles are for the decay $B^- \to D^{*0} l^- \bar{\nu}_l$ while the squares are for the decay $\bar{B}^0 \to D^{*+} l^- \bar{\nu}_l$. The normalization is absolute.

In Fig. 2(a) we show the cosΘ distribution for the candidate events before the subtraction of the backgrounds. The cosΘ distribution for the background due to fake D, cascade leptons, and fake D^* are shown in Figs. 2(b), 2(c), and 2(d), respectively. Requiring $M^2_{\text{miss}} < 0$ GeV removes most of the $D^{**} l^- \bar{\nu}_l$ background. In the Isgur-Scora-Grinstein-Wise (ISGW) model [7] these events are found to have the same cosΘ distribution as the $D^* l^- \bar{\nu}_l$ events. Thus we do not subtract the small residual background from our sample. After subtraction of the fake D's, fake D^*'s, and the cascade backgrounds we are left with 213±21 events in the $D^{*+} l^- \bar{\nu}_l$ sample and 185±22 in the $D^{*0} l^- \bar{\nu}_l$ sample.

The background due to continuum e^+e^- annihilation is determined independently using 204 pb^{-1} of data collected below resonance and it is negligible beyond that accounted for by the other backgrounds. The background due to lepton fakes is obtained by computing the M^2_{miss} distribution of all the D^{*+} candidates and opposite sign hadrons not identified as leptons, within the lepton fiducial volume. This distribution is then weighted by the average fake probability per hadron. These backgrounds are small and therefore neglected in this analysis.

III. MEASUREMENT OF A_{fb} AND $V-A$ TEST

The background-subtracted cosΘ distribution is shown in Fig. 3. Since the angle Θ is related to the momentum of the D^* and the lepton

$$\cos\Theta = -\frac{4m_B p_l - m_B^2 - q^2 + m_{D^*}^2}{2m_B K},$$

the lepton momentum cut p_l^{cut} at 1 GeV introduces a limit in the experimentally accessible angular range:

$$-1 < \cos\Theta < \min[\cos\Theta(q^2, p_l^{\text{cut}}); 1].$$

To eliminate this bias in the calculation of the forward-backward asymmetry, we symmetrize the $\cos\Theta$ acceptance using the requirement,

$$-\min[\cos\Theta(q^2, p_l^{\text{cut}}); 1] < \cos\Theta < \min[\cos\Theta(q^2, p_l^{\text{cut}}); 1].$$

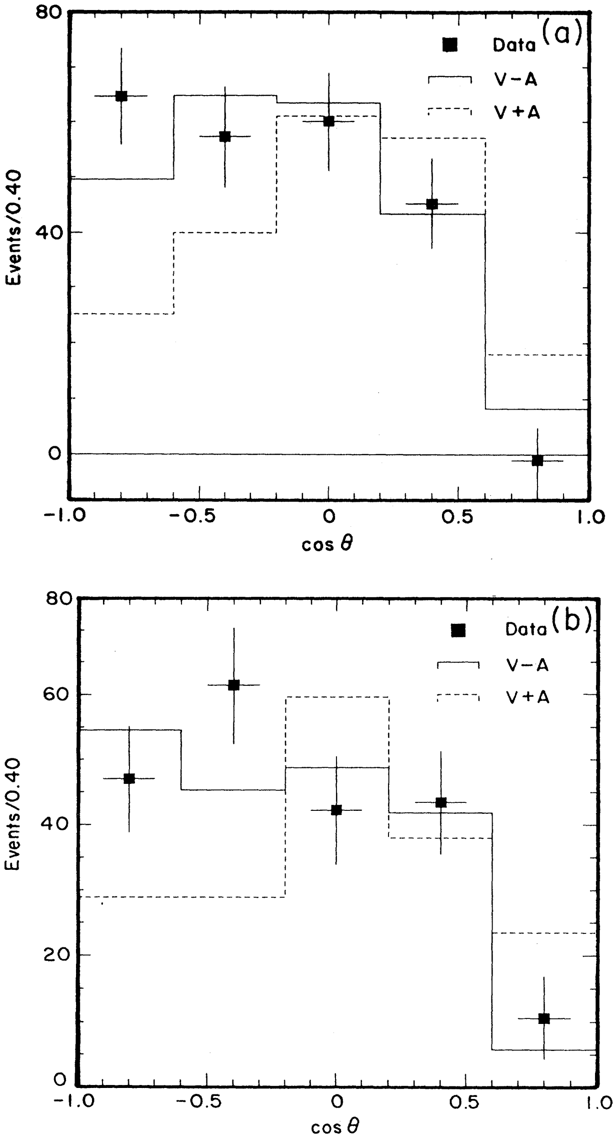

FIG. 3. $dN/d\cos\Theta$ distribution: (a) in the decay $\bar{B}^0\to D^{*+}l^-\bar{\nu}_l$ and (b) in the decay $B^-\to D^{*0}l^-\bar{\nu}_l$. Overlaid are the results of the fits of the ISGW model assuming pure $V-A$ or $V+A$ currents for the $b\to c$ transition.

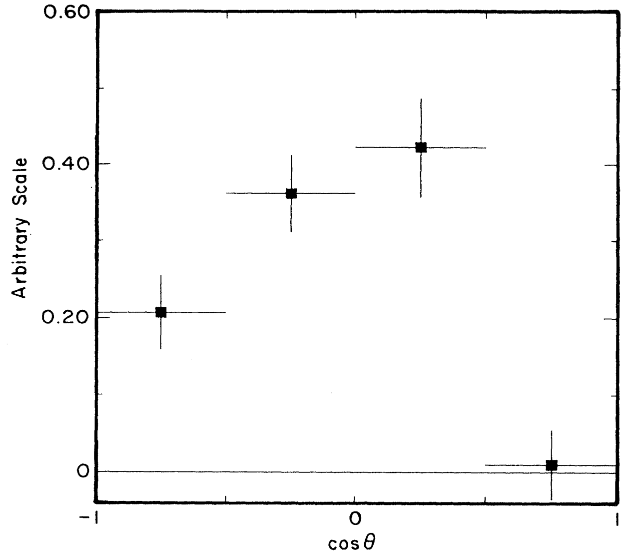

FIG. 4. The acceptance symmetrized and efficiency corrected $dN/d\cos\Theta$ distribution from $\bar{B}\to D^* l^- \bar{\nu}_l$.

We measure the forward-backward asymmetry A_{fb} by averaging the efficiency corrected and the acceptance symmetrized $\cos\Theta$ distributions for $\bar{B}^0\to D^{*+}l^-\bar{\nu}_l$ and $B^-\to D^{*0}l^-\bar{\nu}_l$. The combined $\cos\Theta$ distribution is shown in Fig. 4. The efficiency corrections are estimated with a Monte Carlo simulation of the CLEO II detector and ISGW model [7] assuming either $V-A$ or $V+A$ for the lepton current. The efficiency, which is shown in Fig. 5, is not a strong function of the chirality assumed to generate the Monte Carlo sample. By counting the number of events N_{f} in the forward region ($\cos\Theta < 0$) and N_{b} in the backward region ($\cos\Theta > 0$), we determine

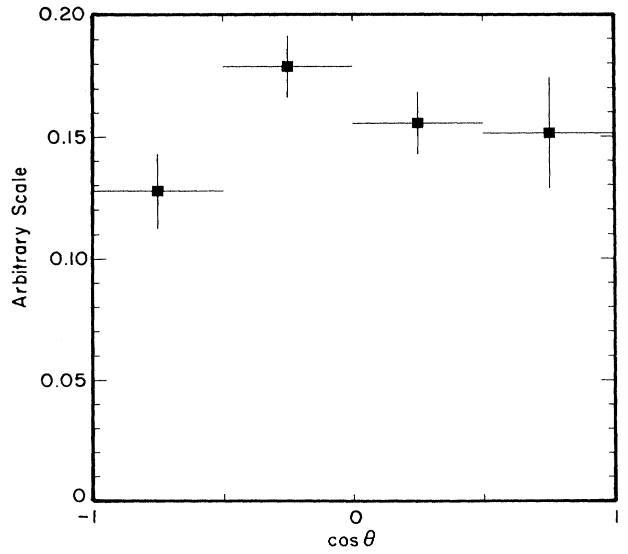

FIG. 5. The average efficiency for the decay $\bar{B}^0\to D^{*+}l^-\bar{\nu}_l$ and $B^-\to D^{*0}l^-\bar{\nu}_l$.

TABLE II. Measurements and model predictions of A_{fb} for $p_l > 1$ GeV/c.

Asymmetry	CLEO	ISGW	KS	WSB	HQET
A_{fb}	$0.14 \pm 0.06 \pm 0.03$	0.13	0.15	0.13	0.14

TABLE III. The χ^2/N_{DF} for $N_{\mathrm{DF}}=4$ for the fits to the cosΘ distribution and 95% C.L. limits for allowed amount of $V+A$ hadronic current.

	$\bar{B}^0 \to D^{*+} l^- \bar{\nu}_l$		$B^- \to D^{*0} l^- \bar{\nu}_l$		Simultaneous fit
Model	$V-A$	$V+A$	$V-A$	$V+A$	$(V+A)/(V-A)$
ISGW	1.6	9.0	1.3	6.8	$<19\%$
KS	0.9	15.7	0.9	7.3	$<30\%$
WSB	2.3	12.0	1.8	5.5	$<24\%$

$$A_{\mathrm{fb}} = \frac{N_{\mathrm{f}} - N_{\mathrm{b}}}{N_{\mathrm{f}} + N_{\mathrm{b}}} = 0.14 \pm 0.06 \pm 0.03 .$$

The systematic error is dominated by the uncertainty in the cosΘ dependence of the cascade background; it also includes a contribution from the uncertainty in the cosΘ dependence of the efficiency.

In Table II we compare the measurement of the asymmetry with the standard model predictions for $p_l > 1$ GeV/c [4]. Theoretical predictions for the asymmetry have an uncertainty of about 20% due to model dependence of the form factor used to calculate the hadronic matrix elements. Table II gives the value of the asymmetry for several calculations. The ISGW model is a nonrelativistic form-factor model [7]. The KS [8] and Wirbel-Stech-Bauer (WSB) [9] models are two relativistic form-factor models which have different q^2 dependence of the form factors. The heavy quark effective theory is labeled as HQET [14].

The value of the asymmetry that we obtain from our data is in good agreement with all the models, and the sign is consistent with the $b \to c$ current being left-handed in the limit of the validity of the KS test.

We establish how much $V+A$ is allowed in our data by comparing the measured cosΘ distributions resulting from Monte Carlo simulations using $V-A$ and $V+A$ currents. Table III gives the χ^2 per degree of freedom for the fits of a pure $V-A$ or $V+A$ current to the cosΘ distribution for the decays $\bar{B}^0 \to D^{*+} l^- \bar{\nu}_l$ and $B^- \to D^{*0} l^- \bar{\nu}_l$. The results of the fits for the ISGW model are shown in Fig. 3. The pure $V-A$ case is shown as the solid line while $V+A$ is shown as the dotted line.

We have considered the possibility that variation of the form factors assumed in these calculations could appreciably reduce the difference between $V-A$ and $V+A$. In order for $V+A$ to look similar to $V-A$, we have to raise the initial value of the vector form factor V by more than 80% of the ISGW model prediction at $q^2 = q^2_{\mathrm{max}}$. In this case the χ^2 for the fit to the $D^{*0} l^- \bar{\nu}_l$ angular distribution improves from 27.2 to 9 for $N_{\mathrm{DF}}=4$ degrees of freedom, but it is still larger than the $V-A$ fit, which yields a χ^2 of 5.2. As we will discuss later in this paper, we have constraints from other measurements performed in B decays that prohibit such a large variation of the form factors. In Table III we also show the χ^2 per degree of freedom for fits to two other models.

The good agreement with $V-A$ shows that only a small admixture of $V+A$ coupling can be accommodated by the data. The simultaneous fit to the $\bar{B}^0$ and B^- distributions with a mixture of $V-A$ and $V+A$ hadronic currents yields 95% confidence level upper limits on the fraction $\mathcal{R}(V+A)/\mathcal{R}(V-A)$. These are also shown in Table III.

Until now we have assumed that the lepton current is $V-A$ as is the case in the standard model. Since the asymmetry involves the product of the chiralities of both quark and lepton currents, a right-handed lepton coupling would change the sign of the asymmetry. Gronau and Wakaizumi [4] have shown that it is possible to construct a nonstandard model in which the $b \to c$ current appears left-handed even if it is right-handed, because the lepton current couples to a right-handed W. Specifically, they have studied the decay $\bar{B}^0 \to D^{*+} l^- \nu$ in a $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)$ model. Our measured asymmetry can be used to constrain the values of the parameters within this model, but cannot exclude a large or even dominant right-handed $b \to c$ coupling. In any case our measured asymmetry is consistent with the standard model and will allow us to estimate the form factors in conjunction with other measurements.

IV. EXTRACTION OF THE FORM FACTORS

The helicity amplitudes H_-, H_+, and H_0 are related to the hadronic form factors as

$$H_{\pm}(q^2) = (m_B + m_{D^*}) A_1(q^2) \mp \frac{2 m_B K}{m_B + m_{D^*}} V(q^2), \tag{5}$$

$$H_0(q^2) = \frac{1}{2 m_{D^*} \sqrt{q^2}} \left[(m_B^2 - m_{D^*}^2 - q^2)(m_B + m_{D^*}) A_1(q^2) - \frac{4 m_B^2 K^2}{m_B + m_{D^*}} A_2(q^2) \right]. \tag{6}$$

$A_1(q^2)$ can be factored out of Eqs. (5) and (6). Then the differential width as expressed in Eq. (1) depends on the form-factor ratios $A_2(q^2)/A_1(q^2)$ and $V(q^2)/A_1(q^2)$, while the total rate is proportional to the branching ratio, B lifetime, $|V_{cb}|^2$, and $A_1^2(q^2)$. Measurement of different physical observables obtained by integrating Eq. (1) can be used to estimate the form-factor ratios at a fixed q^2. The point we choose is the maximum q^2, denoted as $q^2_{\rm max}$. Using measured values for the B lifetime and the branching ratio we extract a value for $|V_{cb}|(A_1(q^2_{\rm max})$. Then, using an estimate of $|V_{cb}|$, we derive a value for $A_1(q^2_{\rm max})$, which allows us to find all three form factors.

We use nine experimental data points to build a χ^2 which is a function of the form-factor ratios $A_2(q^2_{\rm max})/A_1(q^2_{\rm max})$ and $V(q^2_{\rm max})/A_1(q^2_{\rm max})$ and $|V_{cb}|A_1(q^2_{\rm max})$. The experimental data points are the following.

(i) The asymmetry $A_{\rm fb}$.

(ii) The shape of the $d\mathcal{B}(\bar{B}\rightarrow D^{*+}l^-\bar{\nu}_l)/dq^2$ distribution from CLEO and ARGUS [15], which is related to the helicity amplitudes as

$$\frac{d\mathcal{B}(\bar{B}^0\rightarrow D^{*+}l^-\bar{\nu}_l)}{dq^2}=\tau_B\frac{d\Gamma(\bar{B}^0\rightarrow D^{*+}l^-\bar{\nu}_l)}{dq^2}=|V_{cb}|^2\tau_B\frac{G_F^2}{(2\pi)^3}\frac{q^2K}{12m_B^2}\times(|H_-|^2+|H_+|^2+|H_0|^2). \tag{7}$$

Here six distinct data points are used.

(iii) The value of Γ_L/Γ_T from measurements of the D^{*+} polarization, integrated over q^2, of 0.85 ± 0.45, for $p_l>1.0$ from ARGUS [1] and 0.82 ± 0.36, for $p_l>1.4$ from CLEO [2]. The relationship to the helicity amplitudes is given by

$$\frac{\Gamma_L}{\Gamma_T}=\frac{\int|H_0|^2q^2K\,dq^2dp_l}{\int(|H_+|^2+|H_-|^2)q^2K\,dq^2dp_l}. \tag{8}$$

The values of the form factors which best represent the experimental data are found by minimizing

$$\chi^2=\sum_i\left[\frac{P_i^{\rm exp}-P_i^T\left[\dfrac{A_2}{A_1},\dfrac{V}{A_1},|V_{cb}|A_1\right]}{\sigma_i}\right]^2,\quad i=1,9, \tag{9}$$

where $P_i^{\rm exp}$ is the measured value of the physical observable, and σ_i is the error. $P_i^T(A_2/A_1,V/A_1,|V_{cb}|A_1)$ is given by the corresponding integral of Eq. (1) using Eqs. (5) and (6) to express the helicity amplitudes in terms of form factors, and integrating over the appropriate angular and q^2 regions for the ith data point.

Because of the limited amount of available data as a function of q^2, we assume a q^2 dependence of the form factors. This dependence is parametrized in two different ways: (a) We assume an exponential dependence of the form factors on q^2 according to the formalism outlined in Ref. [7]. (b) We fix the q^2 dependence of the form factors according to the fit of Neubert to the CLEO and ARGUS data sample [16].

We relate the value of the asymmetry, $A_{\rm fb}$, to form factors through the helicity amplitudes by substituting Eqs. (5) and (6) in Eq. (3). The resulting expression is then integrated over the phase space allowed by the lepton momentum cut. To find the relationship for the D^* polarization we substitute Eqs. (5) and (6) in Eq. (8). We take into account the different momentum cuts used by the two experiments when we perform the integration over dq^2dp_l. The six data points of the $d\mathcal{B}/dq^2$ distribution are first normalized to the average of the charged and neutral B meson branching ratio for the decay $B\rightarrow D^*l^-\bar{\nu}_l$ [17]:

$$\mathcal{B}(B\rightarrow D^*l^-\bar{\nu}_l)=4.4\pm0.5\%.$$

Then each of the six measurements is compared directly to the value of $d\Gamma/dq^2$ given by Eq. (7) using the B meson lifetime, $\tau_B=1.28\pm0.06$ ps, from the average of measurements at the SLAC e^+e^- storage ring PEP, the DESY e^+e^- collider PETRA, and the CERN e^+e^- collider LEP measurements [18].

The results of minimizing the χ^2 defined in Eq. (9) are shown in Table IV. The first and second rows give the results assuming a form-factor dependence on q^2 according to methods (a) and (b), respectively. The good agreement between methods (a) and (b) indicates that our result is fairly independent of the exact form of the q^2 dependence. For the HQET case we present predictions without [14] and with $1/M$ corrections [19]. The fits indicate that the form-factor ratios predicted by the models agree with the experimental data at the 25% level.

The first error on the experimental determination of the form factors comes from the fit itself. It should be noted that we do not consider possible correlations between the measurements. The systematic error due to the

TABLE IV. Form-factor ratios at $q^2=q^2_{\rm max}$.

	A_2/A_1	V/A_1	$\lvert V_{cb}\rvert A_1$
Fit a	1.02 ± 0.24	1.07 ± 0.57	$0.035\pm0.003\pm0.002$
Fit b	0.79 ± 0.28	1.32 ± 0.62	$0.037\pm0.003\pm0.002$
ISGW [7]	1.14	1.27	
KS [8]	1.39	1.54	
WSB [9]	1.06	1.14	
HQET [14]	1.26	1.26	
HQET [19]	1.14	1.74	

TABLE V. Form factors at $q^2=q^2_{\max}$.

	A_1	A_2	V
Fit a	$0.85\pm0.07\pm0.11$	$0.87\pm0.22\pm0.10$	$0.91\pm0.49\pm0.12$
Fit b	$0.90\pm0.07\pm0.11$	$0.71\pm0.26\pm0.09$	$1.19\pm0.57\pm0.15$
ISGW [7]	0.94	1.08	1.20
KS [8]	0.85	1.18	1.31
WSB [9]	0.85	0.90	0.97
HQET [14]	0.90	1.13	1.13
HQET [19]	0.85	0.97	1.48

uncertainty in τ_B has been estimated by taking a 1σ variation in this quantity; it affects only the determination of $|V_{cb}|A_1$. There is also a systematic error due to the assumed q^2 dependence in each model we used. This error is not given in the table. It must be understood that the form-factor ratios quoted here are explicitly for the assumed q^2 dependences. The models of ISGW and Neubert have the largest differences in q^2 dependences among the currently available models. The differences between the measured ratios therefore give an indication of the largest reasonable difference in the form-factor ratios due to model dependence.

We can finally evaluate all three form factors by using $|V_{cb}|=0.041\pm0.005$ from Stone's review [17]. The results are shown in Table V. The systematic error due to the uncertainty in $|V_{cb}|$ and τ_B has been estimated by taking a 1σ variation in these quantities. The variation in $|V_{cb}|$ accounts for 90% of the systematic error.

V. CONCLUSIONS

In conclusion, the sign of the asymmetry used to test the chirality of the $b\rightarrow c$ coupling is in agreement with the standard model if the lepton current is assumed to be left-handed. Combining the information of both decay modes by a simultaneous fit, the amount of $V+A$ is $<30\%$ at 95% confidence level. Generic $SU(2)_L\times SU(2)_R\times U(1)$ models can give predictions similar to the standard model for certain values of their parameters.

We also obtain the first measurements of the form factors in B decay, and find them to be in agreement with theoretical models.

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