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Flavor-Specific Inclusive B Decays to Charm

CLEO Collaboration

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Abstract

We have measured the rates for $B \to \bar{D}X$, $B \to DX$, and $B \to \bar{D}X\ell^+\nu$. Here B is an average over B^0 and B^+ (as found at the Υ(4S)), D is a sum over D^0 and D^+, and $\bar{D}$ is a sum over $\bar{D}^0$ and D^-. We find:

$$\frac{\Gamma(B \to DX)}{\Gamma(B \to \bar{D}X)} = 0.100 \pm 0.026 \pm 0.016;$$

$$\frac{\Gamma(B \to \bar{D}X)}{\Gamma(B \to all)} / \frac{\Gamma(B \to \bar{D}X\ell^+\nu)}{\Gamma(B \to X\ell^+\nu)} = 0.901 \pm 0.034 \pm 0.014;$$

$$\Gamma(B \to \bar{D}X\ell^+\nu)/\Gamma(B \to X\ell^+\nu)_{meas} = 0.914 \pm 0.027 \pm 0.042.$$

From the first result, along with some previously measured rates, we obtain $\mathcal{B}(b \to c\bar{c}s) = (21.9 \pm 3.7)\%$. From the second result, we obtain $\mathcal{B}(b \to FCNC) = (0.2 \pm 4.1)\%$, $< 6.8\%$ @ 90% c.l. By constraining the third result to have its expected value, we obtain a measurement of the $D^0 \to K^-\pi^+$ absolute branching ratio, $\mathcal{B}(D^0 \to K^-\pi^+) = (3.69 \pm 0.20)\%$. The implications of all three results for the "B semileptonic decay problem" (the fact that the measured branching ratio is below theoretical expectations) are discussed. The increased value of $\mathcal{B}(b \to c\bar{c}s)$ due to $B \to DX$ eliminates about half of the difference.

S. Glenn,[1] S. D. Johnson,[1] Y. Kwon,[1,*] S. Roberts,[1] E. H. Thorndike,[1] C. P. Jessop,[2] K. Lingel,[2] H. Marsiske,[2] M. L. Perl,[2] D. Ugolini,[2] R. Wang,[2] X. Zhou,[2] T. E. Coan,[3] V. Fadeyev,[3] I. Korolkov,[3] Y. Maravin,[3] I. Narsky,[3] V. Shelkov,[3] J. Staeck,[3] R. Stroynowski,[3] I. Volobouev,[3] J. Ye,[3] M. Artuso,[4] A. Efimov,[4] M. Goldberg,[4] D. He,[4] S. Kopp,[4] G. C. Moneti,[4] R. Mountain,[4] S. Schuh,[4] T. Skwarnicki,[4] S. Stone,[4] G. Viehhauser,[4] X. Xing,[4] J. Bartelt,[5] S. E. Csorna,[5] V. Jain,[5,†] K. W. McLean,[5] S. Marka,[5] R. Godang,[6] K. Kinoshita,[6] I. C. Lai,[6] P. Pomianowski,[6] S. Schrenk,[6] G. Bonvicini,[7] D. Cinabro,[7] R. Greene,[7] L. P. Perera,[7] G. J. Zhou,[7] B. Barish,[8] M. Chadha,[8] S. Chan,[8] G. Eigen,[8] J. S. Miller,[8] C. O'Grady,[8] M. Schmidtler,[8] J. Urheim,[8] A. J. Weinstein,[8] F. Würthwein,[8] D. W. Bliss,[9] G. Masek,[9] H. P. Paar,[9] S. Prell,[9] M. Sivertz,[9] V. Sharma,[9] D. M. Asner,[10] J. Gronberg,[10] T. S. Hill,[10] D. J. Lange,[10] S. Menary,[10] R. J. Morrison,[10] H. N. Nelson,[10] T. K. Nelson,[10] C. Qiao,[10] J. D. Richman,[10] D. Roberts,[10] A. Ryd,[10] M. S. Witherell,[10] R. Balest,[11] B. H. Behrens,[11] W. T. Ford,[11] H. Park,[11] J. Roy,[11] J. G. Smith,[11] J. P. Alexander,[12] C. Bebek,[12] B. E. Berger,[12] K. Berkelman,[12] K. Bloom,[12] D. G. Cassel,[12] H. A. Cho,[12] D. S. Crowcroft,[12] M. Dickson,[12] P. S. Drell,[12] K. M. Ecklund,[12] R. Ehrlich,[12] A. D. Foland,[12] P. Gaidarev,[12] R. S. Galik,[12] L. Gibbons,[12] B. Gittelman,[12] S. W. Gray,[12] D. L. Hartill,[12] B. K. Heltsley,[12] P. I. Hopman,[12] J. Kandaswamy,[12] P. C. Kim,[12] D. L. Kreinick,[12] T. Lee,[12] Y. Liu,[12] G. S. Ludwig,[12] N. B. Mistry,[12] C. R. Ng,[12] E. Nordberg,[12] M. Ogg,[12,‡] J. R. Patterson,[12] D. Peterson,[12] D. Riley,[12] A. Soffer,[12] B. Valant-Spaight,[12] C. Ward,[12] M. Athanas,[13] P. Avery,[13] C. D. Jones,[13] M. Lohner,[13] C. Prescott,[13] J. Yelton,[13] J. Zheng,[13] G. Brandenburg,[14] R. A. Briere,[14] A. Ershov,[14] Y. S. Gao,[14] D. Y.-J. Kim,[14] R. Wilson,[14] H. Yamamoto,[14] T. E. Browder,[15] Y. Li,[15] J. L. Rodriguez,[15] T. Bergfeld,[16] B. I. Eisenstein,[16] J. Ernst,[16] G. E. Gladding,[16] G. D. Gollin,[16] R. M. Hans,[16] E. Johnson,[16] I. Karliner,[16] M. A. Marsh,[16] M. Palmer,[16] M. Selen,[16] J. J. Thaler,[16] K. W. Edwards,[17] A. Bellerive,[18] R. Janicek,[18] D. B. MacFarlane,[18] P. M. Patel,[18] A. J. Sadoff,[19] R. Ammar,[20] P. Baringer,[20] A. Bean,[20] D. Besson,[20] D. Coppage,[20] C. Darling,[20] R. Davis,[20] N. Hancock,[20] S. Kotov,[20] I. Kravchenko,[20] N. Kwak,[20] S. Anderson,[21] Y. Kubota,[21] S. J. Lee,[21] J. J. O'Neill,[21] S. Patton,[21] R. Poling,[21] T. Riehle,[21] V. Savinov,[21] A. Smith,[21] M. S. Alam,[22] S. B. Athar,[22] Z. Ling,[22] A. H. Mahmood,[22] H. Severini,[22] S. Timm,[22] F. Wappler,[22] A. Anastassov,[23] J. E. Duboscq,[23] D. Fujino,[23,§] K. K. Gan,[23] T. Hart,[23] K. Honscheid,[23] H. Kagan,[23] R. Kass,[23] J. Lee,[23] M. B. Spencer,[23] M. Sung,[23] A. Undrus,[23,**] R. Wanke,[23] A. Wolf,[23] M. M. Zoeller,[23] B. Nemati,[24] S. J. Richichi,[24] W. R. Ross,[24] P. Skubic,[24] M. Bishai,[25] J. Fast,[25] J. W. Hinson,[25] N. Menon,[25] D. H. Miller,[25] E. I. Shibata,[25] I. P. J. Shipsey,[25] and M. Yurko[25]

[1]University of Rochester, Rochester, New York 14627
[2]Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

[*]Permanent address: Yonsei University, Seoul 120-749, Korea.

[†]Permanent address: Brookhaven National Laboratory, Upton, NY 11973.

[‡]Permanent address: University of Texas, Austin TX 78712

[§]Permanent address: Lawrence Livermore National Laboratory, Livermore, CA 94551.

[**]Permanent address: BINP, RU-630090 Novosibirsk, Russia.

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

I. INTRODUCTION

In heavy flavor physics, there has been a longstanding problem of the measured B semileptonic decay branching ratio [1] being smaller than theoretical expectations [2,3]. One explanation [2] is a larger-than-expected FCNC contribution, due to new physics. Another [3] is an enhanced rate for $b \to c\bar{c}s'$. (s' denotes the weak isopspin partner of c.) An argument against an enhanced $b \to c\bar{c}s'$ rate is that it would conflict with the measured branching ratio for $B \to \bar{D}X$ plus $B \to DX$. This branching ratio relies on $\mathcal{B}(D^0 \to K^-\pi^+)$, and if that is in error, the measurement of the branching ratio of B to charm or anticharm will be also. We address all three issues by measuring the decay rates for the flavor-specific inclusive B decay processes $B \to DX$, $B \to \bar{D}X$, and $B \to \bar{D}X\ell^+\nu$. (Herein, B represents an average over B^0 and B^+, D a sum over D^0 and D^+, and $\bar{D}$ a sum over $\bar{D}^0$ and D^-.)

These rates, and ratios among them, provide information on the above-mentioned issues as follows:

(i) The fraction of semileptonic B decays that proceed through $B \to \bar{D}X\ell^+\nu$ differs from 100% only because of small contributions from $b \to u\ell\nu$ and $B \to D_s^- KX\ell^+\nu$ ("lower vertex D_s"). The measured fraction is proportional to the assumed D absolute branching ratio (in our case $\mathcal{B}(D^0 \to K^-\pi^+)$) and scaling the yield to agree with expectations gives a new method to measure that branching ratio.

(ii) The fraction of all B decays that proceed through $B \to \bar{D}X$ differs from 100% because of $b \to u$ decays, lower vertex D_s, formation of $(c\bar{c})$ bound states, formation of charmed baryons, and flavor-changing neutral processes such as $b \to sg$, $b \to dg$, $b \to sq\bar{q}$, $b \to dq\bar{q}$. As all processes except FCNC are moderately well measured, the ratio of the yields for $B \to \bar{D}X$ and $B \to \bar{D}X\ell^+\nu$ provides a measurement of the branching ratio for FCNC processes.

(iii) The process $B \to DX$ proceeds via the the quark-level process $b \to c\bar{c}s'$, and thus the ratio of the yields for $B \to DX$ and $B \to \bar{D}X$ provides information on the rate of that process relative to $b \to c\bar{u}d'$.

The typical inclusive B decay branching ratio measurement at the Υ(4S) averages over B and $\bar{B}$ initial states for a given final state, and consequently averages over particle and antiparticle final states for a given initial state (B or $\bar{B}$). In 1987 CLEO developed a technique for measuring inclusive B decay branching ratios separately to particle and antiparticle final states, and applied it to inclusive kaon decays [4,5]. Here we apply similar techniques to inclusive charm decays.

The principle underlying the 1987 technique is that if one B from a $B\bar{B}$ pair decays semileptonically, with a high momentum lepton, then the other decay products from that B will have substantial angular correlations with the lepton, tending to come off back-to-back to it, while the decay products from the other B have negligible angular correlations with the lepton. The lepton tags the flavor of its parent B, and thus also the other B (with a small correction needed for mixing). By plotting the distribution in the angle between $D\ell^+$ (and $\bar{D}\ell^-$) pairs, and separately the distribution in the angle between $D\ell^-$ (and $\bar{D}\ell^+$) pairs, and extracting an isotropic component and a peaking component from each, yields are obtained for four processes: $B \to \bar{D}X\ell^+\nu$, $B \to DX\ell^+\nu$, $B \to \bar{D}X$, and $B \to DX$. Of these, $B \to DX\ell^+\nu$ should be zero.

For low D momenta, the technique just described loses statistical power and becomes sensitive to the shape assumed for the peaking component. (In the limit that the D momentum vanishes, the D–lepton angular correlation clearly contains no information.) Consequently, we have developed a second technique, based on charge correlations alone. We measure three yields: the number of D, ℓ^- (and $\bar{D}, \ell^+$) pairs, proportional to the sum of $B \to \bar{D}X\ell^+\nu$ and $B \to DX$; the number of D, ℓ^+ (and $\bar{D}, \ell^-$) pairs; proportional to the sum of $B \to DX\ell^+\nu$ and $B \to \bar{D}X$; and the number of D (and $\bar{D}$) mesons, proportional to the sum of $B \to \bar{D}X$ and $B \to DX$. Using the fact that the rate for $B \to DX\ell^+\nu$ vanishes, these yields give the rates for the other three processes: $B \to \bar{D}X\ell^+\nu$, $B \to \bar{D}X$, and $B \to DX$. Using a combination of the angular correlation and charge correlation techniques, we have obtained those three rates for the sum of D^0 and D^+ mesons.

II. PROCEDURES

The data were taken with the CLEO detector [6] at the Cornell Electron Storage Ring (CESR), and consist of 3.2 fb^{-1} on the $\Upsilon(4S)$ resonance and 1.6 fb^{-1} at a center-of-mass energy 60 MeV below the resonance. The on-resonance sample contains 3.3 million $B\bar{B}$ events and 10 million continuum events. The CLEO detector measures charged particles over 95% of 4π steradians with a system of cylindrical drift chambers. Its barrel and endcap CsI electromagnetic calorimeters cover 98% of 4π. Hadron identification is provided by specific ionization (dE/dX) measurements in the outermost drift chamber and by time-of-flight counters (ToF). Muons are identified by their ability to penetrate iron; electrons by dE/dX, comparison of track momentum with calorimeter cluster energy, and track/cluster position matching.

We select hadronic events containing at least 4 charged tracks. We require a value of Fox-Wolfram parameter [7] $R_2 \equiv H_2/H_0 < 0.5$, to suppress continuum events. Events containing at least one lepton, with momentum between 1.5 and 2.8 GeV/c and surviving a $\psi \to \ell^+\ell^-$ veto, are scanned for D^0, D^+, and charge conjugates. We detect D^0 and D^+ via the $K^-\pi^+$ and $K^-\pi^+\pi^+$ decay mode, respectively. Tracks used as candidate D decay products must have dE/dX and/or ToF values consistent within 2σ of the particle assignment made (K or π). For $D^0 \to K^-\pi^+$, particle identification must rule out the π^-K^+ option.

For each candidate D, we plot the $K\pi$ ($K\pi\pi$) mass for four intervals in $\cos\theta_{D-\ell}$ and four intervals in D momentum, separately for the two charge correlations with the lepton. These 64 mass plots are fit to double-Gaussian signal peaks and polynomial backgrounds, to extract D yields. These are corrected for detection efficiency, determined by Monte Carlo simulation augmented by studies of particle ID efficiency using data (a sample of $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ events). Small subtractions are made for continuum background (using below-$\Upsilon(4S)$-resonance data) and for hadrons misidentified as leptons (using hadrons in place of leptons and weighting by the "faking probability"). Small corrections are made to the D^0 yields for the singly-Cabibbo-suppressed decays $D^0/\bar{D}^0 \to K^-K^+$ and $D^0/\bar{D}^0 \to \pi^-\pi^+$ which combine with a single failure of particle ID to make satellite peaks, for the doubly-Cabibbo-suppressed decay $D^0 \to K^+\pi^-$ [8], and for double failures of particle ID, with π^-K^+ treated as $K^-\pi^+$. A small correction is made to D^+ yields for the decay $D_s^+ \to K^-K^+\pi^+$ with the K^+ misidentified as a π^+.

The D yields for each momentum interval, charge correlation, and D type, are plotted vs. $\cos\theta_{D-\ell}$, 16 plots in all. For the D momentum intervals 1.3 – 1.95 and 1.95 –2.6 GeV/c, we fit the $\ell^- D$ angular distributions to an isotropic component and a backward-peaking component, with fitting functions obtained from Monte Carlo simulation. We fit the $\ell^+ D$ angular distributions to an isotropic component alone. For the D momentum intervals 0.0 – 0.65 and 0.65 – 1.3 GeV/c, we use the charge correlation technique, summing over $\cos\theta_{D-\ell}$. Results are given in Table 1. When correcting for branching ratios, we use $\mathcal{B}(D^0 \to K^-\pi^+)$ = 3.91% [9], and $\mathcal{B}(D^+ \to K^-\pi^+\pi^+)/\mathcal{B}(D^0 \to K^-\pi^+) = 2.35$ [10]. For illustrative purposes, we show $\cos\theta_{D-\ell}$ distributions summed over momentum intervals and over D^0 and D^+, as Fig. 1. The $\ell^- D + \ell^+ \bar{D}$ distribution strong back-to-back peaking from $\bar{B} \to DX\ell^-\nu$, while the $\ell^- \bar{D} + \ell^+ D$ shows no such peaking, due to the nonexistence of $\bar{B} \to \bar{D}X\ell^-\nu$. One also notes a much larger isotropic component in $\ell^- \bar{D} + \ell^+ D$, because of the large rate for $B \to \bar{D}X$ and a small rate for $B \to DX$ (and a small rate for mixing $B^0 \to \bar{B}^0 \to DX$).

If the lepton and D come from the same B, then the lepton tags *that* B correctly. The lepton can't be from decay of D, because the D was *detected* via a hadronic decay mode. It can't be from ψ, because the rate for $\bar{B} \to \psi DX$ is negligible. If the B has mixed, nonetheless the lepton correctly tags the b flavor at the instant of decay, which is what is relevant for understanding the D from the same B. But, if the lepton and D come from different B's, then the tagging of *both* B's is now imperfect: the ancestor of the lepton because leptons from charm decay and leptons from ψ now contribute; and the ancestor of the D for those reasons and in addition because of $B^0 - \bar{B}^0$ mixing. Corrections are thus required for the isotropic components given in Table 1. These depend on f_m (the probability that a lepton mistags its ancestor B), and χ (the mixing parameter).

III. RESULTS AND INTERPRETATION

We extract three distinct pieces of physics from the numbers given in Table 1. For each, we have considered systematic errors due to uncertainties in each of the previously-mentioned corrections, uncertainties from fitting mass peaks and $\cos\theta_{D-\ell}$ distributions, and uncertainties in efficiency and D branching ratios.

(i) First consider $\Gamma(B \to DX)/\Gamma(B \to \bar{D}X)$, the ratio of "upper vertex" charm to "lower vertex" charm. This ratio U/L is obtained from $x = N(\ell^-, D, \text{isotropic})/N(\ell^-, \bar{D}, \text{isotropic})$, correcting for mixing and mistags. $U/L = (x - F_m)/(1 - xF_m)$, where $F_m = (f_m + f')/(2 - f_m - f')$, and $f' = f_m + \chi - 2f_m\chi$. We use $\chi = 0.157$ as measured by CLEO with dileptons [11], and $f_m = 0.027$ as found there, thereby achieving cancellation of some systematic errors in F_m, giving $F_m = 0.112$. From Table 1, $x = 0.210 \pm 0.025$, leading to

$$\frac{\Gamma(B \to DX)}{\Gamma(B \to \bar{D}} = 0.100 \pm 0.026 \pm 0.016, \tag{1}$$

where the first error is statistical and the second is systematic (dominated by the uncertainty in mixing correction). This result is a bit surprising, as conventional wisdom held that $b \to c\bar{c}s$ would hadronize dominantly into D_s. However, Buchalla *et al.* [3] have argued that the D^0, D^+ component should be substantial.

In Fig. 2 we plot the momentum distribution of these "upper vertex" D^0, D^+, obtained by applying the analysis just described to each of the four D momentum bins. The spectrum is softer than that for "lower vertex" D's, also shown. It is well described by 3-body

$D^{(*)}D^{(*)}K^{(*)}$ phase space, if one allows one or two of the particles to be the vector states. CLEO has observed such decay modes [12].

(ii) Next consider the fraction of all B decays to $\bar{D}$, divided by the fraction of semileptonic B decays to $\bar{D}$, i.e., the double-ratio of widths $\frac{\Gamma(B\to\bar{D}X)}{\Gamma(B\to all)}/\frac{\Gamma(B\to\bar{D}X\ell^+\nu)}{\Gamma(B\to X\ell^+\nu)}$. We obtain this from the ratio of yields $N(\ell^-,\bar{D},\text{isotropic})/N(\ell^-,D,\text{peaking}) \equiv z_{raw}$. Corrections are required to the isotropic yield for mixing and mistags. Also, leptons from unvetoed ψ and from secondary decays (3.3% of all leptons) don't contribute to the peaking yield, and so a correction is required for that, leading to $z_{cor} = 0.967z_{raw}/[(1-0.5f_m-0.5f')(1+F_mU/L)]$, where $U/L = 0.100$, as found above. Applying all corrections, we have

$$\frac{\Gamma(B\to\bar{D}X)}{\Gamma(B\to all)}/\frac{\Gamma(B\to\bar{D}X\ell^+\nu)}{\Gamma(B\to X\ell^+\nu)} = 0.901\pm0.034\pm0.015 \tag{2}$$

One expects both $\Gamma(B\to\bar{D}X)/\Gamma(B\to all)$ and $\Gamma(B\to\bar{D}X\ell^+\nu)/\Gamma(B\to X\ell^+\nu)$ to be close to 1.0. The first ratio will be less than 1.0 because of $b\to u$ transitions ($2|V_{ub}/V_{cb}|^2$, where the 2 is a phase space factor), lower vertex D_s (2%), bound $(c\bar{c})$ states ($3.0\pm0.5\%$ [13]), baryons ($6.5\pm1.5\%$ [14]), and $b\to sg$ (to be extracted). The second ratio will be less than 1.0 because of $b\to u$ transitions ($3|V_{ub}/V_{cb}|^2$, enhanced by the 1.5 GeV/c lepton momentum requirement), and lower vertex D_s ($1.0\pm0.5\%$, suppressed by the lepton momentum requirement). These lead to

$$\begin{aligned}\frac{\Gamma(B\to\bar{D}X)}{\Gamma(B\to all)}/\frac{\Gamma(B\to\bar{D}X\ell^+\nu)}{\Gamma(B\to X\ell^+\nu)} &= 1.0+|V_{ub}/V_{cb}|^2-(0.010\pm0.005)-(0.030\pm0.005)\\ &\quad -(0.065\pm0.015)-\mathcal{B}(b\to sg)\end{aligned} \tag{3}$$

Here $b\to sg$ is symbolic for all FCNC processes. Using $|V_{ub}/V_{cb}|^2 = 0.008\pm0.003$, we obtain $\mathcal{B}(b\to sg) = (0.2\pm3.4\pm1.5\pm1.7)\%$, where the first error is statistical, the second systematic on z, and the third the uncertainties in Expression (3). From this we obtain an upper limit $\mathcal{B}(b\to sg) < 6.8\%$, @ 90% C.L.

(iii) Finally consider the fraction of semileptonic B decays to $\bar{D}^0$ or D^-, i.e., $\Gamma(B\to\bar{D}X\ell^+\nu)/\Gamma(B\to X\ell^+\nu)$. We obtain this fraction by dividing the yield $N(\ell^-,D,\text{peaking})$ by the number of "upper vertex" leptons in our sample, 96.7% of the total. We find $\Gamma(B\to\bar{D}X\ell^+\nu)/\Gamma(B\to X\ell^+\nu)_{meas} = 0.914\pm0.027\pm0.042$. This number is inversely proportional to the value used for $\mathcal{B}(D^0\to K^-\pi^+)$. The expected value of the ratio of widths is $\Gamma(B\to\bar{D}X\ell^+\nu)/\Gamma(B\to X\ell^+\nu)_{expected} = 1.0-3|V_{ub}/V_{cb}|^2-0.010\pm0.005(\text{for}\bar{B}\to D_s^+KX\ell^-\nu)$. Taking $3|V_{ub}/V_{cb}|^2 = 0.023\pm0.008$, we find the expected ratio of widths to be 0.968 ± 0.010, differing from the measured value by one standard deviation. We set measured and expected values of the ratio equal to each other, and solve for the D^0 branching ratio, finding $\mathcal{B}(D^0\to K^-\pi^+) = (3.69\pm0.11\pm0.16\pm0.04)\%$, where the first error is statistical, the second systematic in the measured ratio, and the third systematic in the predicted ratio. This value for the branching ratio, $(3.69\pm0.20)\%$, is to be compared with a recent measurements by CLEO of $(3.91\pm0.19)\%$ [9] and $(3.81\pm0.23)\%$ [15], and the PDG value of $(3.83\pm0.12)\%$ [16].

IV. THE B SEMILEPTONIC DECAY BRANCHING RATIO PROBLEM

In Table 2 we list all the components of B decay, give their branching ratios (based on measurement or theory), and see if they sum to 100%. We express some in terms of b_{SL}, the B semileptonic decay branching ratio, whose measured value [1] is $(10.49 \pm 0.46)\%$. The factor of 0.25 for $b \to c/u\tau\nu$ is a phase space factor. The factor r_{ud} for $b \to c/uud'$ would be 3 from color counting, but with QCD corrections [17] is 4.0 ± 0.4. This analysis has two pieces of information to add to Table 2. First, the upper vertex $\bar{D}^0, D^-$ contribution of $(7.9 \pm 2.2)\%$ is obtained from our measured value of $\Gamma(\bar{B} \to \bar{D}^0 \mathrm{or} D^- X)/\Gamma(\bar{B} \to D^0 \mathrm{or} D^+ X)$ combined with the rate for inclusive $D^0 + D^+$ $(63.6\% + 23.5\%)$ [18]. Second, we have a value (with large errors) for the FCNC term. One sees that the upper vertex $\bar{D}^0, D^-$ contribution accounts for close to half of the shortfall. The remaining shortfall is not statistically compelling. Adjusting r_{ud} to bring the sum to 100%, we find $r_{ud} = 5.2 \pm 0.6$.

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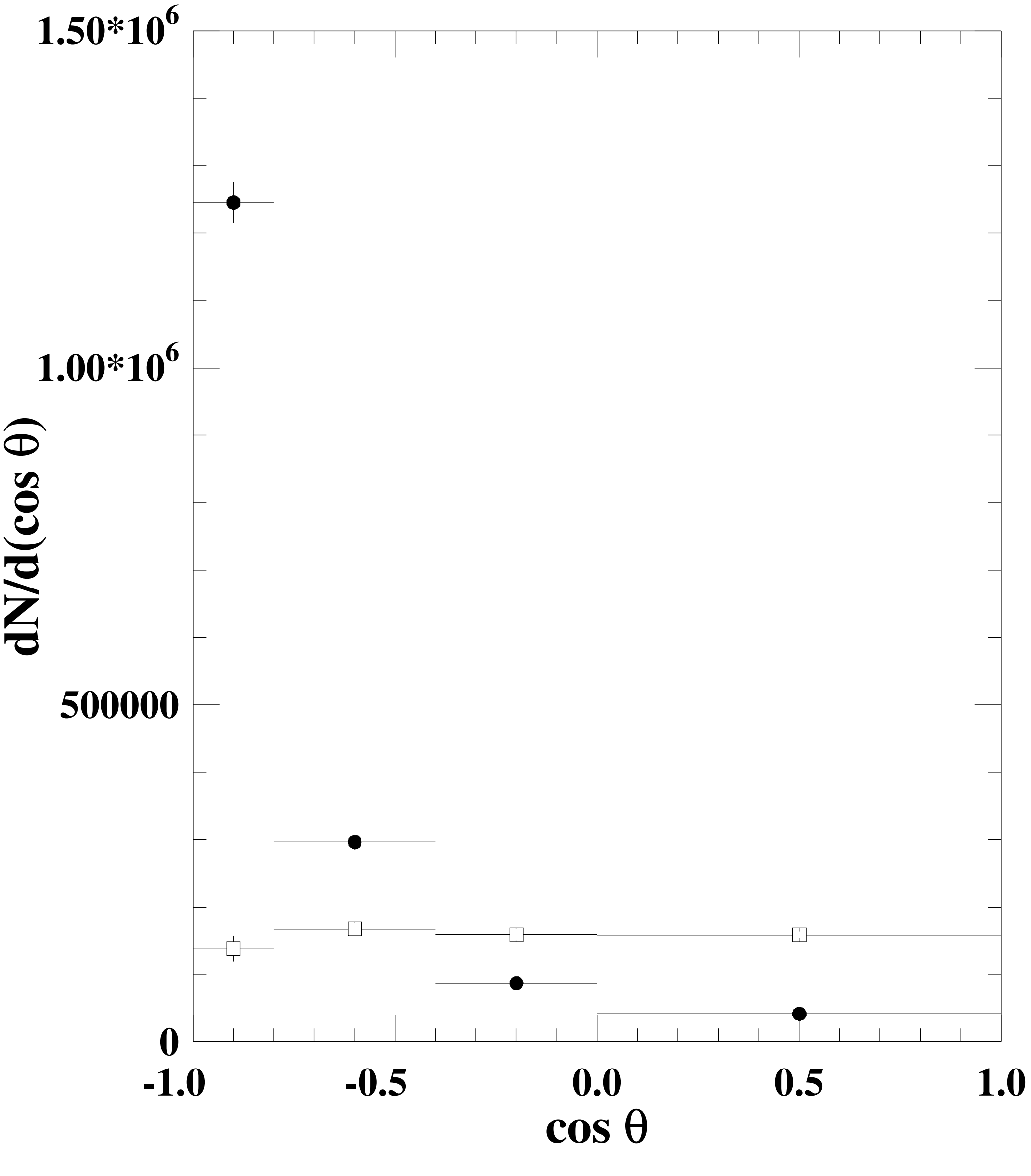

FIG. 1. Yield of (ℓ, D) events vs $\cos\theta_{D-\ell}$: (solid circles) $(\ell^-, D^0) + (\ell^-, D^+)$ plus charge conjugate, summed over D momentum; (open squares) $(\ell^-, \bar{D}^0) + (\ell^-, D^-)$ plus charge conjugate, summed over D momentum.

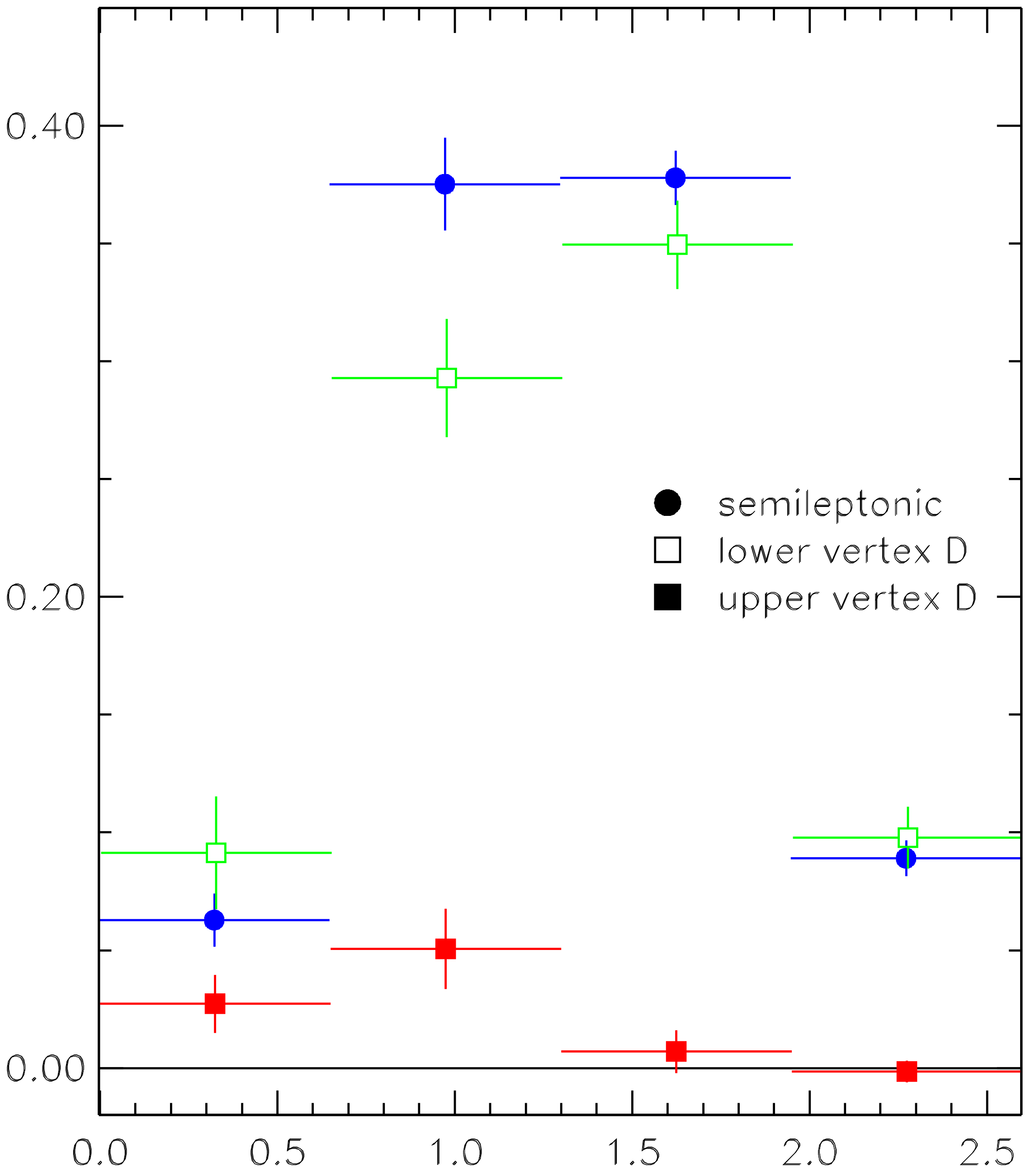

FIG. 2. D momentum distributions: (solid squares) "Upper vertex" $D^0 + D^+$, i.e., from $B \to DX$; (open squares) "Lower vertex" $D^0 + D^+$, from $\bar{B} \to DX$; (solid circles) "Lower vertex" $D^0 + D^+$, from $\bar{B} \to DX\ell\nu$.

TABLE I. Same B (peaking) and other B (isotropic) components of D yields.

Class	P (GeV/c)	Same B(peaking)	Other B(isotropic)
	0.00-0.65	842.5 ± 143.4	456.3 ± 105.7
D^0/ℓ^-	0.65-1.30	4884.4 ± 252.6	767.6 ± 182.2
	1.30-1.95	4619.1 ± 155.7	415.4 ± 98.5
	1.95-2.60	923.3 ± 102.6	38.2 ± 48.7
	0.00-0.65	0.00	1050.7 ± 94.1
D^0/ℓ^+	0.65-1.30	0.00	3496.4 ± 162.3
	1.30-1.95	0.00	3855.6 ± 148.3
	1.95-2.60	0.00	1023.6 ± 82.9
	0.00-0.65	410.2 ± 254.7	226.7 ± 190.0
D^+/ℓ^-	0.65-1.30	2805.0 ± 449.9	1089.0 ± 323.0
	1.30-1.95	3531.1 ± 235.4	622.9 ± 201.5
	1.95-2.60	1220.3 ± 151.1	238.3 ± 101.7
	0.-0-0.65	0.00	809.6 ± 160.8
D^+/ℓ^+	0.65-1.30	0.00	2148.5 ± 273.8
	1.30-1.95	0.00	3100.4 ± 207.2
	1.95-2.60	0.00	984.1 ± 96.1

Summing over P, Correcting for BR, and combining D^0 & D^+,

$(D,\ \ell^-)$		
	SAME B	$(3.7481 \pm 0.1090)\times 10^5$
	OTHER B	$(6.6565 \pm 0.7716)\times 10^4$
$(D,\ \ell^+)$		
	SAME B	0.00
	OTHER B	$(3.1763 \pm 0.0774)\times 10^5$

TABLE II. All components of B decay, with their branching ratios. Upper vertex $\bar{D}^0$ and D^-, and $b \to s/d\ g,\ \ s/d\ q\bar{q}$, are from this analysis.

b decay modes		Branching ratio (%) $b_{SL} = 10.5 \pm 0.5$
$b \to c/u\ e\nu$	b_{SL}	10.5 ± 0.5
$b \to c/u\ \mu\nu$	b_{SL}	10.5 ± 0.5
$b \to c/u\ \tau\nu$	$0.25 b_{SL}$	2.6 ± 0.1
$b \to c/u\ \bar{u}d'$	$r_{ud} b_{SL}$	$42.0 \pm 2.0 \pm 4.2$
$b \to c/u\ \bar{c}s'$		(21.9 ± 3.7)
D_s		10.0 ± 2.7
$(c\bar{c})$		3.0 ± 0.5
baryons		1.0 ± 0.6
upper vertex $\bar{D}^0, D^-$		7.9 ± 2.2
$b \to s/d\ g,\ s/d\ q\bar{q}$		0.2 ± 4.1
TOTAL		87.7 ± 7.4