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Measurement of *b*-Quark Fragmentation Fractions in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.8 TeV

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We have studied the production of B hadrons in 1.8-TeV $p\bar{p}$ collisions. We present measurements of the fragmentation fractions, f_u, f_d, f_s, and f_{baryon}, of produced b quarks that yield B^+, B^0, B_s^0, and

$\overline{\Lambda}_b^0$ hadrons. Reconstruction of five electron-charm final states yields $f_s/(f_u + f_d) = 0.213 \pm 0.068$ and $f_{\text{baryon}}/(f_u + f_d) = 0.118 \pm 0.042$, assuming $f_u = f_d$. If all B hadrons produced in $p\bar{p}$ collisions cascade to one of these four hadrons, we determine $f_u = f_d = 0.375 \pm 0.023$, $f_s = 0.160 \pm 0.044$, and $f_{\text{baryon}} = 0.090 \pm 0.029$. If we do not assume $f_u = f_d$, we find $f_d/f_u = 0.84 \pm 0.16$.

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Bottom (b) quarks are not observed as independent entities but are confined with a partner antiquark or diquark inside hadrons. Once a b quark is produced, the process by which it combines with quarks and gluons to form a hadron is called fragmentation and is governed by the strong force, described by the theory of quantum chromodynamics (QCD) [1]. In this fragmentation process, the color force field creates additional quark-antiquark partners that then combine with the bottom quark to create a B hadron.

The fragmentation process cannot be reliably calculated using perturbative QCD methods. Therefore, the fragmentation properties of the b quark must be determined empirically. In this Letter, we investigate one such property, namely, the flavor dependence of the fragmentation process for bottom quarks produced in 1.8-TeV $p\overline{p}$ collisions. Our results provide the most accurate measurements of this flavor dependence and for the first time bring together in one study all previously studied B hadrons.

We define f_u, f_d, f_s, and f_{baryon} to be the probabilities that the fragmentation of a $\overline{b}$ quark will result in a weakly decaying B^+, B^0, B_s^0 meson and $\overline{\Lambda}_b^0$ baryon, respectively. We explicitly include in these "fragmentation fractions" contributions from production of heavier B hadrons that decay into final states containing a B^+, B^0, B_s^0 meson or $\overline{\Lambda}_b^0$ baryon. The ALEPH experiment used reconstructed $B_s^0 \to D_s^- l^+ \nu X$ decays produced in e^+e^- collisions at the Z^0 resonance to determine the value $f_s = 0.120^{+0.045}_{-0.034}$ [2,3]. The LEP Working Group on B Oscillations has compiled $B^0\overline{B}^0$ mixing results from the four LEP experiments and the Collider Detector at Fermilab (CDF) experiment for the mixing parameters $\overline{\chi}$ and Δm_d [3]. The average values of these parameters constrain the value of f_s, yielding the result $f_s = 0.101^{+0.020}_{-0.019}$ [3]. The CDF experiment has measured $f_s/(f_u + f_d) = 0.210 \pm 0.036^{+0.038}_{-0.030}$ using double semileptonic decays $b \to c\mu X$ with $c \to s\mu X$ [4]. The ALEPH and DELPHI experiments measured f_{baryon} by reconstructing $\overline{\Lambda}_b^0 \to \Lambda_c^- l^+ \nu X$ decays [5,6]. Their combined result is $f_{\text{baryon}} = 0.101^{+0.039}_{-0.031}$ [3]. The CLEO experiment determined the quantity analogous to f_d/f_u, $f^0/f^+ = [\Upsilon(4S) \to B^0\overline{B}^0]/[\Upsilon(4S) \to B^+B^-] = 0.88 \pm 0.16$ and 0.90 ± 0.14, by reconstructing $B \to D^* l \nu$ decays [7] and $B \to J/\psi K^{(*)}$ decays [8], respectively. Both of these measurements are consistent with the isospin symmetry expectation that $f_d = f_u$.

Our measurement, described in detail in Ref. [9], is performed by reconstructing B hadron semileptonic decays to electrons and charm hadrons from a 107 pb^{-1} sample of 1.8-TeV $p\bar{p}$ collisions recorded by CDF during 1992–1995. The ratios of the b quark fragmentation fractions, namely, f_d/f_u, $f_s/(f_u + f_d)$, and $f_{\text{baryon}}/(f_u + f_d)$, are determined from the B hadron production ratios. We reconstruct the B hadrons in the following decay modes and their charge conjugates: $B^+ \to \overline{D}^0 e^+ \nu_e X$ where $\overline{D}^0 \to K^+\pi^-$; $B^0 \to D^{*-} e^+ \nu_e X$ where $D^{*-} \to \overline{D}^0 \pi^-$ and $\overline{D}^0 \to K^+\pi^-$; $B^0 \to D^- e^+ \nu_e X$ where $D^- \to K^+\pi^-\pi^-$; $B_s^0 \to D_s^- e^+ \nu_e X$ where $D_s^- \to \phi\pi^-$ and $\phi \to K^+K^-$; and $\overline{\Lambda}_b^0 \to \Lambda_c^- e^+ \nu_e X$ where $\Lambda_c^- \to \overline{p} K^+ \pi^-$. The average transverse momentum of the B hadrons we reconstruct is 20 GeV/c.

The CDF has been described in detail elsewhere [10]. The CDF coordinate system defines the z axis along the proton beam direction and the polar angle θ with respect to the z axis. The azimuthal angle ϕ is measured in the plane transverse to the beam. The relevant detector components for this measurement are the charged-particle tracking system and the calorimeters. The tracking detectors lie inside a 1.4-T solenoidal magnetic field. The silicon vertex detector (SVX), positioned immediately outside the beam pipe, provides precise charged-particle reconstruction and allows identification of displaced vertices from secondary decays. The central tracking chamber (CTC), which encompasses the SVX, measures the momenta of charged particles over a pseudorapidity range $|\eta| < 1.1$, where $\eta \equiv -\ln\tan(\theta/2)$. The central electromagnetic (CEM) and hadronic calorimeters, arranged in a projective tower geometry, surround the tracking volume and are used to measure clusters of energy deposited by electrons, photons, and hadrons. The central electromagnetic strip chamber (CES), embedded in the CEM at the position of shower maximum, measures the electromagnetic shower profiles in the ϕ and z directions.

A three level trigger system is used to identify electron candidates, with the first level requiring a CEM energy deposition greater than 8 GeV. The electron candidates satisfy a level 2 trigger that requires a spatial match between a track in the CTC with $P_T > 7.5$ GeV/c and an energy cluster in the CEM with $E_T > 8.0$ GeV, where $P_T \equiv P\sin\theta$ and $E_T \equiv E\sin\theta$. The fraction of hadronic energy in the cluster is required to be small. We require a spatial match of the CTC track to a cluster of energy in the CES and apply a threshold requirement to the energy deposition in the CES. The level 3 trigger requires that the lateral shower profiles in the CES and CEM be consistent with those expected for an electron, and reapplies the previous trigger criteria with greater precision. Approximately 6×10^6 electron candidates survive this trigger selection. We reduce the sample to 3×10^6 candidates by applying more stringent criteria [9]. We require that the fraction of hadronic energy in the cluster be less than 4%. We reject electron candidates that are likely to be from photon conversions and from $W^{\pm}$ and Z^0 boson decays. Finally, to ensure a uniform electron identification efficiency in the different B hadron decay topologies, we reject candidates with more than one track pointing at the CEM cluster and demand that the ratio of cluster energy to track momentum be in the range $0.75 < E_T/P_T < 1.40$.

The semileptonic B hadron decays are identified by reconstructing the charm hadron in the vicinity of the electron. The $\overline{D}^0$ meson is reconstructed by identifying the products of the $\overline{D}^0 \to K^+\pi^-$ decay in a cone $R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 1.0$ around the electron track. The charge correlation between the electron and the charm-hadron daughters from semileptonic B hadron decays is exploited to reduce the contamination from random combinations of leptons and charm hadrons. Particles arising from the weak decay of a B hadron are normally displaced from the primary vertex. Therefore, we require the charm-hadron daughter tracks to have an impact parameter (d_0) inconsistent with zero [$|d_0|/\sigma(d_0) > 1.5$, where $\sigma(d_0)$ is the uncertainty on d_0]. The combinatorial background is further reduced by requiring that $P_T(K) > 1.2$ GeV$/c$ and $P_T(\pi) > 0.5$ GeV$/c$, which are the same criteria used in the reconstruction of the other channels, except where noted. The daughter tracks are required to be consistent with coming from a secondary vertex that is displaced in the transverse plane from the $p\bar{p}$ interaction point [$L_{xy}/\sigma(L_{xy}) > 1$]. Finally, the invariant mass of the electron-charm system is required to be less than 5.0 GeV$/c^2$.

The invariant mass distribution of the $K\pi$ candidates in the electron sample is shown in Fig. 1(a). To this distribution we fit the sum of a Gaussian signal and an exponential background and count 1848 ± 58 $\overline{D}^0$ signal events.

The D^{*-} meson is reconstructed in the $D^{*-} \to \overline{D}^0\pi^-$ channel. We consider $\overline{D}^0$ candidates with $1.80 < M(K\pi) < 1.95$ GeV$/c^2$, where M is the mass, and consider all charged particles with $P_T > 0.4$ GeV$/c$ for the additional pion. The mass difference distribution, $\Delta M = M(K\pi\pi) - M(K\pi)$, is shown in Fig. 1(b). To this distribution we fit a double-Gaussian signal and a background modeled by a threshold function. We reconstruct 249 ± 19 D^{*-} signal events.

The D^- meson is reconstructed in the $D^- \to K^+\pi^-\pi^-$ channel. In this channel, the three daughter tracks are required to form a vertex. The invariant mass distribution of the $K\pi\pi$ candidates is shown in Fig. 1(c). To this distribution we fit the sum of a Gaussian signal and a linear background and count 736 ± 62 D^- signal events.

The D_s^- meson candidates are identified by looking for the products of the $D_s^- \to \phi\pi^-$ decay, where $\phi \to K^+K^-$. Both kaons and the pion are required to come from a common vertex. This decay chain provides two additional criteria effective in rejecting combinatorial back-

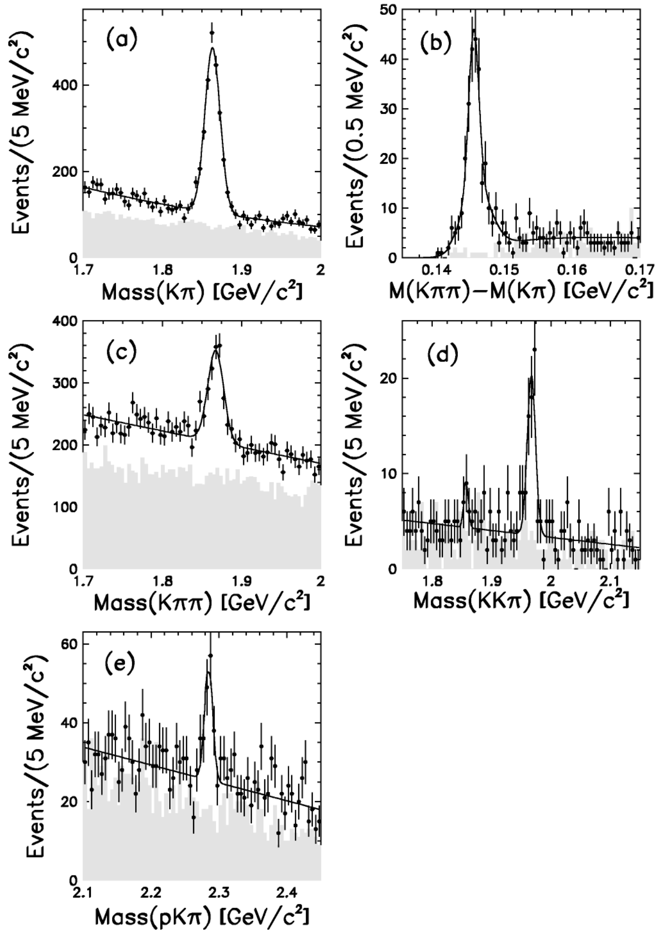

FIG. 1. Invariant mass distributions of charm-hadron candidates in 107 pb^{-1} of inclusive electron data. (a) $K\pi$ invariant mass distribution for $\overline{D}^0$ candidates. (b) Mass difference distribution, $\Delta M = M(K\pi\pi) - M(K\pi)$, for D^{*-} candidates. (c) $K\pi\pi$ invariant mass distribution for D^- candidates. (d) $KK\pi$ invariant mass distribution for D_s^- candidates. (e) $pK\pi$ invariant mass distribution for Λ_c^- candidates. The shaded histograms represent the combinations with the wrong electron-hadron charge correlation. The shaded area in (a) has been scaled by 0.5 for display purposes.

grounds. First, we require that the mass of the K^+K^- system be within 0.010 GeV$/c^2$ of the world average ϕ mass of 1.019 GeV$/c^2$. Second, we impose the criterion $|\cos\psi| > 0.4$, where ψ is the helicity angle between the D_s and K meson candidates in the ϕ rest frame. The invariant mass distribution of the $KK\pi$ candidates is shown in Fig. 1(d). We reconstruct 59 ± 10 D_s^- signal events. The small peak at 1.87 GeV$/c^2$ is consistent with the yield expected for $D^- \to \phi\pi^-$ decays.

The Λ_c^- baryon candidates are identified by looking for the products of the $\Lambda_c^- \to \overline{p}K^+\pi^-$ decay. We require $P_T(p) > 2.0$ GeV$/c$. Since the relative combinatorial background under the Λ_c^- signal is large, we also require that the specific ionization (dE/dx) deposited by the proton candidate in the CTC be consistent with that expected for a proton. The invariant mass distribution of the $pK\pi$ candidates is shown in Fig. 1(e). We reconstruct 79 ± 17 Λ_c^- signal events.

We can exclude various sources of systematic uncertainty in our determined event yields. Sources of charm-hadron candidates not arising from B hadron semileptonic decay would be apparent in events with the wrong electron-hadron charge correlation, but none is observed (see Fig. 1). Signal reflections arising from other charm-hadron decays would result in broad distributions that do not contribute to observed signal peaks. Finally, we have investigated different parametrizations for the signal and background shapes and found our estimates to be insensitive to these choices.

The $D_s^- e^+$ and $\Lambda_c^- e^+$ final states represent relatively pure samples of the B_s^0 and $\overline{\Lambda}_b^0$ hadrons, respectively. However, the remaining electron-charm final states that we reconstruct come from several B meson species through feed-down from vector and orbitally excited D meson decays. For example, the decay $B_s^0 \to D_s^{**-} e^+ \nu_e$ can be followed by the decay $D_s^{**-} \to D^- K^0$. This channel contributes to the $D^- e^+$ sample but reflects B_s^0 production rather than B^0 production. We use the branching fractions for each decay to determine the feed-down contributions. These branching fractions are derived from the measured values [3] according to the spectator model and isospin symmetries [9].

The spectator model predicts that the inclusive semileptonic decay widths for the various B hadrons are equal, yielding, for example, the relation

$$\mathcal{B}(B_s^0 \to e^+ \nu_e X) = \frac{\tau(B_s^0)}{\langle \tau(B) \rangle} \mathcal{B}(B \to e^+ \nu_e X),$$

where $\mathcal{B}$ represents the branching fraction and τ is the lifetime. A similar relationship holds for the exclusive semileptonic branching fractions for the three B mesons. We use isospin symmetry to calculate the branching fractions for the D^* and D^{**} decays that feed down into the final state D mesons that we reconstruct.

The acceptance and reconstruction efficiency for each final state vary according to whether the D meson is produced directly in the B meson decay or is the daughter of an excited D meson state. Several efficiencies, such as the electron identification efficiency, the conversion removal efficiency, and the two-track finding efficiency, cancel in the ratio of fragmentation fractions. Of the remaining efficiencies, the single-track finding efficiency and the electron trigger efficiency are measured using CDF data. We use a Monte Carlo calculation to determine all other acceptances and efficiencies. This uses a next-to-leading-order perturbative calculation of the differential cross section for b quark production in $p\bar{p}$ collisions [11] followed by fragmentation governed by the Peterson formulation [12]. To determine the semileptonic B hadron decay kinematics [13], we use the Isgur-Scora-Grinstein-Wise model in which the D^{**} fraction is allowed to float (ISGW**) [14].

The systematic uncertainties on the reconstruction efficiencies include those associated with the tracking and trigger efficiencies and Monte Carlo statistics. We also assign an uncertainty to account for the poor knowledge of the $\overline{\Lambda}_b^0$ production polarization in $p\bar{p}$ collisions. We neglect any uncertainty associated with the choice of the Monte Carlo B hadron decay model, as it is expected to cancel in the ratios of the fragmentation fractions. We do, however, consider the possibility that the Peterson fragmentation parameter ϵ_b may differ for each B hadron species. We assign the fractional uncertainties of 6.4% and 6.1% to account for the possible variation of ϵ_b for B_s^0 and $\overline{\Lambda}_b^0$ hadrons, respectively. We determine these values by calculating the larger variation in the reconstruction efficiency for values of ϵ_b 1 standard deviation away from a central value of $\epsilon_b = 0.006 \pm 0.002$ [15]. These contributions represent the largest uncertainties associated with the reconstruction efficiencies.

In order to determine the fragmentation fractions taking into account the cross contamination and feed-down, we fit the five observed event yields and their uncertainties to the three ratios of fragmentation fractions. We formulate the problem by defining a χ^2 function comparing the predicted with observed event yields. We allow the semileptonic branching fractions for the B mesons to vary in the fit, constrained to their measured or calculated uncertainties. We note that the measured branching fractions include the implicit assumption that $f^0/f^+ = 1$. The uncertainties that arise from the branching fractions for the decays $D_s^- \to \phi\pi^-$ and $\Lambda_c^- \to \overline{p}K^+\pi^-$ (fractional values of 25% and 26%, respectively) exceed the statistical uncertainties of the B_s^0 and $\overline{\Lambda}_b^0$ event yields (fractional values of 16.9% and 21.5%, respectively). The semileptonic branching fraction uncertainties vary from 2.6% to 11.2% and those associated with reconstruction efficiencies vary from 2.1% to 8.7%. Finally, the charm decay branching fractions contribute between 1.6% and 6.7%. The uncertainty on the f_d/f_u measurement is dominated by the statistical uncertainties and the cross contamination (fractional uncertainty of 16%) between the three channels involved in determining this fraction.

We make this measurement assuming isospin symmetry by fixing $f_d/f_u = 1$ in the fit. The fit results in the values $f_s/(f_u + f_d) = 0.213 \pm 0.068$ and $f_{\text{baryon}}/(f_u + f_d) = 0.118 \pm 0.042$, where uncertainties on the event yields, the reconstruction efficiencies, and the branching fractions are included. We can determine the absolute fragmentation fraction values from our fits by assuming that the B^+, B^0, B_s^0, and $\overline{\Lambda}_b^0$ hadrons saturate the b quark production rate, i.e., $f_u + f_d + f_s + f_{\text{baryon}} \equiv 1$. This relationship yields $f_u = f_d = 0.375 \pm 0.023$, $f_s = 0.160 \pm 0.044$, and $f_{\text{baryon}} = 0.090 \pm 0.029$. By incorporating another term in the χ^2 function, we have combined these results together with the complementary measurement by CDF of f_s using double semimuonic decays [4] to determine the more precise values of

$f_u = f_d = 0.375 \pm 0.015$, $f_s = 0.160 \pm 0.025$, and $f_{\text{baryon}} = 0.090 \pm 0.028$. Results for the fragmentation fractions obtained using all available measured exclusive semileptonic branching fractions instead of employing the spectator model predictions are consistent with the results presented here.

By relaxing the isospin symmetry requirement, we find that $f_d/f_u = 0.84 \pm 0.16$, consistent with isospin symmetry and the measurements of f^0/f^+ by the CLEO Collaboration. The individual values for f_s and f_{baryon} remain unchanged.

In conclusion, we have measured the four b quark fragmentation fractions for weakly decaying B hadrons produced in $p\bar{p}$ collisions. We measure $f_{\text{baryon}} = 0.090 \pm 0.029$, in good agreement with measurements made on B hadrons produced in high energy e^+e^- collisions at LEP. The $p\bar{p}$ result, $f_s = 0.160 \pm 0.025$, is 2 standard deviations higher than the current world average value, which is dominated by LEP measurements and by inference from $B^0\overline{B}^0$ mixing measurements.

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