Charged Multiplicity of Hadronic Events Containing Heavy-Quark Jets

P. C. Rowson, G. H. Trilling, G. S. Abrams, D. Amidei,[a] A. R. Baden, T. Barklow, A. M. Boyarski, J. Boyer, M. Breidenbach, P. Burchat, D. L. Burke, F. Butler, J. M. Dorfan, G. J. Feldman, G. Gidal, L. Gladney, M. S. Gold, G. Goldhaber, L. J. Golding, J. Haggerty, G. Hanson, K. Hayes, D. Herrup, R. J. Hollebeek, W. R. Innes, J. A. Jaros, I. Juricic, J. A. Kadyk, D. Karlen, A. J. Lankford, R. R. Larsen, B. W. LeClaire, M. E. Levi,[b] N. S. Lockyer,[c] V. Lüth, C. Matteuzzi,[b] M. E. Nelson,[d] R. A. Ong, M. L. Perl, B. Richter, K. Riles, M. C. Ross, T. Schaad, H. Schellman, D. Schlatter,[b] W. B. Schmidke, P. D. Sheldon, C. de la Vaissiere,[e] D. R. Wood, J. M. Yelton, and C. Zaiser

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
Department of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 15 January 1985)

The charged-particle multiplicities of hadronic events deriving from produced bottom or charm quarks have been measured in the Mark II detector at PEP in e^+e^- annihilation at 29 GeV. For events containing one semileptonic and one hadronic weak decay, we find multiplicities of $15.2 \pm 0.5 \pm 0.7$ for bottom and $13.0 \pm 0.5 \pm 0.8$ for charm. The corresponding multiplicities of charged particles accompanying the pair of heavy hadrons are $5.2 \pm 0.5 \pm 0.9$ for bottom, and $8.1 \pm 0.5 \pm 0.9$ for charm.

PACS numbers: 13.65.+i, 13.85.Qk, 14.80.Dq

The properties of hadronic events produced in e^+e^- annihilation have generally been studied as averages over all flavors weighted by the relative flavor populations. There is little reason to assume much difference between hadronic jets from up, down, and strange quarks, but for charm and especially bottom, the weak decay products and quark fragmentation properties play an important role. We present in this Letter measurements of the charged-particle multiplicities in events containing bottom jets, and in events with charm jets. Prompt leptons produced in heavy-flavor decays tag bottom or charm production, and kinematic cuts on the leptons statistically separate the two heavy flavors. From the known decay multiplicities of the heavy-flavor hadrons, which we shall denote as *leading* multiplicities, we can deduce the *nonleading* multiplicities of charged particles produced in association with the two heavy hadrons. Knowledge of these nonleading multiplicities provides a way of studying heavy-quark fragmentation.

This analysis is based on an integrated luminosity of 205 pb^{-1} collected with the Mark II detector at the Stanford Linear Accelerator Center storage ring PEP at a center-of-mass energy of 29 GeV. The Mark II detector has previously been described in detail[1,2]; here we summarize the features relevant to our measurement. Charged-particle tracking is accomplished by means of two cylindrical drift chambers concentric with the beam line and immersed in a 2.35-kG solenoidal magnetic field. The inner chamber consists of seven high-resolution axial sense-wire layers, while the outer chamber has sixteen layers, including both axial and stereo orientations. The momentum resolution is $\delta p/p \approx [(0.025)^2 + (0.01p)^2]^{1/2}$, where the units of p are GeV/c. Eight lead–liquid-argon calorimeter modules, located outside the magnetic coil, cover 64% of 4π and are used for electron identification and photon detection. Finally, four layers of proportional tubes, sandwiched between steel plates and covering 45% of 4π, are used for muon identification.

We select candidate hadronic events by requiring that the total observed energy (charged plus neutral) exceed $0.25E_{\mathrm{c.m.}}$, and that the charged multiplicity be at least 5. The sample is enriched with well-reconstructed events by the requirement that the event thrust axis (determined from charged and neutral tracks) point away from the edges of the detector's active region ($|\cos\theta_{\mathrm{thrust}}| \leq 0.5$). We consider in these events only those charged tracks which extrapolate to the origin within 4 cm in the plane perpendicular to the beams (x-y) and 8 cm in z, and which have measured momenta between 100 MeV/c and 16 GeV/c. In addition, a cut is made on the polar angle of each track ($|\cos\theta| \leq 0.7$) to insure that it lies within the high-efficiency volume of the drift chamber. An electron-pair-finding algorithm is used to remove γ conversion and Dalitz pair electrons.

Samples with enhanced heavy-flavor content are obtained by the selection of events containing a single lepton. The lepton sample is divided into bottom- and charm-enriched subgroups on the basis of the lepton's momentum transverse to the event thrust direction.[3] The high-p_T lepton sample is bottom enriched, whereas the low-p_T sample is more often due to charm decay. We require lepton momentum $p \geq 2$ GeV/c, and take $p_T \geq 1$ GeV/c for the bottom-enriched sample and $p_T < 1$ GeV/c for the charm-enriched sample. Both electron and muon selection criteria are described elsewhere.[3,4] For the above kinematic regions, hadron misidentification probabilities for electrons are typically (0.5–1.0)%, and for muons are 0.5% (punchthrough) and 0.4% (decays in flight). From a detailed analysis of the p and p_T distributions of prompt leptons[5] we determine that for the b region, (64 ± 8)% of the lepton candidates arise from bottom, (16 ± 8)% from charm, and (20 ± 8)% are background, while for the c region, (19 ± 8)% are from bottom, (35 ± 8)% from charm, and (46 ± 8)% are background. Background here refers to either hadrons misidentified as leptons or leptons which do not arise from charm or bottom decays. The numbers for the b region include the contributions of leptons from charmed particles originating in b decay. The observed multiplicity distributions for b, c, and untagged data sets, after subtraction of γ conversions and Dalitz decays, are truncated below a multiplicity of 5, and then corrected for acceptance with the unfold technique described below. The background in our hadronic sample due to beam-gas, two-photon, and $\tau^+\tau^-$ events is less than 4%, and is negligible in the lepton-tagged samples.

Monte Carlo simulation is used to generate the unfold efficiency matrix defined by

$$\epsilon_{pq}=\frac{O_{p,q}}{N_p},$$

where $O_{p,q}$ is the number of times q tracks are observed when p tracks are produced, and N_p is the number of times p tracks are produced. The produced track count is the total number of charged Monte Carlo tracks exclusive of those arising from pair conversion or Dalitz decays. Thus the two charged tracks from K_S and Λ decay are included.

We then make a maximum-likelihood fit of the observed distribution by the following parametrization of the parent distribution:

$$P_{\mu,a}(p)=N(\mu,a)\frac{e^{-\mu/a}(\mu/a)^{p/a}}{\Gamma(p/a+1)},\quad p \text{ even}, \qquad (1)$$

where both μ and a are taken as free parameters. This distribution (1) is a generalization of the Poisson distribution with mean value approximately equal to μ and rms width approximately equal to $(\mu a)^{1/2}$. The overall normalization factor $N(\mu,a)$ is absorbed by our normalization method. Using the unfold matrix and the fitting function (1), we obtain, as a function of the two parameters, the expected number of events in each multiplicity bin, with the sum over all bins constrained to be equal to the total number of observed events. A Poisson likelihood function is then maximized to obtain the best estimates of μ and a.

The effect of background in both the b and c regions has been simulated by the application to real hadron data of lepton misidentification probability tables, binned by p and p_T.[5] The muon misidentification tables include the effects of hadron punchthrough and nonprompt muons due to pion and kaon decays, while the electron tables take account of the effect of showering hadrons and the overlap of showers and charged tracks. This procedure is designed to model correctly the correlation between higher multiplicity and the probability that a given event contains a fake lepton.

We obtain the unfolded mean multiplicities for the overall hadronic sample, and for the b and c regions, and their respective backgrounds. For the b region, c region, b-region background, and the c-region background, the fit results (μ,a) are respectively $(13.9\pm0.25, 1.0\pm0.2)$, $(12.6\pm0.1, 0.9\pm0.1)$, $(13.6\pm0.1, 1.2\pm0.1)$, and $(12.6\pm0.05, 1.2\pm0.05)$. The high multiplicity of the b-region background reflects the fact, also seen in our Monte Carlo simulation, that the requirement of a high-p_T track tends to enrich the background with high-multiplicity three-jet events and with bottom events themselves. Figure 1 shows the observed multiplicity distributions for both the b and c regions, and the expected distributions deduced from our fits. We use the results for the tagged regions and

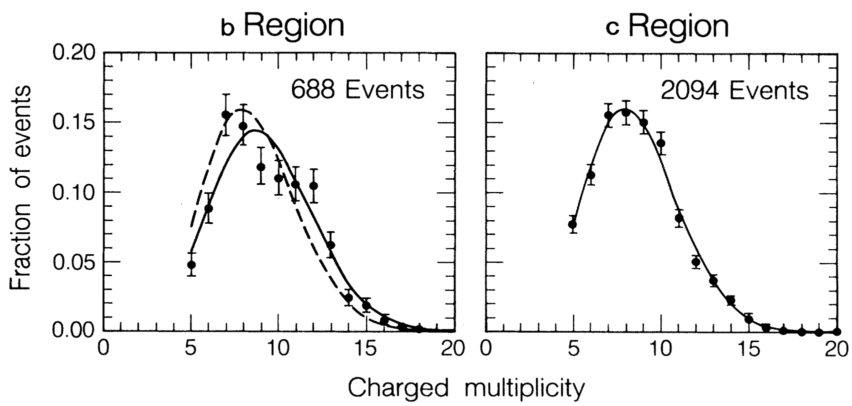

FIG. 1. The observed multiplicity distribution for both the b and c regions, with the expected distributions deduced from the fit results (solid lines). In the b-region plot, the c-region result is overlayed for comparison (dashed line).

their backgrounds to solve for the pure $b\bar{b}$ and $c\bar{c}$ event mean charged multiplicities from the equations

$$\mu_b = f_b^b m_{b\bar{b}} + f_c^b m_{c\bar{c}} + f_{\text{bkgrnd}}^b \mu_{\text{bkgrnd}}^b,$$
$$\mu_c = f_b^c m_{b\bar{b}} + f_c^c m_{c\bar{c}} + f_{\text{bkgrnd}}^c \mu_{\text{bkgrnd}}^c, \tag{2}$$

where the μ's are the four fit results, the f_x^X's are the x enrichment factors in the X region, and the m's are the unknown pure-flavor mean multiplicities.

Final corrections, determined from Monte Carlo analysis, are applied to the fit results to take account of effects that tend to bias our multiplicity measurement. Firstly, initial-state radiation reduces the effective center-of-mass energy ($E_{\text{c.m.}}$) and hence the observed multiplicity. From existing measurements of multiplicity vs $E_{\text{c.m.}}$ we obtain a correction of $+0.25 \pm 0.10$ particle. Secondly, the lepton momentum lower limit of 2 GeV/c biases the data in favor of smaller multiplicities. The corrections, for this effect, to be *added* to the final pure-heavy-flavor fit results are 0.3 ± 0.1 ($b\bar{b}$) and 0.9 ± 0.3 ($c\bar{c}$), where the errors include statistical and systematic Monte Carlo uncertainties. The corrected results are insensitive within errors to an increase in the lepton momentum cut of up to 500 MeV/c. The same effect produces a small downward bias for the width parameters quoted above for the enriched samples and their backgrounds. Finally, the requirement in the b-region that the lepton transverse momentum be at least 1 GeV/c tends to enrich the charm component of this region with high-multiplicity three-jet events, a bias not present in the c region. We determine the corresponding corrections to be -0.4 ± 0.3 ($b\bar{b}$) and $+0.2 \pm 0.2$ ($c\bar{c}$).

The dominant sources of systematic error are the efficiency uncertainties in the event selection and track quality cuts (0.5), and the errors on the flavor composition percentages listed above (0.3, $b\bar{b}$; 0.5, $c\bar{c}$). Other contributing factors include the details of the fitting procedure (0.2), the background simulation (0.1, $b\bar{b}$; 0.3, $c\bar{c}$), and the radiative and kinematic corrections discussed above (0.3). Combined in quadrature, the systematic errors to be applied to the pure bottom ($b\bar{b}$) and charm ($c\bar{c}$) fit results are ± 0.7 and ± 0.8, respectively. The systematic error for the overall hadronic fit, where no tag lepton is required, is ± 0.6.

The results for the overall hadronic sample, corrected for initial-state radiation, are $12.9 \pm 0.1 \pm 0.6$ for the mean multiplicity, and 1.4 ± 0.1 for the width parameter a. Both of these results are in good agreement with existing measurements.[6,7] The pure-heavy-flavor events in our selected sample consist almost entirely of combinations of one semileptonic decay and one hadronic decay of the produced heavy-meson pair. From our known lepton identification efficiencies, we correct for the small contamination of double-lepton events in which one lepton has been missed. The corresponding pure-heavy-flavor results are given in the first line of Table I. We use results from Giles *et al.* for both hadronic and semileptonic B-meson-decay charged multiplicities,[8] as well as known D-meson-decay multiplicities,[1] to subtract out the average leading charged multiplicities in our $b\bar{b}$ and $c\bar{c}$ events[9] and obtain the nonleading multiplicities shown in the last line of Table I. We also give the "unbiased" results, where the relative numbers of semileptonic and hadronic heavy-meson decays are determined by the respective branching ratios, in the second line of Table I. By combining our overall hadronic multiplicity result with these unbiased multiplicities for bottom and charm, we can extract the light-quark (u,d,s) event multiplicity, also given in Table I. The results given in Table I are compatible with charm-jet (7.5 ± 0.5 at 34.5 GeV)[10] and bottom-jet (7.61 ± 0.46 at 29 GeV)[11] multiplicity measurements at comparable energies.

We can relate the nonleading multiplicities in Table I to the b and c quark fragmentation functions. The lower nonleading multiplicity for $b\bar{b}$ relative to $c\bar{c}$ provides independent evidence that b fragmentation is harder than c fragmentation. We can approximately translate these nonleading multiplicities to energies via existing multiplicity data for e^+e^- annihilation over a large range of center-of-mass energies shown in Fig. 2. The procedure used here depends on the assumption that the relation between energy and multiplicity is unaffected by the flavor population of the events. The available multiplicity data are based on u, d, s, c, and b whereas our measured nonleading multiplicities arise from u, d, and s fragmentation. As shown in this paper, this assumption is not exactly fulfilled, but the deviations are small enough to have no significant impact

TABLE I. Mean charged multiplicities.

	$b\bar{b}$	$c\bar{c}$	Light quarks	All hadrons
One semileptonic and one hadronic	$15.2 \pm 0.5 \pm 0.7$	$13.0 \pm 0.5 \pm 0.8$	...	...
Nominal mixture	$16.1 \pm 0.5 \pm 1.0$	$13.2 \pm 0.5 \pm 0.9$	$12.2 \pm 0.4 \pm 1.3$	$12.9 \pm 0.1 \pm 0.6$
Nonleading	$5.2 \pm 0.5 \pm 0.9$	$8.1 \pm 0.5 \pm 0.9$	...	...

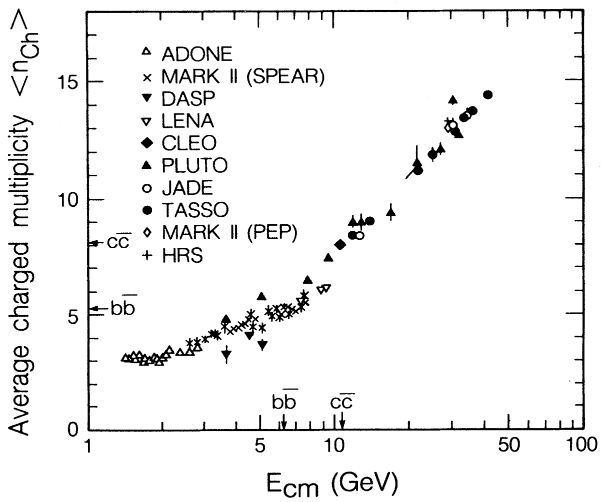

FIG. 2. The energy dependence of charged multiplicity in e^+e^- annihilation (Refs. 6 and 7), where the errors are statistical. The arrows indicate the nonleading charged multiplicities for $b\bar{b}$ and $c\bar{c}$ events, and the corresponding energies.

on the quoted energy fractions. Using this information we find from the nonleading multiplicities that bottom and charm hadrons fragment with mean energy fractions of $0.79^{+0.10}_{-0.05}$ and $0.60^{+0.09}_{-0.11}$, respectively. These values are in good agreement with measurements based on leptonic inclusive spectra,[3,12–15] and D^* fragmentation.[10,16–18]

In conclusion, we have separately measured charged-particle multiplicities for light quark, charm quark, and bottom quark pair fragmentation at 29 GeV. Coupled with known weak-decay multiplicities these measurements independently confirm that heavy quarks have hard fragmentation functions.

This work was supported by the U.S. Department of Energy under Contracts No. DE-ACO3-76SR00515 and No. DE-AC03-76SF0098.

[a]Present address: University of Chicago, Chicago, Ill. 60637.

[b]Present address: CERN, CH-1211 Geneva 23, Switzerland.

[c]Present address: University of Pennsylvania, Philadelphia, Penn. 19104.

[d]Present address: California Institute of Technology, Pasadena, Cal. 91125.

[e]Present address: Laboratoire de Physique Nucléare et Hautes Energies, Université Pierre et Marie Curie, Paris, F-75230, France.

[1]R. H. Schindler *et al.*, Phys. Rev. D **24**, 78 (1981).

[2]J. Jaros, in Proceedings of the International Conference on Instrumentation for Colliding Beam Physics, edited by W. Ash, SLAC Report No. SLAC-1982 (unpublished), p. 29.

[3]M. E. Nelson *et al.*, Phys. Rev. Lett. **50**, 1542 (1983).

[4]N. S. Lockyer *et al.*, Phys. Rev. Lett. **51**, 1316 (1983).

[5]M. E. Nelson, thesis, University of California at Berkeley, Report No. LBL-16724, 1983 (unpublished).

[6]M. Althoff *et al.*, Z. Phys. C **22**, 307 (1984).

[7]D. Bender *et al.*, Phys. Rev. D **31**, 1 (1985).

[8]R. Giles *et al.* Phys. Rev. D **30**, 2279 (1984).

[9]Our estimates of leading multiplicities are based on measured *D*- and *B*-meson-decay multiplicities, where we have included the contribution of the pion in the decay $D^{*\pm} \rightarrow D^0 + \pi^\pm$ as part of the leading charm multiplicity. This procedure neglects possible small multiplicity differences due to heavy baryons or other charm and bottom states.

[10]M. Althoff *et al.*, Phys. Lett. **135B**, 243 (1981), give a multiplicity measurement for charm jets opposite to a D^* tag at 34.5 GeV.

[11]M. Sakuda *et al.*, California Institute of Technology Report No. CALT-68-1164, 1984 (to be published), give a multiplicity measurement for bottom jets opposite to a lepton tag at 29 GeV.

[12]E. Fernandez *et al.*, Phys. Rev. Lett. **50**, 2054 (1983).

[13]B. Adeva *et al.*, Phys. Rev. Lett. **51**, 443 (1983).

[14]M. Althoff *et al.*, Z. Phys. C **22**, 219 (1984).

[15]D. E. Koop *et al.*, Phys. Rev. Lett. **52**, 970 (1984).

[16]J. Yelton *et al.*, Phys. Rev. Lett. **49**, 430 (1982).

[17]P. Avery *et al.*, Phys. Rev. Lett. **51**, 1139 (1983).

[18]M. Derrick *et al.*, Phys. Lett. **146B**, 261 (1984).