CHARM QUARK PRODUCTION AND FRAGMENTATION IN e^+e^- ANNIHILATION AT 29 GeV

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The electroweak production asymmetry and the decay fragmentation function for $e^+e^- \to c\bar{c}$ have been measured at $\sqrt{s}$ = 29 GeV using charged D* production over the full kinematic range. The data were taken at PEP using the High Resolution Spectrometer. The measured asymmetry is -0.12 ± 0.08. The total production cross section in units of the point cross section corrected for initial state radiation is $R_{D^*} = 2.7 \pm 0.9$.

The characteristics of charm quark production and fragmentation in high energy e^+e^- annihilations have been analyzed previously using charged D^* production [1–5]. We have also reported results based on direct D^0 and D^+ production [5,6]. In this paper we use charged D^* production to measure the charm fragmentation function and electroweak asymmetry. The data come from an integrated luminosity of 106 pb^{-1} collected by the High Resolution Spectrometer (HRS) over a two year running period at PEP at a center of mass energy of 29 GeV [‡1].

In the standard model [7] the e^+e^- annihilation

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[‡1] This data sample includes the 19.6 pb^{-1} of data reported in ref. [5].

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proceeds via γ and Z^0 intermediate states so that in the reaction $e^+e^- \to c\bar{c}$ the amplitudes of the two processes interfere to produce an asymmetry in the production angular distribution. The angular distribution is described by the form $1 + a\cos\theta + \cos^2\theta$, where θ is the angle between the incoming electron and the outgoing c quark, and the integrated forward–backward asymmetry $A = 3a/8$ is given by

$$A = \frac{3}{2}\frac{1}{q}g^e g^c \frac{G_F}{2\sqrt{2}\pi\alpha}\frac{s}{1 - s/M_Z^2}, \tag{1}$$

where M_Z is the Z^0 mass, q is the charge of the c quark, and g^e, g^c are the electron and quark axial vector coupling constants. The predicted asymmetry at $\sqrt{s} = 29$ GeV, using $M_Z = 94$ GeV, $q = 2/3$, and $g^c = -g^e = 1/2$, is $A = -0.095$. Since the charm quark cannot be observed directly, θ is determined by the line of flight of charmed D^* mesons with high fractional energy $Z = 2E_{D^*}/\sqrt{s}$, where E_{D^*} is the energy of the meson ‡2.

We have observed charged D^* production in the decay mode

$$D^{*+} \to D^0\pi^+, \tag{2}$$

with the D^0 decaying into the $K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^0$ modes. Our analysis also includes the charge conjugate states. The D^*'s were isolated using the excellent mass resolution of the HRS and by exploiting the fact that the Q value of reaction (2) is only 5.8 MeV, so that the D^{*+}–D^0 mass difference (δ) is well determined.

The HRS is a general purpose detector using a 1.62 T solenoidal magnetic field and is described elsewhere [8]. The resolution for high momentum tracks at large angles is measured to be $\sigma_p/p \simeq 2 \times 10^{-3}p$ (p in GeV/c). The shower energy is measured with an electromagnetic calorimeter in both barrel and endcap regions with a typical resolution of $\sigma(E)/E = 0.18/\sqrt{E}$ (E in GeV). The detector was triggered if (i) at least two tracks were observed in the central drift chamber, or (ii) a minimum of 4.8 GeV shower energy was deposited in the calorimeter, or (iii) at least one track and a minimum of 2.4 GeV shower energy were observed. To select a clean sample of the annihilation multihadron events, the following was required: (i) a minimum of five well reconstructed charged tracks, (ii) $\Sigma|\boldsymbol{p}_i| \geqslant 7.5$ GeV, where $\Sigma|\boldsymbol{p}_i|$ is the scalar sum of the total momenta of the tracks, (iii) total shower energy deposited in the barrel calorimeter $\geqslant 1.0$ GeV. In reconstructing D^0 and D^* decays, no particle identification was used and each

‡2 A Monte Carlo analysis, using our observed Z distribution, shows our asymmetry measurement is not significantly affected by this choice of angle.

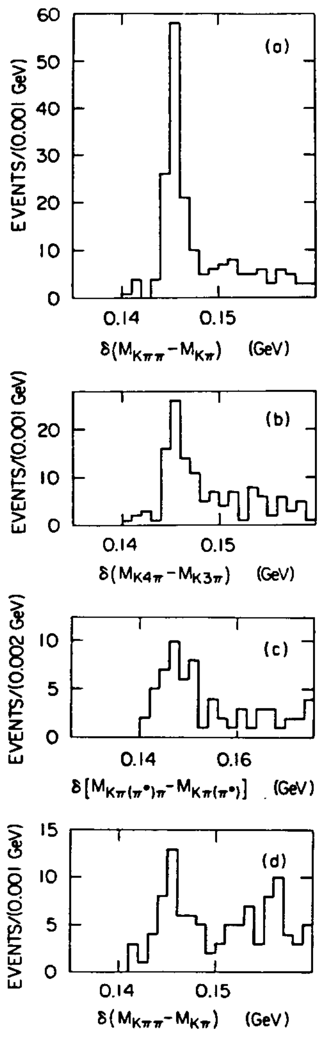

Fig. 1. The quantity δ, (a) for $D^0 \to K^-\pi^+$ with $1.81 \leqslant M_{K\pi} \leqslant 1.92$ GeV and $Z \geqslant 0.4$, (b) for $D^0 \to K^-\pi^+\pi^+\pi^-$ with $1.81 \leqslant M_{K3\pi} \leqslant 1.92$ GeV and $Z \geqslant 0.6$, (c) for $D^0 \to K^-\pi^+\pi^0$ with $1.55 \leqslant M_{K\pi} \leqslant 1.70$ GeV and $Z \geqslant 0.6$, (d) for $D^0 \to K^-\pi^+$ with $1.81 \leqslant M_{K\pi} \leqslant 1.92$ GeV and $0.2 \leqslant Z \leqslant 0.4$ and $|\cos\theta_\pi^*| \leqslant 0.8$.

track in the events passing the above cuts was taken as both a kaon and a pion. All $K^-\pi^+$ combinations were used and the quantity $\delta = (M_{K^-\pi^+\pi^+} - M_{K^-\pi^+})$ was determined for those combinations with $1.81 < M_{K^-\pi^+} < 1.92$ GeV which is the mass region for D^0 decays. The same technique was used also for the $K^-\pi^+\pi^+\pi^-$ decay of the D^0. Fig. 1a shows the mass difference δ distribution for the $K^-\pi^+$ decay mode with $Z_{D^*} \geqslant 0.4$ and fig. 1b the δ distribution for the $K^-\pi^+\pi^-\pi^+$ decay mode with $Z_{D^*} \geqslant 0.6$. Prominent peaks are evident at $\delta \sim 0.145$ GeV. Fig. 2a shows the $K^-\pi^+$ ($Z_{D^*} \geqslant 0.4$) and fig. 2b the $K^-\pi^+\pi^-\pi^+$ ($Z_{D^*} \geqslant 0.6$) effective mass distributions for $0.143 \leqslant \delta \leqslant 0.149$ GeV. The peaks at 1.86 GeV show clear evidence for D^* production with small backgrounds. These D^* candidates were used for the asymmetry measurement.

For the $K\pi\pi^0$ decay mode of the D^0, no attempt was made to reconstruct the π^0. The well known kinematic enhancement around 1.6 GeV, the so called S^0 peak [9], formed by the $K^-\pi^+$ from the D^0 was used. This region corresponds to the D^0 decays where the D^0 has a velocity close to that of the $K^-\pi^+$ system, so that the resolution in δ is still good. Fig. 1c shows the distribution of $\delta = M_{K^-\pi^+\pi^+} - M_{K^-\pi^+}$ for $1.55 \leqslant M_{K^-\pi^+} \leqslant 1.70$ GeV. A signal, corresponding to D^{*+} production is observed around $\delta = 0.145$ GeV, although the peak is broadened due to the missing π^0. The uncertainty in the calculated D^* direction of flight due to the unobserved π^0 was minimized by demanding a high observed fractional momentum in the $K^-\pi^+\pi^+$ system, namely $Z_{K^-\pi^+\pi^+} \geqslant 0.6$. Events with $0.143 \leqslant \delta \leqslant 0.153$ GeV were chosen for the asymmetry measurement.

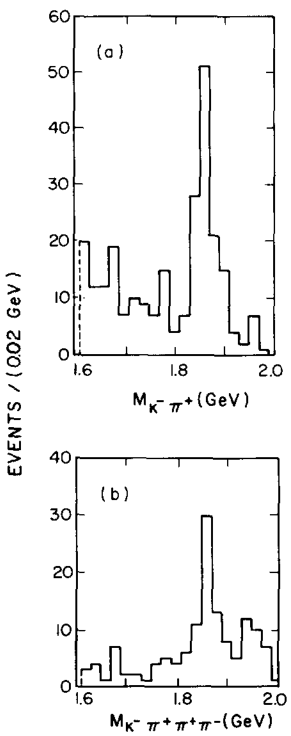

Fig. 1. (a) Mass of the $K\pi$ system with $0.143 \leqslant \delta \leqslant 0.149$ GeV and $Z \geqslant 0.4$. (b) Mass of the $K\pi\pi\pi$ system with $0.143 \leqslant \delta \leqslant 0.149$ GeV and $Z \geqslant 0.6$.

The production angular distribution for the D^{*+} is shown in fig. 3 after combining all the decay modes. There are 182 events in the range $|\cos\theta| \leqslant 0.7$ with an estimated background of $\simeq 10\%$. We have checked these data for systematic biases and other effects which could influence the asymmetry measurement and have found none of any significance. Using events generated with the LUND Monte Carlo program with Feynman–Field fragmentation [10] we have found a uniform acceptance for the Z and $\cos\theta$ ranges used. In addition, this study indicates that less than 5% of D^{*+} in this sample originate from b fragmentation. No corrections are, therefore, required and a fit of the data to the form $1 + a\cos\theta + \cos^2\theta$ gives $a = -0.39 \pm 0.23$ and $A = -0.15 \pm 0.09$.

We have also independently measured the charm quark asymmetry using the inclusive $K^-\pi^+$ decay of the D^0 and the $K^-\pi^+\pi^+$ decay of the D^+. This anal-

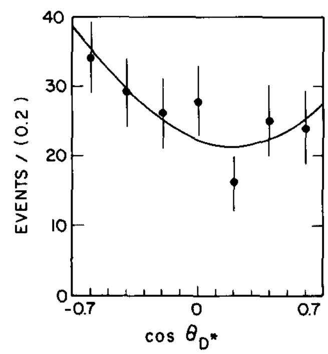

Fig. 3. The production angular distribution of D^{*+} events.

ysis ‡3 yielded an asymmetry of $A = -0.08 \pm 0.12$. This result combined with our D^* measurement yields our most precise value of $A = -0.12 \pm 0.08$ which is in good agreement with the standard model prediction of $A = -0.095$. This result can be compared with previous measurements by the TASSO collaboration [4] at $\sqrt{s} = 34.4$ GeV of $A = -0.28 \pm 0.13$ which was later updated [11] to $A = -0.13 \pm 0.10$.

In measuring the fragmentation function over the range $0.2 < Z_{D^*} < 1.0$ only the $K\pi\pi$ decay mode was used and a more restrictive vertex requirement was imposed. To reduce background in the region of $0.2 \leqslant Z_{D^{*+}} < 0.4$, events were selected with $|\cos\theta_\pi^*| < 0.8$ where θ_π^* is the decay angle of the D^0 in its helicity frame ‡4. A clear signal is observed as shown in fig. 1d for this Z range when the angle cut is imposed. This angle cut was not imposed for $Z_{D^*} > 0.4$ where the background is low. The number of D^{*+} observed as a function of Z were corrected for the decay branching ratios ‡5 and the detector acceptance. No correction for $D^0\overline{D^0}$ mixing was made since it is not observed in the data. This is consistent with an expected mixing amplitude [12] of $< 10^{-3}$ and the best experimental limit [13] of $< 5\%$.

Fig. 4a shows the fragmentation function $D(Z) = (1/N)\mathrm{d}N/\mathrm{d}Z$ and fig. 4b the scaling cross section $(s/\beta)\mathrm{d}\sigma/\mathrm{d}Z$ for this analysis together with previous results [1,4]. Fitting the data to the parameterization of ref. [14] ‡6 yields $\epsilon = 0.41\,^{+0.10}_{-0.08}$. Table 1 lists the data for each region of Z, along with the corresponding efficiencies. The experimental data peaks near $Z = 0.55$ and has a mean value of 0.53 ± 0.03. This hard fragmentation is undoubtedly due to the process $e^+e^- \to c\bar{c}$, with the D^* containing the primary charmed quark since charmed mesons from the process $e^+e^- \to b\bar{b}$ are expected to carry a much smaller fraction of the available energy. We note that although our results extend to low Z where b fragmentation is expected to be important compared to charm fragmentation we have not separated the two components in our analysis.

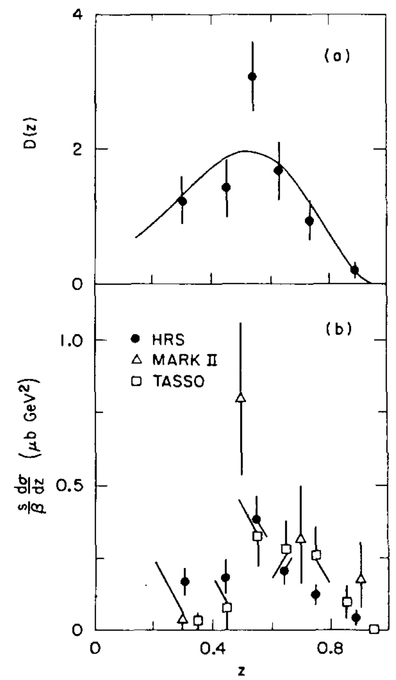

Fig. 4. (a) The fragmentation function $D(Z) = (1/N)\mathrm{d}N/\mathrm{d}Z$ versus Z. (b) The scaling cross section as a function of Z for this experiment and previous results.

Assuming $\sigma(D^{*+}) = \sigma(D^{*0})$ from isospin conservation, the measured total D^* cross section, corrected

Table 1
The invariant cross section and fragmentation function for D^{*+} production.

Z	Efficiency	$\frac{s}{\beta}\frac{\mathrm{d}\sigma}{\mathrm{d}z}$ (μb GeV^2)	$D(z) = \frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}z}$
0.2–0.4	0.24 a)	0.168 ± 0.049	1.23 ± 0.36
0.4–0.5	0.42	0.185 ± 0.060	1.44 ± 0.46
0.5–0.6	0.45	0.391 ± 0.070	3.07 ± 0.55
0.6–0.7	0.49	0.211 ± 0.050	1.68 ± 0.40
0.7–0.8	0.55	0.118 ± 0.035	0.94 ± 0.28
0.8–1.0	0.62	0.026 ± 0.011	0.21 ± 0.08

a) Includes correction for decay angle cut.

‡3 We observe inclusive signals for $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$ which when added yield $N_F = 120$, $N_B = 139$, where subscripts F and B refer to the forward and backward regions of the angular distribution. A detailed analysis of this inclusive D^0 and D^+ production is in ref. [6].

‡4 In the region $Z_{D^*} > 0.4$ where the background is negligible, the D^0 decay is observed to be isotropic as expected for a 0^- object. At low Z however, significant background is observed which peaks in the region $|\cos\theta_\pi^*| > 0.8$.

‡5 We use the D branching fractions $B(D^0 \to K^-\pi^+) = 0.030 \pm 0.006$ and $B(D^{*+} \to D^0\pi^+) = 0.44 \pm 0.10$.

‡6 Peterson et al. [14] suggest, $D(z) = (A/z)[1 - 1/z - \epsilon/(1-z)]^{-2}$, where the parameter ϵ is a function of the charmed-quark mass.

for acceptance, is $\sigma(D^* + \bar{D}^*) = 0.31 \pm 0.10$ nb. This value, divided by the muon pair point cross section corrected for initial state radiation, gives an R value of $R(D^* + \bar{D}^*) = 2.7 \pm 0.9$ in good agreement with $2.5 \pm 0.64 \pm 0.88$ measured by the TASSO group [4]. The expected inclusive R value for all charm production using $\alpha_s = 0.17$ is 3.53, which includes 0.7 units of R for the b decay into charm.

In conclusion D^{*+} production has been studied at a center of mass energy of 29 GeV with the HRS. The charm quark asymmetry measured at $\sqrt{s} = 29$ GeV is $A = -0.15 \pm 0.09$, from the charged D^* sample, where the D^0 from the D^{*+} decayed into $K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$, or $K^-\pi^+\pi^0$. Combining this result with the asymmetry measured in inclusive D production gives $A = -0.12 \pm 0.08$. The fragmentation function is hard indicating that the D^* contains the primary charmed quark and the size of the production cross section indicates that a large fraction of charmed quark events proceeds through D^* formation.

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