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 $e^+e^- \rightarrow c\bar{c}$ 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 $-0.12 \pm 0.08$. 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 $^{41}$.

In the standard model [7] the $e^+e^-$ annihilation data sample includes the 19.6 pb$^{-1}$ of data reported in ref. [5].
proceeds via $\gamma$ and $Z^0$ intermediate states so that in the reaction $e^+e^-\rightarrow c\bar{c}$ 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 $\theta$ is the angle between the incoming electron and the outgoing $c$ quark, and the integrated forward-backward asymmetry $A = 3a/8$ is given by

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

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 $g^e = -g^c = 1/2$, is $A = -0.095$. Since the charm quark cannot be observed directly, $\theta$ 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.

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

$$D^{**+} \rightarrow D^0\pi^+,$$

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 $D^{**+} \rightarrow D^0$ mass difference ($\delta$) 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 $\sigma_p/p \approx 2 \times 10^{-3} p$ (p in GeV/c). The shower energy is measured with an electromagnetic calorimeter in both barrel and end-cap 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 antihadron multihadron events, the following was required: (i) a minimum of five well reconstructed charged tracks, (ii) $\Sigma|p_i| \geqslant 7.5$ GeV, where $\Sigma|p_i|$ 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

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**Fig. 1.** The quantity $\delta$, (a) for $D^0 \rightarrow K^-\pi^+$ with $1.81 < M_{K\pi} < 1.92$ GeV and $Z > 0.4$, (b) for $D^0 \rightarrow K^-\pi^+\pi^-\pi^-$ with $1.81 < M_{K3\pi} < 1.92$ GeV and $Z > 0.6$, (c) for $D^0 \rightarrow K^-\pi^0$ with $1.55 < M_{K\pi} < 1.70$ GeV and $Z > 0.6$, (d) for $D^0 \rightarrow K^-\pi^+$ with $1.81 < M_{K\pi} < 1.92$ GeV and $0.2 < Z < 0.4$ and $|\cos \theta^*_\mu| < 0.8$. 

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track in the events passing the above cuts was taken as both a kaon and a pion. All K−π+ combinations were used and the quantity $\delta = (M_{K^-\pi^+} - M_{K^-\pi^+})$ was determined for those combinations with 1.81 < $M_{K^-\pi^+}$ < 1.92 GeV which is the mass region for D0 decays. The same technique was used also for the K−π+π−π− decay of the D0. Fig. 1a shows the mass difference $\delta$ distribution for the K−π+ decay mode with $Z_{D*} \geq 0.4$ and fig. 1b the $\delta$ distribution for the K−π+π−π− decay mode with $Z_{D*} \geq 0.6$. Prominent peaks are evident at $\delta \sim 0.145$ GeV. Fig. 2a shows the K−π+ (ZD* > 0.4) and fig. 2b the K−π+π−π+ (ZD* > 0.6) effective mass distributions for 0.143 < $\delta$ < 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 Kππ0 decay mode of the D0, no attempt was made to reconstruct the π0. The well known k-
ysis 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 $0.2 \leq Z_{D^*} < 0.4$, events were selected with $|\cos \theta^*_D| < 0.8$ where $\theta^*_D$ is the decay angle of the $D^0$ in its helicity frame. 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 $D^*+0$ observed as a function of $Z$ were corrected for the decay branching ratios and the detector acceptance. No correction for $D^0D^0$ 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 $D(Z) = (1/N)dN/dZ$ and fig. 4b the scaling cross section $(s/\beta)ds/dZ$ for this analysis together with previous results [1,4]. Fitting the data to the parameterization of ref. [14] yields $\epsilon = 0.41 \pm 0.10$. 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 $0.53 \pm 0.03$. This hard fragmentation is undoubtedly due to the process $e^+e^- \rightarrow c\bar{c}$, with the $D^0$ containing the primary charmed quark since charmed mesons from the process $e^+e^- \rightarrow b\bar{b}$ 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.

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

\begin{table}[h]
\centering
\begin{tabular}{cccc}
\hline
$Z$ & Efficiency & $s \beta ds/dZ$ ($\mu b$ GeV$^2$) & $D(z) = \frac{1}{N} \frac{dN}{dz}$ \\
\hline
0.2–0.4 & 0.24 & 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 \\
\hline
\end{tabular}
\caption{The invariant cross section and fragmentation function for $D^{*+}$ production.}
\end{table}

\textsuperscript{a)} Includes correction for decay angle cut.
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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