PRODUCTION CROSS SECTION AND ELECTROWEAK ASYMMETRY OF D* AND D MESONS PRODUCED IN e^+e^- ANNIHILATIONS AT 29 GeV

P. BARINGER, B.G. BYLSMA, R. DE BONTE, D.S. KOLTICK, E.H. LOW, R.L. McILWAIN, D.H. MILLER, C.R. NG, E.I. SHIBATA
Purdue University, West Lafayette, IN 47907, USA

S. ABACHI, M. DERRICK, P. KOOIJMAN [1], B. MUSGRAVE, L.E. PRICE, J. REPOND, K. SUGANO
Argonne National Laboratory, Argonne, IL 60439, USA

D. BLOCKUS, B. BRABSON, J.-M. BROM, C. JUNG [2], H. OGREN, D.R. RUST, A. SNYDER
Indiana University, Bloomington, IN 47405, USA

C. AKERLOF, J. CHAPMAN, D. ERREDE, M.T. KEN, D.I. MEYER, H.A. NEAL, D. NITZ, R. THUN, R. TSCHIRHART
University of Michigan, Ann Arbor, MI 48109, USA

and

B. CORK
Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA

Received 4 March 1988

The production of D* and D mesons has been studied in e^+e^- annihilations at $\sqrt{s}=29$ GeV. The data, corresponding to an integrated luminosity of 300 pb^{-1}, were obtained using the HRS detector at PEP. The cross section is measured to be R (D^0+D^+) $=2.40\pm0.35$ and we determine the electroweak asymmetry to be $-9.9\pm2.7\%$, which corresponds to an axial vector coupling constant product $g^e g^c=0.26\pm0.07$.

Measurements of charm quark production and fragmentation provide tests of the standard model and are important in understanding fragmentation processes as well as weak decays of heavy quarks. The primary reaction $e^+e^-\to c\bar{c}$ is expected to have a forward–backward asymmetry due to interference between the electromagnetic and weak production amplitudes. Results already published on the electroweak asymmetry are in agreement with predictions although each individual measurement has significant errors [1]. Measurements of the cross section for charm meson production in the continuum are dependent on the decay branching ratios of the D mesons. The values of these ratios [2] have changed significantly in the last few years which led to the possibility of a charm deficit in e^+e^- annihilation and B decay [3].

The results presented in this paper use fully reconstructed D*, D^0 and D^+ mesons together with the new MARK III branching ratios [4] to determine the total cross section and fragmentation functions. The

[1] Present address: NIKHEF, P.O. Box 41882, 1009 DB Amsterdam, The Netherlands.
[2] Present address: Stanford Linear Accelerator Center, Stanford, CA 94305, USA.

0370-2693/88/$ 03.50 © Elsevier Science Publishers B.V.
(North-Holland Physics Publishing Division)

most accurate measurement to date of the electroweak asymmetry is also presented using both reconstructed charm mesons and a new technique that involves tagging the $D^{*+}\to D^0\pi_s^+$ decay using just the π_s^+. We have recently used this new technique to determine the $D^0\to K^-\pi^+$ branching ratio [5].

The data, taken at a center of mass energy $\sqrt{s}=29$ GeV, were obtained using the high resolution spectrometer (HRS) at PEP and correspond to an integrated luminosity of 300 pb^{-1}. The HRS is a general purpose detector using a solenoidal magnetic field of 1.62 T giving a resolution for high momentum tracks at large angles of $\sigma_p/p\simeq 2\times 10^{-3}p$ (p in GeV/c) [6]. No particle identification was used in the analysis and all particles produced were taken as both a kaon and a pion in the reconstruction of the charm D* and D mesons.

We have previously published results on charm meson production [7] using fully reconstructed decays and the results presented here employ similar techniques. The charm mesons are observed in the decay modes $D^0\to K^-\pi^+$, $D^+\to K^-\pi^+\pi^+$ and $D^{*+}\to D^0\pi^+$ (with the D^0 decaying into the $K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^0$ modes) using our total sample of hadronic events and all possible mass combinations. Our analysis also includes the charge conjugate states. The backgrounds in each channel are different and in general are much higher at low Z ($=2E_{\rm meson}/E_{\rm CM}$).

Fig. 1a shows the $K^-\pi^+$ mass spectrum for $Z>0.45$ and $|\cos\theta_\pi^*|\leqslant 0.7$ and a clear D^0 signal is observed. The cut on the helicity angle (θ_π^*) greatly reduces the combinatorial background. Similarly, clear D^+ production is seen in fig. 1b which shows the $K^-\pi^+\pi^+$ mass spectrum with $Z>0.45$ and $|\cos\theta_p^*|\geqslant 0.3$. The cut on the perpendicular to the three body decay plane in the $K\pi\pi$ center of mass with respect to its line of flight (θ_p^*) reduces the combinatorial background. The mass resolution in the D region is $\sigma\simeq 17$ MeV. Charged D* production in the decay mode $D^{*+}\to D^0\pi^+$ with the D^0 decaying into the $K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^0$ modes is isolated by using the excellent mass resolution of the HRS and the fact that the Q value of the decay is only 5.8 MeV, so that the $D^{*+}-D^0$ mass difference (δ) is well determined, and clear signals with small backgrounds can be observed. For the decay $D^0\to K^-\pi^+$, the quantity $\delta=(M_{K^-\pi^+\pi^+}-M_{K^-\pi^+})$ was determined for those

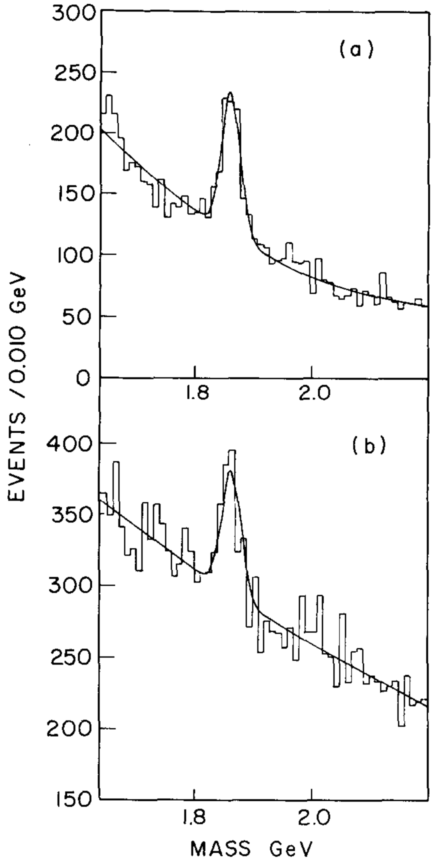

Fig. 1. (a) The mass of $K^-\pi^+$ system with $Z>0.45$ and $|\cos\theta_\pi^*|\leqslant 0.7$ (b) The mass of the $K^-\pi^+\pi^+$ system with $Z>0.45$ and $|\cos\theta_p^*|\geqslant 0.3$.

combinations with $1.81<M_{K^-\pi^+}<1.92$ GeV which is the mass region for D^0 decays seen in fig. 1a. The same technique was also used for the $K^-\pi^+\pi^+\pi^-$ decay of the D^0. The distribution in δ for the $K^-\pi^+$ decay mode is shown in fig. 2a with the selection $0.2\leqslant Z_{D^*}\leqslant 0.4$ and in fig. 2b for $Z_{D^*}>0.4$. Prominent peaks are evident at $\delta\simeq 0.145$ GeV. In order to reduce background the events in fig. 2a were selected with $|\cos\theta_\pi^*|<0.8$ where θ_π^* is the decay angle of the D^0 in its helicity frame. The distributions for the $K^-\pi^+\pi^+\pi^-$ decay of the D^0 are similar and a clear signal is observed for the region $Z>0.6$. For the $K\pi\pi^0$ decay mode of the D^0, no attempt was made to reconstruct the π^0 and instead the well known kinematic enhancement around 1.6 GeV (the S^0 peak) formed by the $K^-\pi^+$ from the D^0 was used. A clear signal

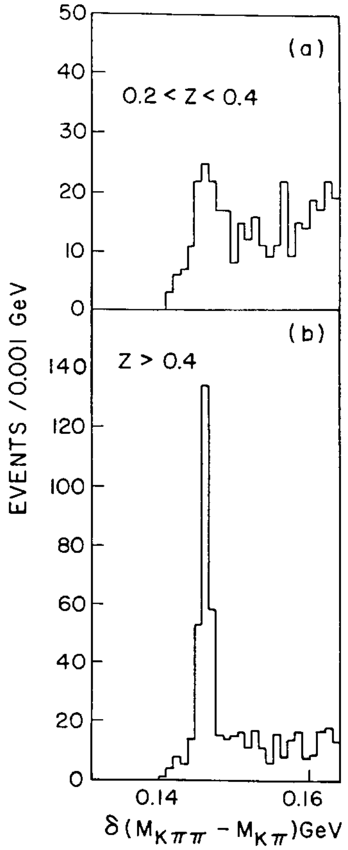

Fig. 2. The quantity δ (a) for $D^0 \to K^-\pi^+$ with $1.81 \leqslant M_{K\pi} \leqslant 1.92$ GeV and $0.2 \leqslant Z \leqslant 0.4$ and $|\cos\theta^*_\pi| \leqslant 0.8$; (b) for $D^0 \to K^-\pi^+$ with $1.81 \leqslant M_{K\pi} \leqslant 1.92$ GeV and $Z \geqslant 0.4$.

corresponding to D^{*+} production is observed for the region $Z > 0.4$, although the peak is broadened due to the missing π^0.

The data shown in figs. 1 and 2 have been used to determine the total cross sections for D^0, D^+ and D^{*+} production and the $D^* \to D^0\pi$ ($D^0 \to K^-\pi^+$) events to determine the fragmentation functions over the whole Z range. The data have been corrected for acceptance using Monte Carlo events and a full detector simulation.

The main uncertainty in determining cross sections comes from the errors in the branching ratios for the observed decay modes. Recently the MARK III Collaboration has published new values the for D^0 and D^+ decays [4]; these values are used adding the systematic and statistical errors in quadrature. This

Table 1
Differential cross sections for charm meson production in e^+e^- annihilation at $\sqrt{s} = 29$ GeV.

	Z	$(s/\beta)\, d\sigma/dZ$	$(1/N)\, dN/dZ$
D^* fragmentation	0.2→0.4	0.129±0.029	1.366±0.22
	0.4→0.5	0.168±0.035	1.868±0.27
	0.5→0.6	0.237±0.047	2.667±0.31
	0.6→0.7	0.122±0.027	1.391±0.23
	0.7→0.8	0.070±0.017	0.800±0.13
	0.8→1.0	0.024±0.007	0.270±0.05
D^0	0.3→0.5	0.290±0.058	
	0.5→0.6	0.286±0.053	
	0.6→0.7	0.235±0.043	
	0.7→1.0	0.054±0.011	
D^+	0.3→0.5	0.053±0.036	
	0.5→0.6	0.124±0.031	
	0.6→0.7	0.099±0.023	
	0.7→1.0	0.017±0.005	

procedure gives $BR(D^0 \to K^-\pi^+) = 4.2 \pm 0.56\%$ and $BR(D^+ \to K^-\pi^+\pi^+) = 9.1 \pm 1.4\%$. Our recent measurement [5] of $BR(D^0 \to K^-\pi^+)$ of $4.5 \pm 0.8 \pm 0.5\%$ is consistent with this. The $D^* \to D^0\pi^+$ branching ratio we use is 0.57 ± 0.056 [8] [#1]. The resulting cross sections obtained from our data are listed in tables 1 and 2. The fragmentation function $D(Z) = (1/N) \times dN/dZ$ and the scaling cross section $(s/\beta)\, d\sigma/dZ$ ($\mu b\ GeV^2$) are determined over the whole Z range only for the D^{*+}. The data peaks near $Z = 0.53$ with a mean value of $\langle Z \rangle = 0.523 \pm 0.017$. 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

[#1] We have used the measurement of ref. [8] of $0.57 \pm 0.04 \pm 0.04$ combining the errors in quadrature.

Table 2
Total cross sections and R values for charm meson production in e^+e^- annihilation at $\sqrt{s} = 29$ GeV.

	σ (nb)	R
$D^{*+} + D^{*0}$	0.232±0.041	1.99±0.35
$D^0 + \bar{D}^0$	0.205±0.031	1.76±0.27
$D^+ + D^-$	0.075±0.014	0.64±0.12
total $D^\pm$, D^0	0.280±0.040	2.40±0.35

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. 2a does show a significant D* peak presumably due to b fragmentation.

The cross section expected for $c\bar{c}$ production using $\alpha_s = 0.17$ is 2.8 units of R with an additional 0.8 units resulting from the $b \to c$ transition. The values of R are determined using D* production over the whole Z range and the D^0 and D^+ measurements for $Z > 0.45$. The D^0 and D^+ measurements are corrected to the whole Z range assuming the ratio of D/D* is the same for $Z < 0.45$ as it is for $Z > 0.45$. This extrapolation implies that the ratio of D*/D in B decays is the same as for charm quark fragmentation, which is in agreement with measurements from the CLEO Collaboration [9]. Since the decay of the D* results in either a D^0 or D^+ the total R for charm meson production, using the radiatively corrected cross section $\sigma_{\mu\mu} = 0.116$ nb for $\sqrt{s} = 27.3$ GeV, is $R(D^0 + D^+) = 2.40 \pm 0.35$. Our result when compared to the $R = 3.6$ expected, gives $67 \pm 10\%$ for the fraction of charm quark fragmentation that leads to D mesons in agreement with the $(71 \pm 6 \pm 10)\%$ found by the CLEO Collaboration at $\sqrt{s} = 10.55$ GeV [10]. With the expected rates for charm D_s and charm baryon production it appears that the data are consistent with a rather small charm deficit. Clearly more precise branching ratio measurements are required. The ratio of the cross sections for $D^0 + D^+$ production to the D* production is 1.20 ± 0.25 in agreement with the 4/3 expected from simple spin counting and the ratio R_{D^0}/R_{D^+} for those D mesons not coming from a D* parent is 0.9 ± 0.9.

In the standard model it is expected that the integrated forward-backward asymmetry for $e^+e^- \to c\bar{c}$ is given by

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

where M_Z is the Z^0 mass, q is the charge of the c quark, and g^e and g^c are the electron and quark axial vector coupling constants. This expression gives an asymmetry at $\sqrt{s} = 29$ GeV, using $M_Z = 94$ GeV, $q = 2/3$, and $g^c = -g^e = 1/2$, of $A = -0.094$. The polar angle θ used in our analysis is taken as the line of flight of charm mesons with high fractional energy. This energy cut also removes any significant $b\bar{b}$ production from our analysis. The production angular distribution for the sample of D^{*+} mesons is shown in fig. 3a, with 660 events in the range $|\cos\theta| \leq 0.7$ and an estimated background of $< 10\%$. These data have been checked for systematic biases and other effects which could influence the asymmetry measurements

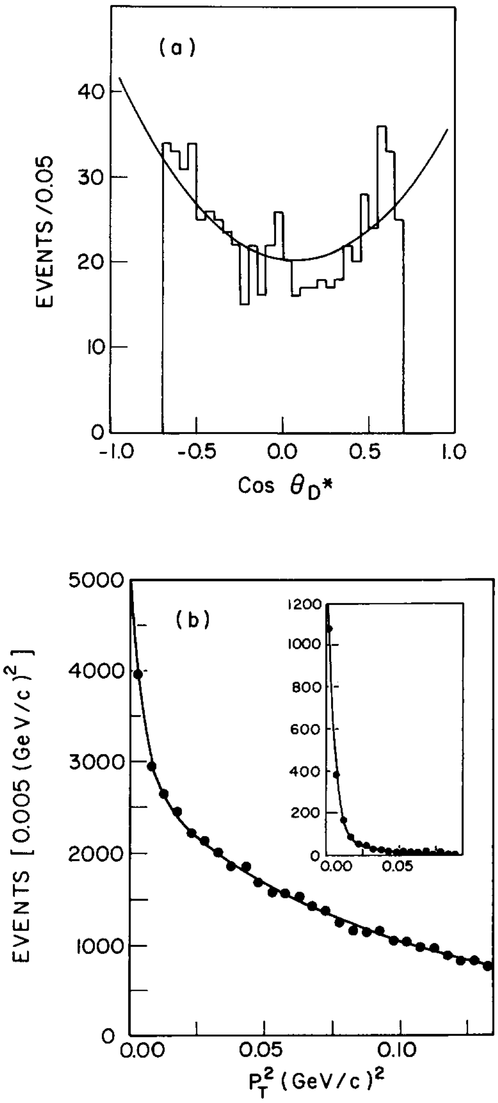

Fig. 3. (a) The production angular distribution for the D^{*+} sample at high Z. (b) The transverse momentum squared for all particles with rspect to the thrust axis. The inset is the distribution expected for the π_s from D* decay.

and none of any significance were found. A fit of the data to the form $(1+a(\cos\theta)+\cos^2\theta)$ gives $A=-0.061\pm0.039$ for the full solid angle.

We have also measured the charm quark asymmetry using the inclusive $K^-\pi^+$ decay of the D^0 and the $K^-\pi^+\pi^+$ decay of the D^+. The mass spectra shown in fig. 1 were combined and then divided into forward and backward hemispheres and the asymmetry $A=(F-B)/(F+B)$ was measured by a simultaneous fit using identical background shapes and signal shapes. Corrected to the full solid angle, this technique yields $A=-0.178\pm0.082$.

A third measurement has been made using just the direction of the pion (π_s^+) from the decay $D^*\to D^0\pi_s^+$. This pion has a maximum p_t of 0.039 GeV/c with respect to the D^* line of flight and since the fragmentation function is hard it also has a small p_t with respect to the jet axis and hence the original quark line of flight.

The actual width of the p_t^2 distribution for the π_s has important contributions from the uncertainty on the determination of the jet axis and Monte Carlo simulation was used to obtain the distribution expected for the pions produced in $D^*\to D\pi$ decays. The angular distribution of the $D^{*+}\to D^0\pi_s^+$ decay was taken to be flat as is indicated by our recent measurement [11]. The axis used to define p_t is a thrust axis computed using momentum squared weights and all charged particles in the hemisphere.

Event cuts were applied to reduce the background due to events with poorly determined thrust axis or evidence of hard gluon emission. We have successfully used this technique to measure the $D^0\to K^-\pi^+$ branching ratio and general details of the analysis can be found in ref. [5].

Fig. 3b shows the p_t^2 distribution for the data in the region $0.03<x_F<0.07$ ($x_F=2p/E_{CM}$) and $0.4<|\cos\theta|<0.75$, where θ is the laboratory angle of the particle. These cuts were chosen to minimize the effect of $b\bar{b}$ events and to maximize the sensitivity to the asymmetry. A sharp low p_t^2 structure is apparent due to the pions from D^* decays. The inset in fig. 3b is the expected distribution for the π_S from D^* decays in our Monte Carlo sample of events with respect to a thrust axis calculated as for the real data. To extract the number of $D^{*+}\to D^0\pi_s^+$ decays from the p_t^2 distribution, a fit was performed to the shape of the signal as determined from the Monte Carlo simulation and a smooth background term. The shape of the signal was represented by two exponentials and determined by fitting the Monte Carlo spectrum of $D^{*+}\to D^0\pi_s^+$ decays shown in the inset of fig. 3b. A fit to the form

$$F(p_t^2)=N_0\,[\exp(-B_1p_t^2)+C\exp(-B_2p_t^2)]\,, \qquad (2)$$

where N_0 is a normalisation factor chosen so that the integral over p_t^2 is 1.0, yields $B_1=222.5$ $B_2=33.4$ and $C=0.049$. The magnitude of the signal and the shape and magnitude of the background were determined by fitting the data to

$$dN/dp_t^2=N_SF(p_t^2)+N_B\,[\exp(-Bp_t^2)+K]\,, \qquad (3)$$

where N_S is the number of D^* decays and N_B is the background normalization. The curve in fig. 3b is the result of this fit. The fit yields $N(p_t^2>0.01)=1732\pm100$ for the number of π_s particles contributing to this low p_t^2 region and with a signal to noise in the $p_t^2<0.01$ (GeV/c)^2 region of about one to three. To determine the electroweak asymmetry the data were divided into $\cos\theta<0$ and $\cos\theta>0$ regions and these were subtracted. The result is an excess of 243 ± 83 events in the backward region for $p_t^2<0.01$ which, after correcting for the angular region used, leads to a final asymmetry of -0.123 ± 0.042. The effect of events being used twice was corrected for and the three asymmetry measurements were combined to yield an asymmetry for $e^+e^-\to c\bar{c}$ using the charm meson as the direction of the quark to be -0.099 ± 0.027 corresponding to $g^eg^c=0.26\pm0.07$, values which are in excellent agreement with the predictions of the standard model.

In summary, for D^* and D charm meson production in e^+e^- annihilations at $\sqrt{s}=29$ GeV, we have found the total cross section $R(D^0+D^+)=2.40\pm0.35$ and the electroweak asymmetry to be $-9.9\pm2.7\%$.

This work was supported in part by the US Department of Energy under contracts W-31-109-ENG-38, DE-AC02-76ER01112, DE-AC76SF000998, DE-AC02-76ER014828, and DE-AC02-84ER0125. This experiment was made possible by the support provided by the PEP staff and the technical staffs of the collaborating institutions.

References

[1] A. Bodek, in: Physics in collision 6, ed. M. Derrick (World Scientific, Singapore, 1987) p. 83;
B. Naroska, in: Physics in collision 5, eds. B. Aubert and L. Montanet (Editions Frontières, Dreux, 1986) p. 287;
H. Martyn, in: The standard model the supernova 1987A, ed. J. Tran Thanh Van (Editions Frontières, Dreux, 1987) p. 63.
[2] R.H. Schindler et al., Phys. Rev. D 24 (1981) 78;
I. Peruzzi et al., Phys. Rev. Lett. 39 (1977) 1301;
D.L. Sharre et al., Phys. Rev. Lett. 40 (1978) 74;
R.M. Baltrusaitis et al., Phys. Rev. Lett. 56 (1986) 2140.
[3] R.H. Schindler, SLAC Report SLAC-PUB-4417 (1987);
D. Bortoletto et al., Phys. Rev. D 35 (1987) 19;
W. Schmidt-Parzefall, Proc. Intern. Symp. on Lepton and photon interactions at high energies (Hamburg, Fed. Rep. Germany, 1987).
[4] J. Adler et al., Phys. Rev. Lett. 60 (1988) 89.
[5] S. Abachi et al., Phys. Lett. B 205 (1988) 411.
[6] D. Bender et al., Phys. Rev. D 30 (1984) 515.
[7] S. Ahlen et al., Phys. Rev. Lett. 51 (1983) 1147;
M. Derrick et al., Phys. Lett. B 146 (1984) 261; Phys. Rev. Lett. 53 (1984) 1971.
[8] J. Adler et al., SLAC Report SLAC-PUB-4518 (1988).
[9] B. Gittleman and S. Stone, Cornell Report CLNS 87-81 (Revised) (1987).
[10] D. Bortoletto et al., Cornell Report CLNS 87/105 (1987).
[11] S. Abachi et al., Phys. Lett. B 199 (1987) 585.