$D^{*\pm}$ PRODUCTION BY e^+e^- ANNIHILATION NEAR 34.4 GeV CM ENERGY

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$D^{*\pm}$ production via $e^+e^- \to D^{*\pm}X$ has been measured at an average CM energy of 34.4 GeV. The $D^{*\pm}$ energy spectrum is hard, with a maximum near $x = 0.6$. The size of the D^* cross section, $R_{D^*} = \sigma(e^+e^- \to D^*X)/\sigma_{\mu\mu} = 2.50 \pm 0.64 \pm 0.88$ (assuming $R_{D^{*0}} = R_{D^{*+}}$) indicates that a large fraction of charm quark production yields D^* mesons. The $D^{*\pm}$ angular distribution exhibits a forward–backward asymmetry, $A = -0.28 \pm 0.13$. This is consistent with that expected in the standard theory for weak neutral currents and leads to $|g_A^c| = 0.89 \pm 0.44$ for the axial vector coupling of the charm quark.

High energy electron–positron annihilation into hadrons is believed to proceed via quark pair formation, $e^+e^- \to \bar{q}q$. The detection of the final state hadron which carries the primary quark (antiquark) appears to be rather difficult in the case of the light quarks, u, d, s since many other low mass hadrons are produced in addition. For heavy quarks such as charm the situation is different: a fast charmed hadron will in general contain the primary charm quark since the production of charmed hadrons from the sea is expected to be negligible at our energies and since hadrons originating from the decay of bottom hadrons should have lower momenta. In this paper we present a cross section measurement for $D^{*\pm}$ production in e^+e^- annihilation to study charm fragmentation and a first measurement of the $D^{*\pm}$ production angular distribution in a search for weak neutral current contributions to charm quark pair production.

The experiment was carried out at the DESY storage ring PETRA using the TASSO detector [1]. Data used here were collected at CM energies W between 30.0 and 36.7 GeV with an average $\bar{W} = 34.4$ GeV for a total luminosity of 79 pb^{-1}. A total of 22 356 events from e^+e^- annihilation into hadrons were selected using the charged particle information as described in refs. [1,2]. The momentum resolution was improved by using the average beam position in the track reconstruction as a constraint. The coordinates of the beam position in the plane perpendicular to the beam were determined from Bhabha scattering events, using averages over run periods. This resulted in a momentum resolution of $\sigma_p/P = 0.010(2.9 + p^2)^{1/2}$, p in GeV/c, as determined from μ-pair events.

The $D^{*\pm}$ mesons were identified using a procedure first proposed in ref. [3] and recently applied in refs. [4,6] [‡1]. It is based on the fact that the Q value of the decay $D^{*+} \to \pi^+D^0$ is only 5.8 MeV. As a result, the direction of the π^+ relative to that of the D^0 and the momentum of the π^+ are severely restricted. The D^0 was detected in the decay mode $D^0 \to K^-\pi^+$. For brevity we shall indicate only the particle states; the analysis includes also the antiparticle states.

For each event all possible $(K^-\pi^+)$ and $(K^-\pi^+)\pi^+$ mass combinations $(M_{K^-\pi^+}, M_{K^-\pi^+\pi^+})$ were formed assuming each particle in turn to be a kaon and a pion. The particles forming the $(K^-\pi^+)$ system were required to have each a momentum $p > 0.8$ GeV/c, and the lone π^+ to have $p > 0.3$ GeV/c. Fig. 1a shows the distribution of the mass difference $\Delta M \equiv M_{K^-\pi^+\pi^+} - M_{K^-\pi^+}$ for those combinations where $M_{K^-\pi^+}$ is in the D^0 mass region (1.744–1.984 GeV) and for which $x > 0.5$, where $x = 2E_{K^-\pi^+\pi^+}/W$ is the fractional energy of the $K^-\pi^+\pi^+$ system. A narrow peak is seen centered around $\Delta M = 0.145$ GeV which is indicative of the decay $D^{*+} \to \pi^+D^0$. The r.m.s. width of the peak, $\sigma_{\Delta M} = 1.5$ MeV, is consistent with the expected resolution. No such peak is observed when $M_{K^-\pi^+}$ is required to be in a control region outside of the D^0 mass (2.10–2.34 GeV) as shown by fig. 1b. In fig. 1d

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[‡1] MARK II data with higher statistics were presented in ref. [5].

the distribution of $M_{K^-\pi^+}$ is shown for all $K^-\pi^+\pi^+$ combinations with $\Delta M < 0.150$ GeV. A clear D^0 signal centered at 1.87 GeV is observed with an r.m.s. width of $\sigma_M = 0.075$ GeV in agreement with our resolution. There is a second mass peak centered around 1.62 GeV. As was pointed out by Goldhaber [7] this so-called satellite enhancement S^0 in the $K^-\pi^+$ mass distribution arises from the decays

$$D^0 \to K^-\rho^+ \; (\rho^+ \to \pi^+\pi^0), \quad D^0 \to \pi^+K^{*-} \; (K^{*-} \to K^-\pi^0) .$$

The spin of the $\rho^+(K^{*-})$ is perpendicular to the direction of the recoiling $K^-(\pi^+)$ leading to a decay distribution $\sim\cos^2\theta_H$ where θ_H is the angle between the decay $\pi^+(K^-)$ and the recoiling $K^-(\pi^+)$ in the rest system of the $\rho^+(K^{*-})$. This produces peaks in the $K^-\pi^+$ mass distribution near 1.62 GeV and at low $K^-\pi^+$ masses. The shape and magnitude of the S^0 peak are consistent with what we expect from the measured [8] branching ratios for the $D^0 \to K^-\rho^+$ and $D^0 \to \pi^+K^{*-}$ decays.

We turn to the determination of the cross section for D^{*+} production. The number of D^{*+}'s was determined as a function of x from the number of D^0 candidates defined by $1.744 < M_{K^-\pi^+} < 1.984$ GeV and $\Delta M < 0.15$ GeV. For small x, $0.3 < x < 0.5$, no clear D^0 signal is observed (fig. 1c): there are 19 D^0 candidates of which 17 are estimated to be due to background. For $x > 0.5$ there are 40 $D^{*+} \to D^0\pi^+$ candidates with a background of 8 events of which 2 come from the S^0. The background (see curves in fig. 1a, c) was estimated by generating Monte Carlo events [2] according to $e^+e^- \to \bar{q}q, \bar{q}qg \to$ hadrons and applying the same cuts as for the D^{*+} selection. The event acceptance, detection efficiency and radiative corrections were calculated by the same Monte Carlo program. The detection efficiency for the decay $D^{*+} \to \pi^+D^0 \to K^-\pi^+\pi^+$ varied between 32 and 45% for $x > 0.3$. We used the branching ratios [4]: $B(D^{*+} \to D^0\pi^+) = 44 \pm 10\%$ and $B(D^0 \to K^-\pi^+) = 3.0 \pm 0.6\%$ to compute the cross section.

Fig. 2 shows the scaled $D^{*\pm}$ cross section $(s/\beta)\mathrm{d}\sigma/\mathrm{d}x$

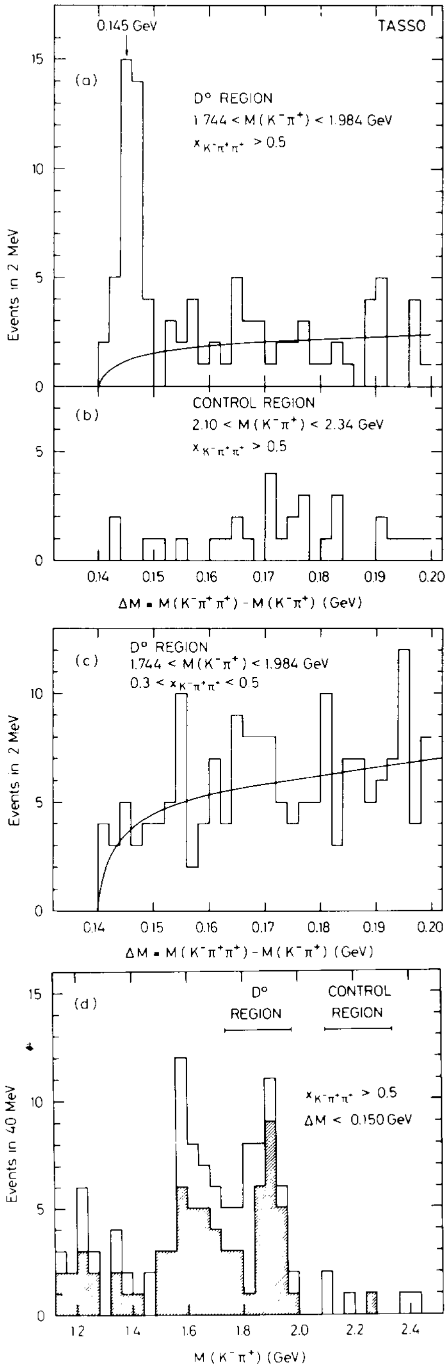

Fig. 1. (a) The spectrum of the mass difference $\Delta M = M_{(K^-\pi^+)\pi^+} - M_{(K^-\pi^+)}$ for $x > 0.5$ and $(K^-\pi^+)$ combinations in the D^0 mass region (1.744–1.984 GeV). The curve shows the expected background contribution. (b) The ΔM spectrum for $x > 0.5$ and $(K^-\pi^+)$ combinations in the control region (2.10–2.34 GeV). (c) The ΔM spectrum for $0.3 < x < 0.5$ and $(K^-\pi^+)$ combinations in the D^0 mass region. The curve shows the expected background contribution. (d) The $(K^-\pi^+)$ mass spectrum for $(K^-\pi^+)\pi^+$ combinations with $\Delta M < 0.15$ GeV and $x > 0.5$. The dashed histogram shows the mass spectrum obtained with the stricter cuts used for the analysis of the angular distribution (see text).

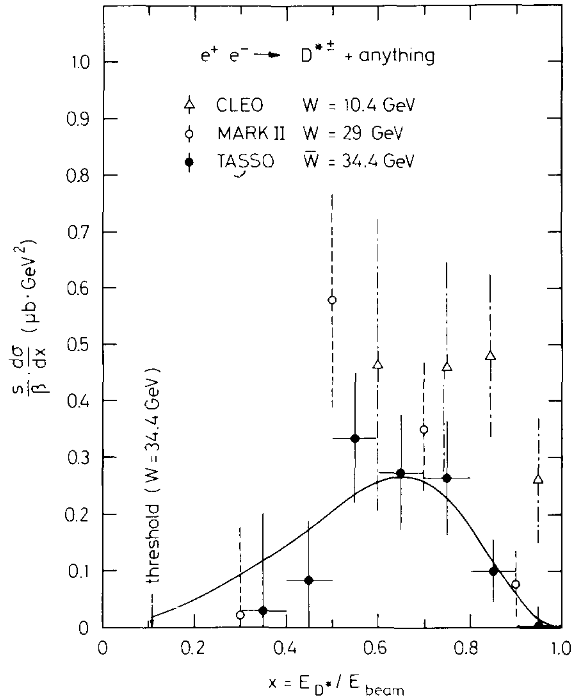

Fig. 2. The scaled cross section $(s/\beta)\mathrm{d}\sigma/\mathrm{d}x$ for $e^+e^- \to D^{*\pm}X$. The errors shown are statistical. A 35% normalization uncertainty is not included. Also shown are measurements from CLEO [6] at W = 10.4 GeV and MARK II [5] at 29 GeV. The curve shows the fit described in the text.

as a function of x (note that the cross section includes D^{*+} *and* D^{*-} production, see above). The error bars shown are only statistical. An overall normalization uncertainty of ±35% due mainly to the uncertainty in the D^{*+} and D^0 branching ratios is not included. Our cross sections are consistent with those of MARK II [4] at 29 GeV but are somewhat lower than those measured by CLEO [6] at W = 10.4 GeV (see fig. 2). Note that all three experiments use the same values for the D^{*+} and D^0 branching ratios. Qualitatively, all three experiments observe a similar behaviour: the D^* mesons are concentrated at large x values, the maximum being at x = 0.6–0.7. This agrees with results on charm quark fragmentation produced by neutrinos [9] and muons [10], the former yielding for the average x value $\langle x_D \rangle = 0.68 \pm 0.08$ and $\langle x_D \rangle = 0.59 \pm 0.03 \pm 0.03$, respectively (see also ref. [11]). It agrees also with theoretical expectations [12].

A fit was made to our scaled cross section to the form advocated in ref. [13] for heavy quark fragmentation:

$$(s/\beta)\mathrm{d}\sigma/\mathrm{d}x \sim \frac{1}{x[1 - 1/x - \epsilon/(1-x) - \sigma)^2}$$

The fit yielded $\epsilon = 0.18 \pm 0.07$ and is shown by the curve in fig. 2.

The integration of the measured $D^{*\pm}$ cross section over $x > 0.3$ yields relative to the μ pair cross section ($\sigma_{\mu\mu} = 4\pi\alpha^2/3s = 0.073$ nb at W = 34.4 GeV):

$$R_{D^{*\pm}}(x > 0.3)$$
$$\equiv [\sigma_{D^{*+}}(x > 0.3) + \sigma_{D^{*-}}(x > 0.3)]/\sigma_{\mu\mu}$$
$$= 1.25 \pm 0.32(\mathrm{stat.}) \pm 0.44(\mathrm{syst.})\ .$$

Assuming equal rates for charged and neutral D*'s the total D* production is found to be

$$R_{D^*}(x > 0.3) = 2.50 \pm 0.64 \pm 0.88\ .$$

This can be compared with the expected total inclusive primary charm quark and antiquark yield of

$$R_c = 2 \cdot \tfrac{4}{3} \cdot (1 + \alpha_s/\pi) \approx 2.80\ ,$$

assuming for the strong coupling $\alpha_s = 0.17$. The data indicate that a large fraction of charm quark production proceeds via D* formation.

The hard spectrum suggests strongly that D*'s carry the primary c quark. The large CM energy available in this experiment offers then the possibility to search for a contribution of the weak neutral current to $e^+e^- \to \bar{c}c$ and to obtain a first measurement of the c quark coupling strength to the weak neutral current. Similar to the observation for μ and τ pair production ($e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \tau^+\tau^-$) [14], we expect the most conspicuous effect in the D* angular distribution where the interference between the electromagnetic and the weak current should produce a forward–backward asymmetry

$$A = \frac{N(\theta < \pi/2) - N(\theta > \pi/2)}{N(\theta < \pi/2) + N(\theta > \pi/2)}\ .$$

The angle θ is taken between the incoming e^- and the outgoing D^{*+} which carries the c (i.e. not the $\bar{c}$) quark.

Assuming the weak neutral current to be mediated by Z^0 exchange, A has the form

$$A \simeq \frac{3}{2}\frac{g_A^e g_A^c}{e_Q}\frac{G_F}{2\sqrt{2}\pi\alpha}\frac{W^2}{1 - W^2/M_Z^2}\ , \quad W \ll M_Z\ ,$$

where M_Z is the Z^0 mass, $e_Q = 2/3$ is the charge of the charm quark, G_F is the Fermi coupling constant, and g_A^e and g_A^c are the electron and c quark axial vector coupling constants. In the standard theory [15] $g_A^e = -1/2, g_A^c = 1/2$, which for M_Z = 94 GeV and W = 35 GeV leads to the prediction $A = -0.14$.

For the determination of the angular distribution we used both the D^0 and S^0 candidates, i.e. we accepted all D^{*+} candidates with $1.50 < M(K^-\pi^+) < 1.984$ GeV and $\Delta M < 0.15$ GeV; x was restricted to $x > 0.5$. In order to enhance the sensitivity to the weak contribution only events with $W > 34$ GeV were accepted, the average W being 35 GeV. The background under the D^0 and S^0 peaks was reduced by requiring the momenta of each of the particles forming the $(K^-\pi^+)$ system to have $p > 1.4$ GeV/c. The resulting $K^-\pi^+$ mass distribution is shown by the dashed histogram in fig. 1d. In total there are 51 D* candidates with an estimated background of 5. The angle θ was taken to be the angle between the incoming e^- and the $K^-\pi^+\pi^+$ system. Fig. 3 shows the D^{*+} angular distribution. The acceptance is uniform over the range $|\cos\theta| < 0.8$. The angular distribution is consistent with the form

$$d\sigma/d\cos\theta \sim 1 + a\cos\theta + \cos^2\theta \ .$$

Fitting this form to the data for $|\cos\theta| < 0.8$ and extrapolating to $\cos\theta = \pm 1$ yielded for the asymmetry

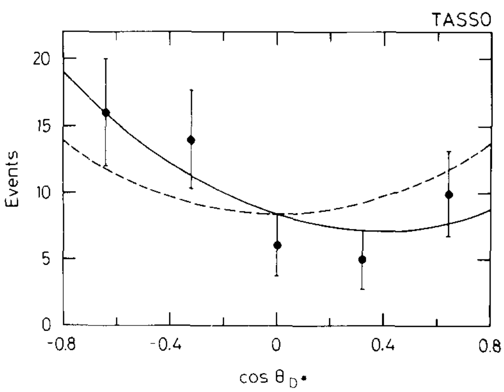

Fig. 3. The $D^{*\pm}$ production angular distribution; θ is the angle between the e^- beam and the $K^-\pi^+\pi^+$ system. The full curve indicates the fit $d\sigma/d\cos\theta \sim 1 + a\cos\theta + \cos^2\theta$. The dashed curve is proportional to $1 + \cos^2\theta$.

$A = \frac{3}{8}a = -0.28 \pm 0.13$ ‡2. No correction was applied for the background. Assuming the latter to be forward-backward symmetric would change A to -0.31 after correction. The fraction of $D^{*\pm}$ mesons with $x > 0.5$ coming from bottom hadrons was estimated to be ~4% (see ref. [12]) and gives a negligible contribution to the measured asymmetry. Higher order QED corrections introduce a forward–backward asymmetry which we estimate to be approximately -0.005. All three corrections are well within the statistical uncertainties and were neglected. Note that the sign and the magnitude of A are in agreement with the prediction of the standard model. This result is the first indication for a weak current contribution to $e^+e^- \to \bar{c}c$ production. From the value of $A = -0.28 \pm 0.13$ we obtain $g_A^e g_A^c = -0.49 \pm 0.23$. Assuming lepton universality and using an average of the results on μ pair production [14], $|g_A^e|^2 = 0.30 \pm 0.04$ yields $|g_A^c| = 0.89 \pm 0.44$ which is consistent with the prediction of the standard model, $g_A^c = 0.5$.

In conclusion, we have studied $D^{*\pm}$ production at an average CM energy of 34.4 GeV. In agreement with previous measurements we observe a hard x spectrum. Assuming equal rates for charged and neutral D* production, the observed D* yield accounts for a large fraction of the expected charm contribution. The $D^{*\pm}$ angular distribution shows a forward–backward asymmetry of $A = -0.28 \pm 0.31$ which indicates the presence of a weak neutral current contribution to $e^+e^- \to \bar{c}c$ and which yields $|g_A^c| = 0.89 \pm 0.44$ for the axial vector coupling of the charm quark.

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‡2 The angular difference between the D^{*+} and the $K^-\pi^+\pi^+$ system in the case of the S^0 is on the average 1° and has a negligible effect on the angular distribution. Using the sphericity axis instead of the D* direction to compute θ changed A to -0.26 ± 0.12.

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