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Charged-D^*-meson production in e^+e^- annihilation at $\sqrt{s}=29$ GeV

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The production of charmed D^* mesons in e^+e^- annihilations at a center-of-mass energy of 29 GeV has been studied using the time-projection-chamber (TPC) detector at the SLAC storage ring PEP. The production cross section, fragmentation function, and forward-backward asymmetry due to electroweak effects are measured, and a limit on D^0-$\overline{D}^0$ mixing is determined.

Several experiments[1] have reported measurements of the production of charged D^* mesons in e^+e^- annihilation, and all have used the cascade decay to the D^0 by single-pion emission as a clean kinematic feature[2] in the identification and isolation of the D^* signal from the combinatorial background. Employing the same technique, we have measured several characteristics of D^* production in e^+e^- annihilation at a center-of-mass energy of 29 GeV using data collected with the PEP-4 time-projection-chamber (TPC) detector at the SLAC storage

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ring PEP. The TPC was used to identify kaons and pions by simultaneous measurement of momentum and ionization energy loss dE/dx. The apparatus, monitoring, calibration, and event selection have been previously described.[3] The data sample reported on here corresponds to 77 pb^{-1}, or about 29 000 hadronic events.

In this analysis all charged tracks are reconstructed from the TPC measurements in a 0.4-T magnetic field with a momentum resolution of about $(\sigma_p/p)^2 \simeq (0.06)^2+(0.035p)^2$, with p in GeV/c. The specific ionization rate of each track is sampled up to 183 times by ionization energy loss in the argon (80%)—methane (20%) gas volume of the TPC. We define dE/dx for each track to be the mean of the smallest 65% of all available samples, where samples may be missing due to either geometrical acceptance or spatial overlap with other tracks of the event. On the average 110 dE/dx samples are obtained for each track in multihadronic events, and by requiring at least 40 samples to define the mean, we obtain a typical dE/dx resolution of 3.7%. From the measured dE/dx and momentum, one-constraint χ^2 values are calculated for electron, pion, kaon, and proton hypotheses using an empirically determined formula to relate the expected dE/dx to the momentum for each mass. The parameters of the formula have been calibrated using minimum ionizing particles in multihadronic events, cosmic-ray muons, and Bhabha-scattered electrons identified by the hexagonal (barrel) calorimeter. At each momentum, the measured dE/dx distribution is observed[3] to be very nearly Gaussian for each particle species. Therefore we have assumed a Gaussian in computing the confidence level of each mass hypothesis.

For the D^* analysis, tracks so measured are required to meet the following criteria: (a) the distance of closest approach to the beam-beam interaction point is smaller than 3 cm in the plane transverse to the beam and smaller than 5 cm along the beam, (b) the momentum is greater than 0.4 GeV/c for pions and 1.0 GeV/c for kaons, (c) the curvature error in the orbit fit is less than 0.26 $(\text{GeV}/c)^{-1}$ for momenta above 1 GeV/c, and the fractional momentum error is less than 0.26 for momenta below 1 GeV/c, (d) the angle from the beam direction is greater than 33°, (e) for a pion or a kaon the confidence level of the χ^2 for the corresponding mass hypothesis must exceed 3%, and in addition, (f) for a kaon below 1.5 GeV/c, the χ^2 of the kaon hypothesis must be less than the χ^2 of both the pion and electron hypothesis by at least 1.0 unit. This last criterion is used to reduce the contamination of the kaon sample by pions and electrons at their respective crossover points.

Assuming the decay sequence $D^{*+}\to\pi^+D^0 \to\pi^+K^-\pi^+$, and its charge conjugate, D^0 decay hypotheses are considered for all pairs of tracks satisfying the above criteria for K^- and π^+. Each pair is constrained to the D^0 mass by fitting the inverse momenta of both tracks while the invariant mass of the system is constrained to the D^0 mass. Only D^0 decay hypotheses passing this fit at the 1% confidence level and having the decay cosine of the K in the D^0 rest frame less than 0.8 with respect to the D^0 line of flight are retained. The mass difference $M(\pi^+D^0)-M(D^0)$ is formed by combining the tracks of each D^0 hypothesis with pions of charge opposite to the charge of the kaon. This distribution is shown in Fig. 1(a) for a selection of the energy fraction, $z_{D^*}=E_{D^*}/E_{\text{beam}}$, of the π^+D^0 system of $z_{D^*}>0.5$.

For the decay sequence $D^{*+}\to\pi^+D^0$, where the D^0 decays as $D^0\to K^-\pi^+\pi^0\to K^-\pi^+\gamma\gamma$, all two-track combinations consistent with the kaon and pion hypotheses, and all pairs of photons measured in the hexagonal calorimeter, subject to $E_\gamma>0.4$ GeV, are considered. A least-squares fit of the inverse momenta of the two charged tracks and of the energies of the two photons, i.e., four parameters, is performed with two mass constraints: that the two photons have the neutral pion mass, and that the overall system of kaon, pion, and two photons have the D^0 mass. D^0 hypotheses with a confidence level from this fit exceeding 1% and with a decay cosine of the K in the D^0 rest frame less than 0.8 are retained. The D^0's are

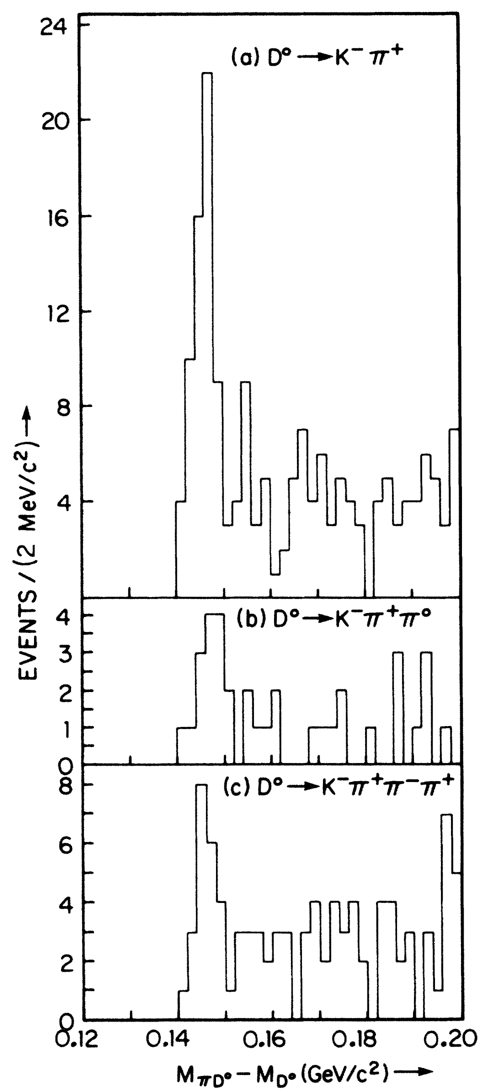

FIG 1. Mass-difference distributions for (a) $D^0\to K^-\pi^+$ with $z_{D^*}>0.5$, (b) $D^0\to K^-\pi^+\pi^0$ with $z_{D^*}>0.7$, and (c) $D^0\to K^-\pi^+\pi^-\pi^+$ with $z_{D^*}>0.7$.

then paired with all pion tracks of charge opposite to that of the kaon, and the mass difference $M(\pi^+D^0)-M(D^0)$ is computed. This distribution for events with a more restrictive cut in z_{D^*} to remove background combinations, $z_{D^*}>0.7$, is shown in Fig. 1(b).

For the D^0 decay mode $D^0 \to K^-\pi^+\pi^-\pi^+$ the same procedure as for the $D^0 \to K^-\pi^+$ mode is followed. The resulting mass difference distribution for $z_{D^*}>0.7$ is shown in Fig. 1(c).

For all D^0 decays, if more than one decay mode hypothesis passes all cuts, only that hypothesis with the lowest summed mass χ^2 and fit χ^2 is kept.

The D^* detection efficiencies were estimated using a Monte Carlo calculation which generates multihadronic events with initial-state radiation,[4] and an analysis procedure identical to that used for the data. The physics event generator used was the Lund Monte Carlo program,[5] with spin alignment of the pseudovector decay products for the D^0 to three final-state particles, as suggested in Ref. 6. The detector simulation includes the geometrical acceptance of the apparatus, particle energy loss, multiple scattering and nuclear interactions in the materials of the detector, and decay loss of pions and kaons. In addition the analysis of the simulated data includes charged-track pattern recognition, the loss of dE/dx wire samples due to overlap of nearby tracks and its effect on the dE/dx resolution. For photons, it includes pair production and subsequent bremsstrahlung in the materials before the TPC volume and before the lead mass of the calorimeter, and the pattern-recognition efficiency and energy resolution of the hexagonal calorimeter.

The fragmentation of the charmed quark into a charmed vector meson may be measured by extracting the numbers of D^* mesons detected as a function of z_{D^*}. After correction for detection and acceptance efficiency, initial-state radiation, and finite momentum resolution the fragmentation function determined from the $D^0 \to K^-\pi^+$ decay mode is shown in Fig. 2(a) and tabulated in Table I. A fit to the Peterson form[7] of the fragmentation function $D(z)=z^{-1}[1-1/z-\epsilon/(1-z)]^{-2}$, yields a mean value of $\langle z_{D^*}\rangle_c=0.58\pm0.03\pm0.05$ and an ϵ parameter of $\epsilon_c=0.25\pm0.12$. The D^* in our data have a mean $z_{D^*}=0.55\pm0.02$. These measurements are in agreement with our inclusive electron and muon data.[8] The cross section for the production of D^* mesons is shown in Fig. 2(b),

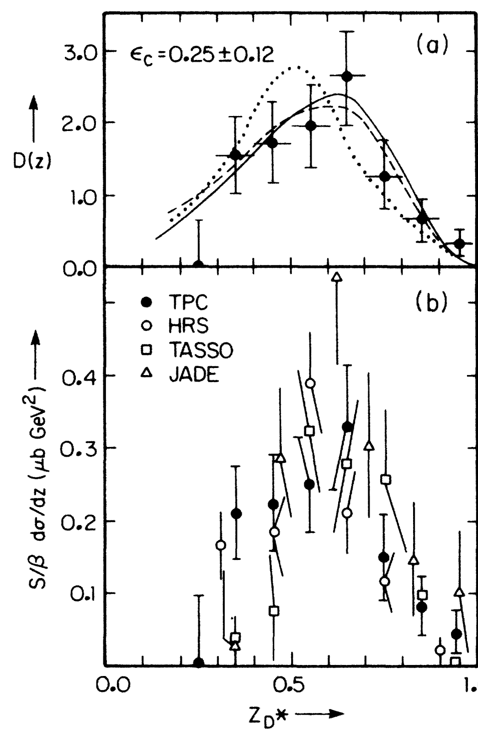

FIG. 2. (a) The fragmentation function for $c \to D^*$. The solid line is our fit to the Peterson form (Ref. 7), the dashed line is the expectation of the Lund Monte Carlo simulation (Ref. 10), and the dotted line is the expectation of the Webber Monte Carlo simulation (Ref. 11). (b) The invariant cross section as measured in this and previous experiments.

and compared to other data from PEP and the DESY storage ring PETRA (Ref. 1). The branching ratios for $D^{*+} \to D^0\pi^+$ and $D^0 \to K^-\pi^+$ are taken from Ref. 9.

The shape of the fragmentation function of a quark into a meson, and its dependence on the mass of the quark, is of fundamental interest in understanding the hadronization process. The D^* fragmentation function is particularly interesting, since at high z it is anticipated that it corresponds to a direct transition of a leading charmed quark to an observed meson, while competing processes yielding D^* mesons, such as decays from bottom mesons, decays from higher-mass D mesons, or $c\bar{c}$ creation in the color field, are expected to be small and

TABLE I. The cross section and fragmentation function for charged-D^*-meson production. The z-dependent corrections for detector resolution and initial-state radiation are also shown.

z_{D^*}	Radiation correction	Resolution correction	$\frac{s}{\beta}\frac{d\sigma}{dz}$ (μb GeV^2)	$D(z)=\frac{1}{N}\frac{dN}{dz}$
0.2–0.3	0.65	0.94	0.0 ±0.10	0.0 ±0.74
0.3–0.4	0.69	0.96	0.21±0.07	1.54±0.48
0.4–0.5	0.72	0.99	0.22±0.07	1.70±0.55
0.5–0.6	0.80	1.07	0.25±0.07	1.94±0.57
0.6–0.7	0.91	1.10	0.33±0.08	2.61±0.67
0.7–0.8	1.03	1.07	0.15±0.06	1.22±0.51
0.8–0.9	1.14	0.86	0.08±0.04	0.65±0.33
0.9–1.0	1.22	0.51	0.04±0.02	0.33±0.18

have little effect on the measurement of the fragmentation function. Since this fragmentation involves a heavy quark, it also provides a useful mass-dependent comparison to the case of light-quark fragmentation.

Our measured fragmentation function is well represented by the Peterson form, as shown by the solid line in Fig. 2(a). The Lund Monte Carlo[10] expectation is shown as a dashed line, and the Webber Monte Carlo expectation[11] is shown as a dotted line. Our measurements slightly favor the Peterson and Lund forms over the Webber form. The data of the HRS Collaboration,[1] on the other hand, yield a cross section smaller than ours at high z_{D^*} and therefore disfavor the Peterson form. The ARGUS Collaboration data[1] at $\sqrt{s} \simeq 10$ GeV analyzed in the kinematic variable $x_p \equiv P_{D^*}/P_{\max}$, favor the Kartvelishvili[12] over the Peterson form, but this disagreement with the Peterson form is largely in their highest-x_p bin 0.9—1.0. Precise comparisons with these several fragmentation functions await larger data samples.

The interference of the Z^0 boson with the photon in the annihilation process producing a quark-antiquark pair is expected to lead to an asymmetry in the polar angular distribution of the charmed quark with respect to the initial e^+ direction.[13] An estimate of this asymmetry can be obtained by assuming that the D^* meson maintains the direction of the primary charmed quark at production, and measuring the angular distribution of the D^{*+} with respect to the beam direction, shown in Fig. 3. A maximum-likelihood fit to the expected form of this asymmetry

$$\frac{dN}{d(\cos\theta)} = 1 + \cos^2\theta + \tfrac{8}{3} A \cos\theta$$

yields an asymmetry of $A = -0.16 \pm 0.16$, compared to the expected value of $A = -0.09$ from the standard model at $\sqrt{s} = 29$ GeV.

It is expected that the pseudoscalar meson D^0 will mix with its partner of opposite charm, the $\bar{D}^0$, with a probability given roughly by $\sin^4\theta_C = 2.5 \times 10^{-3}$ (Ref. 14). We have studied this by examining the wrong-sign combinations which would result from the following sequence: $D^{*+} \to \pi^+ D^0$ followed by $D^0 \to \bar{D}^0$, and subsequent decay $\bar{D}^0 \to K^+\pi^-$. This would yield a kaon of the wrong sign (and strangeness), and would be detectable as a signal in the distribution of the mass-difference distribution $M(\pi^+K^+\pi^-) - M(K^+\pi^-)$ when the pion from the decay of the D^{*+} into D^0 now has the same charge as the kaon from the D^0 decay. This mass-difference distribution for tighter cuts on mass χ^2 (30% C.L.) and kinematic-fit χ^2 (20% C.L.) is shown in Fig. 4(b), while the correct-sign distribution with the same cuts is shown in Fig. 4(a). At the 90% confidence level we place a limit of 10% on the rate for D^0-$\bar{D}^0$ mixing. This limit is comparable to other direct limits[15] in e^+e^- annihilation into charmed quarks employing similar techniques, but far less stringent than limits derived from leptonic production rates in hadron-hadron interaction experiments, for example, papers by Bodek *et al.* and Louis *et al.*, of Ref. 15.

In summary, we have studied the production of charmed D^* mesons in e^+e^- annihilation at $\sqrt{s} = 29$ GeV by detecting their cascade decay to $D^0\pi^+$ in which the D^0 decays through its $K^-\pi^+$, $K^-\pi^+\pi^0$, or $K^-\pi^+\pi^-\pi^-$ mode. We have measured the production cross section, the charmed-quark fragmentation function, the electroweak asymmetry of the charmed quark, and placed a limit of 10% (at the 90% confidence level) on the rate at which the pseudoscalar meson D^0 will mix with its partner of opposite charm, the $\bar{D}^0$.

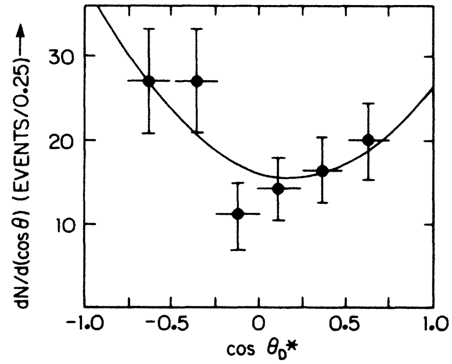

FIG. 3. The production angular distribution of the D^{*+}.

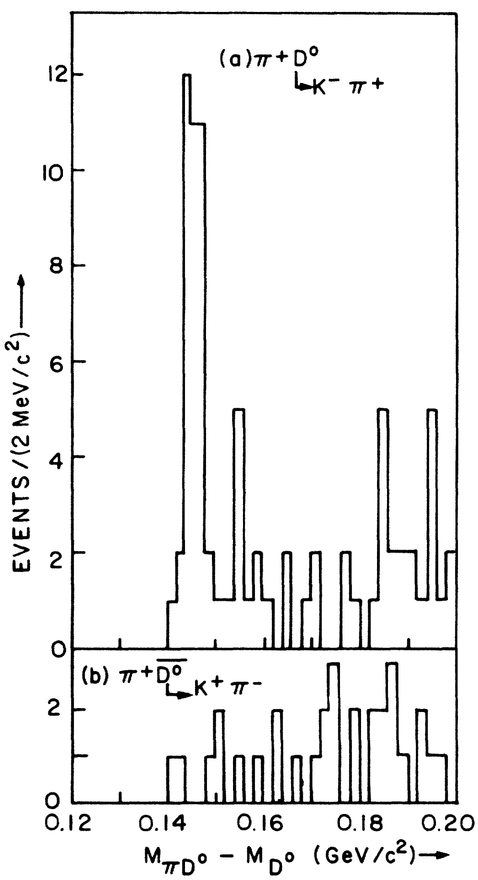

FIG. 4. Mass-difference distributions for (a) $\pi^+D^0 \to \pi^+K^-\pi^+$ and (b) $\pi^+\bar{D}^0 \to \pi^+K^+\pi^-$ with more restrictive cuts on the mass identification and kinematic-fit confidence levels.

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$$f(z)\frac{(1-z)^a}{z}\exp(-bm_t{}^2/z)$$

describes the general features of our data with $a=1.3$ and $b=0.7$ [see H-U. Bengtsson, UCLA report (unpublished)].

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