D AND D* MESON PRODUCTION NEAR 4 GeV IN e^+e^- ANNIHILATION ☆

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We have studied momentum spectra for D^0 ($\bar{D}^0$) and $D^\pm$ mesons produced near 4 GeV in e^+e^- annihilation and find that production is dominated by two-body reactions involving D and D* states where the D* (charged and neutral) have masses near 2.01 GeV/c^2. A detailed study of D momentum spectra near E_{cm} = 4.028 GeV allows determination of masses and branching ratios of D and D* states. Lastly we find that events containing a D^0 meson conserve strangeness, thus establishing upper limits on D^0-$\bar{D}^0$ mixing and on the effects of charm changing neutral currents.

There is now ample evidence that both members of the isotopic spin doublet (D^0, D^+) of charmed mesons are produced by e^+e^- annihilation at center-of-mass energies E_{cm} near 4 GeV [1–3]. We report here on some of the properties of these new states that were determined from a study of multihadronic events collected by the SLAC/LBL magnetic detector at SPEAR. The integrated luminosity for our data sample is 5 pb^{-1} approximately equally divided between two fixed energies E_{cm} = 4.028 and 4.415 GeV and a distribution of E_{cm} between 3.9 GeV and 4.6 GeV. These fixed energies were studied because they represent peaks in $R = \sigma_{HAD}/\sigma_{\mu\mu}$, the ratio of the total hadron cross section to the point-like mu pair cross section [4]. Recoil mass spectra at the two fixed energies indicate that D's are produced in association with, and as decay products of additional states D^{*0}, D^{*+} (and the their antiparticles) having masses near 2.01 GeV/c^2. Analysis of D momentum spectra at E_{cm} = 4.028 GeV gives values of D and D* masses, allows measurement of D^{*0} branching ratios, and indicates that D production at this energy is dominated by two-body processes involving only D and D* states.

The D^0, $\bar{D}^0$ candidates, in events with three or more prongs, were identified through their $K^\mp\pi^\pm$ decay modes by selecting all neutral, two-prong combinations having a K-π invariant mass in the range 1.82 GeV/c^2 to 1.90 GeV/c^2. The K was chosen to be the track where time-of-flight (TOF) information was most consistent with the K hypothesis. We estimate that 75% of K's from real D^0 decays are correctly chosen, but even in cases where the wrong choice was made, the D^0 momentum was correctly measured and the event fell within the invariant mass cut. Two-prong combinations falling in the invariant mass ranges 1.72–1.80 and 1.92–200 GeV/c^2 were used to estimate background contamination to the D^0 signal. The $D^\pm$ candidates were identified through the exotic decay modes $K^\mp\pi^\pm\pi^\pm$ using TOF criteria described in ref. [3] to select K's and π's. Their invariant mass was required to be in the range 1.85 GeV/c^2 to 1.91 GeV/c^2. Nonexotic combinations satisfying the same cuts were used to determine background shape.

Fig. 1 shows the background-subtracted D^0 recoil mass spectrum at E_{cm} = 4.028 GeV computed assuming a fixed nominal D^0 mass of 1865 MeV/c^2 for both signal and background $K\pi$ combinations. The spectrum

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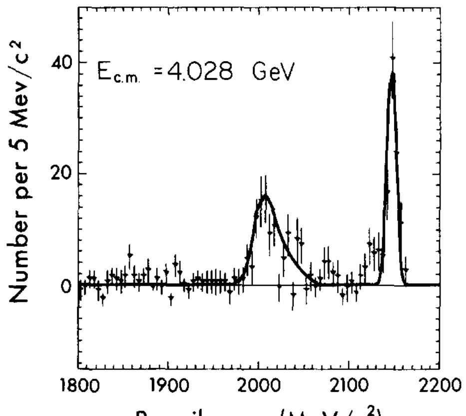

Fig. 1. The $D^0 \to K^- \pi^+$ recoil spectrum at E_{cm} = 4.028 GeV computed with a nominal fixed D^0 mass value. The curve shows the expected shapes of peaks due to $D\bar{D}^* + \bar{D}D^*$ and $D^*\bar{D}^*$ production. Here we neglect radiative D^* decays and only show the narrow reflections due to $D^{*0} \to \pi^0 D^0$ decays.

is dominated by two peaks at 2.01 GeV/c^2 and 2.15 GeV/c^2 with weaker evidence for a peak at 1.87 GeV/c^2 which would correspond to $D^0\bar{D}^0$ production. The same spectrum for events collected at E_{cm} = 4.415 GeV is presented in fig. 2. The 2.01 GeV/c^2 peak is still present, but the 2.15 GeV/c^2 peak has moved to 2.20 GeV/c^2 and has broadened. From this behavior, we conclude that the 2.01 GeV/c^2 peak represents a state D^{*0} produced in association with the observed D^0, while the other peak moves with E_{cm} in the manner expected for a kinematic reflection arising from D^{*0} pair production followed by the decay of

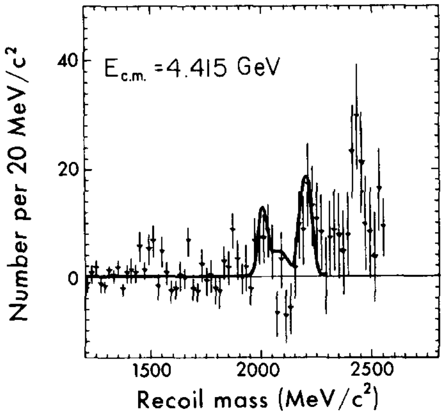

Fig. 2. The $D^0 \to K^- \pi^+$ recoil spectrum at E_{cm} = 4.415 GeV. The curve corresponds to the same D and D^* masses as in fig. 1.

D^{*0} to D^0. As discussed below, the detailed shapes of these distributions depend on masses, D^{*0} branching ratios, and contributions from the decay $D^{*+} \to \pi^+ D^0$ [5] In fig. 2 we also note an 0.10 GeV/c^2 wide enhancement at 2.44 GeV/c^2. This enhancement could be due to multibody processes such as $D^*\bar{D}^*\pi$, for example or, alternatively, production of a charmed state of higher mass.

To measure the masses of the charged and neutral D and D^* states and to study D^* decay modes, we have examined in detail the observed D^0 and $D^\pm$ momentum spectra at E_{cm} = 4.028 GeV ‡1 and compared it to a model of D and D^* production. These D^0 and D^+ momentum spectra are presented in figs. 3b and 3c, respectively. The D momentum resolution (± 18 MeV/c) and detection efficiency vary by less than ±10% over the allowed momentum range for both the $K\pi$ and $K\pi\pi$ systems.

The model assumptions are:

(a) All D and D^* production occurs through the two-body reactions

$$e^+e^- \to D\bar{D} \quad (1)$$

$$e^+e^- \to D\bar{D}^* + \bar{D}D^* \quad (2)$$

$$e^+e^- \to D^*\bar{D}^* \quad (3)$$

(b) The allowed D^* decay modes are

$$D^{*0} \to \pi^0 D^0 \quad (4)$$

$$D^{*0} \to \gamma D^0 \quad (5)$$

$$D^{*+} \to \pi^0 D^+ \quad (6)$$

$$D^{*+} \to \gamma D^+ \quad (7)$$

$$D^{*+} \to \pi^+ D^0 \quad (8)$$

(c) D^* decays are isotropic in the D^* rest frame ‡2.

‡1 The uncertainty on the incident energy E_0 is ±2.5 MeV. This is composed of a ±1.4 MeV beam spread due to synchrotron radiation and a 0.1% uncertainty in the absolute SPEAR ring energy calibration. Only the latter can contribute to the uncertainty in our mass values. This uncertainty is not reflected in the errors of the masses quoted in table 1. The present absolute calibration corresponds to a ψ mass of 3.095 GeV/c^2.

‡2 We note that D^*'s produced via reaction (2) are expected, under conventional spin-parity assignments, to decay anisotropically. Monte-Carlo studies indicate, however, that the momentum spectrum obtained with the correct decay distribution differ insignificantly from those obtained assuming isotropic decay, even for the radiative decay.

Table 1
Results from simultaneous fits to the D^0, D^+ momentum spectra at E_{cm} = 4.028 GeV.

	Fit parameter	Normal fit	Isospin constrained fit	Estimated values
Masses in MeV/c^2	M_{D^0}	1864 (1.5) [a]	1862 (0.5) [a]	1863 ± 3 [b]
	M_{D^+}	1874 (2.5)	1873 (2.0)	1874 ± 5
	$M_{D^{*0}}$	2006 (0.5)	2007 (0.5)	2006 ± 1.5
	$M_{D^{*+}}$	2009 (1.5)	2007 (0.5)	2008 ± 3
Branching ratios	BR ($D^{*0} \to \gamma D^0$)	0.45 (0.08)	0.75 (0.05)	0.55 ± 0.15
	BR ($D^{*+} \to \pi^+ D^0$)[c]	–	0.60 ± 0.15	–
	$\frac{\text{BR}(D^+ \to K^-\pi^+\pi^+)}{\text{BR}(D^0 \to K^-\pi^+)}$[c]	–	1.60 ± 0.60	–
D^0 source fractions	$D^0\bar{D}^0$	0.05 (0.03)	0.05 (0.02)	0.05 ± 0.03
	$D^0\bar{D}^{*0} + \bar{D}^0D^{*0}$	0.42 (0.04)	0.34 (0.04)	0.38 ± 0.08
	$D^{*0}\bar{D}^{*0}$	0.47 (0.05)	0.32 (0.05)	0.40 ± 0.10
	$D^{*+}D^-$; $D^{*+} \to \pi^+D^0$	0.03 (0.02)	0.09 (0.04)	0.06 ± 0.05
	$D^{*+}D^{*-}$; $D^{*+} \to \pi^+D^0$	0.03 (0.03)	0.20 (0.07)	0.11 ± 0.10
D^+ source fractions	D^+D^-	0.09 (0.05)	0.09 (0.05)	0.09 ± 0.05
	$D^{*+}D^- + D^{*-}D^+$	0.65 (0.07)	0.58 (0.06)	0.62 ± 0.09
	$D^{*+}D^{*-}$	0.26 (0.08)	0.33 (0.08)	0.29 ± 0.10

[a] Quantities in parentheses are typical statistical errors for a single fit.
[b] Errors quoted include estimated systematic uncertainty.
[c] These values can only be obtained under the assumptions of the isospin constrained fit. The quoted errors do not reflect possible breakdown of these assumptions.

Assumption (a) was tested by including in the assumed D^0 spectrum the three-body process $D^0\bar{D}^0\pi^0$. This process produces a very broad peak centered near 400 MeV/c that is not seen in the data. We estimate that it contributes less than 10% of the D^0 signal. Decay mode (8) complicates the momentum spectra because it couples produced D^{*+} events to observed D^0 events. The masses deduced from our fits indicate that the corresponding $D^{*0} \to D^+\pi^-$ reaction is kinematically forbidden.

D^0 and $D^\pm$ momentum spectra expected under these assumptions, folded with detector resolution, were simultaneously fit to the data by varying the parameters shown in the first column of table 1. The Q-value for decay mode (8) was fixed at 5.7 MeV through our direct measurement [5] of this process. The momentum spectrum for background events was estimated by smoothing the spectrum of the background events discussed above. Fig. 3a illustrates the contributions to the D^0 spectrum from the various processes that were considered in the fits.

The limited statistics, particularly in the D^+ spectrum, preclude the possibility of determining all of the independent parameters describing processes (1–8). Therefore, a second fit to the data was performed with the additional assumptions:

(d) D and D* are produced at E_{cm} = 4.028 GeV in states of pure isospin and the phase space corrections to reactions (1), (2) and (3) follow a p^3 law, where p is the center-of-mass momentum of the D or D*.

(e) Isospin is a good quantum number in pionic decays of D*, and the transition probability for decay mode (7) is 1/4 that of decay mode (5) [e.g. 6]. Phase space corrections for D* decay also behave like p^3, where p is now the momentum of the D in the D* rest frame.

The p^3 dependence follows from the assumption [7] that the D and D* are pseudoscalar and vector particles respectively.

The data were fit under both sets of assumptions with various starting points, background functions, and resolutions in order to study the stability of the results. The solid curves of figs. 3b and 3c show the results of a typical fit of the second type. The typical

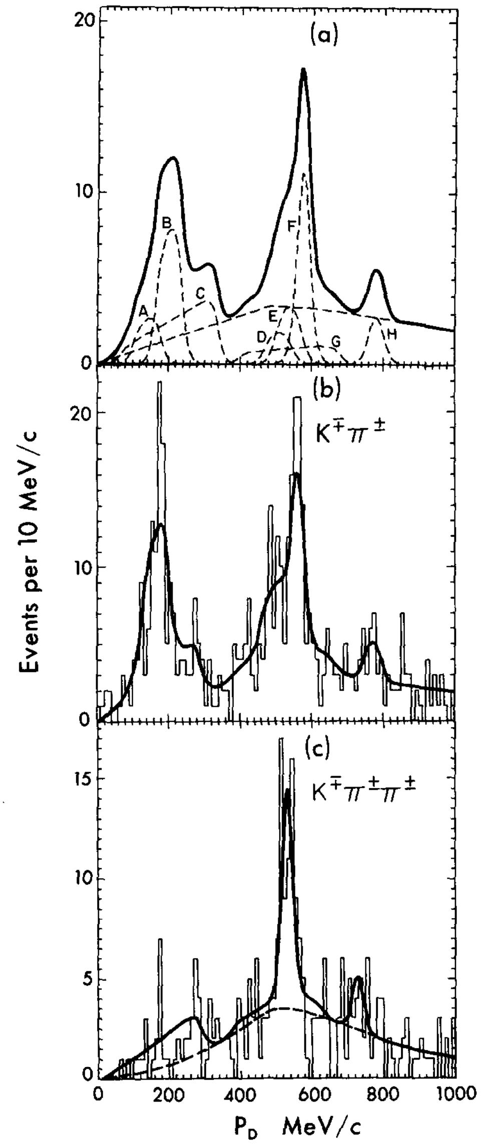

Fig. 3. (a) Illustrative example of the contributions to the expected D^0 momentum spectrum near threshold:

$e^+e^- \to D^{*+}D^{*-}$	,	$D^{*+} \to \pi^+D^0$	(A)
$\to D^{*0}\bar{D}^{*0}$	,	$D^{*0} \to \pi^0D^0$	(B)
$\to D^{*0}\bar{D}^{*0}$	,	$D^{*0} \to \gamma D^0$	(C)
$\to D^{*+}D^-$	,	$D^{*+} \to \pi^+D^0$	(D)
$\to D^{*0}\bar{D}^0$	,	$D^{*0} \to \pi^0D^0$	(E)
$\to \bar{D}^{*0}D^0$		Direct D^0	(F)
$\to D^{*0}\bar{D}^0$	,	$D^{*0} \to \gamma D^0$	(G)
$\to D^0\bar{D}^0$		Direct D^0	(H)

The unlabeled dashed curve corresponds to the smoothed background of uncorrelated $K^-\pi^+$ combinations. (b) $D^0 \to K^-\pi^+$ momentum spectrum at E_{cm} = 4.028 GeV. The solid curve is a typical fit described in text. (c) $D^+ \to K^-\pi^+\pi^+$ momentum spectrum at E_{cm} = 4.028 GeV compared to a typical fit. The dashed curve corresponds to the smoothed background from nonexotic $K\pi\pi$ combinations.

χ^2 per degree of freedom for either fit is 1.2 with about 200 degrees of freedom. Fitted values of the parameters, obtained under the two sets of assumptions, are shown in columns 2 and 3 of table 1. The corresponding quoted errors are statistical errors for a given fit and should not be interpreted as a true measure of the uncertainty of the parameters. We note that the extent of the D^0 contribution due to decay mode (8) is highly model dependent. In fits of the first kind, only 6% of observed D^0's can be attributed to D^{*+} production followed by decay mode (8). In the isospin constrained fits, this fraction increases to 29%. This forces the D^{*0} and D^{*+} masses to be nearly equal in order to match the narrowness of the peak near 180 MeV/c in fig. 3b. It is important to note that the population at low momenta in fig. 3c is too large to be interpreted as just background. Indeed if one restricts the $K\pi\pi$ invariant mass analysis to combinations having momentum less than 320 MeV/c, one finds a three standard deviation peak at the D^+ mass. The natural interpretation of this result is the presence of significant $D^{*+}D^{*-}$ production followed by decays via modes (6) and/or (7).

The decay mode (5) is well established by the data of fig. 3b. The characteristic triangular momentum spectrum below 300 MeV/c (see fig. 3a) and overall structure between 400 MeV/c and 700 MeV/c demand this reaction. The value for BR ($D^{*0} \to \gamma D^0$) determined from the isospin constrained fit is a sensitive function of the assumed ratio

$$S = \Gamma(D^{*+} \to \gamma D^+)/\Gamma(D^{*0} \to \gamma D^0).$$

We have assumed $S = 1/4$, but theoretical estimates [e.g. 6] range from $1/4 \to 1/25$. As S decreases from $1/4 \to 1/16$ the fitted value of BR ($D^{*0} \to \gamma D^0$) increases from 0.75 to 0.90 while no other parameters change appreciably. Values for BR ($D^{*0} \to \gamma D^0$) in excess of 0.75, however, no longer fit the triangular portion of the D^0 momentum spectrum below 300 MeV at all well.

In column 4 of table 1, we present our best estimates of the parameters, taken from the results of our fits, with uncertainty estimates which take account of the degree of model dependence of the fit results.

The relative importance of reactions (1), (2) and (3) for the D^0, D^{*0} channels can be expressed as:

$$D^0\bar{D}^0 : D^0\bar{D}^{*0} + \bar{D}^0 D^{*0} : D^{*0}\bar{D}^{*0}$$

$$0.2 \pm 0.1 : \quad 4.0 \pm 0.8 \qquad 128 \pm 40$$

where a p^3 phase space factor has been explicitly removed. These ratios are to be compared with the spin counting estimates [8] of 1 : 4 : 7, which are in strong disagreement with the data. Various explanations of this behavior have been discussed in the literature [8, 9].

Finally we have established an upper limit on charm events exhibiting apparent strangeness violation; i.e., events where the kaon observed in the recoil system has the same charge as the kaon found in the D^0. This study bears on the question of D^0-$\bar{D}^0$ mixing. Using the time-of-flight kaon identification technique described in ref. [3], we find 77 events in our total data sample with a D^0 (or $\bar{D}^0$) $\rightarrow K^{\mp}\pi^{\pm}$ candidate and an additional kaon in the recoil system. We estimate that 39% of these events correspond to background. In the signal region the two kaons have like charge in 15 events and thus a like charge fraction of 20±5%, while for the background regions we obtain 32±6% for this fraction ‡3. After background corrections we find a like charge fraction of 12±9%. This fraction is consistent with 13%, the fraction obtained by a Monte-Carlo simulation predicated on no D^0-$\bar{D}^0$ mixing, thus suggesting that the 12% apparent strangeness violation is primarily due to residual time-of-flight misidentification. After correcting for this effect, we find that less than 18% of events containing a D^0 exhibit an apparent strangeness violation (90% C.L.).

It has been suggested [e.g. 10] that the presence of first-order $|\Delta C| = 2$ neutral currents would create D^0-$\bar{D}^0$ mixing on time scales considerably shorter than the D^0 lifetime. If this were true, nearly 1/2 of events containing a D^0 would exhibit strangeness nonconservation. Our results clearly rule this out ‡4.

‡3 In spite of the fact that the background is expected to be strangeness conserving, we note that the like charge fraction is larger for the background than for the signal. This is reasonable because misidentified $\pi^+\pi^-$ combinations constitute a major D^0 background source.

‡4 A similar upper limit on D^0-D^0 mixing has been obtained through a study of the reaction $D^{*+} \rightarrow \pi^+ D^0$ [5]. The relationship between these measurements depends in detail on the D^0 production mechanism over the full energy range from 3.9 to 4.6 GeV, which is unknown at present. A discussion of this relationship appears in ref. [11].

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