The Charm Threshold in Electron-Positron Annihilation

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Available data on new mesons discovered at SPEAR is sufficient to determine the spectrum of low-lying charmed mesons and to provide a complete description of the threshold structure of R in the framework of the charmonium model. A number of simple tests are proposed to confirm the charm interpretation.

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⁺Supported in part by the National Science Foundation.

^{*}Supported in part by ERDA Grant No. E (11-1)-2220.

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Recent observation at SPEAR of the reaction $e^+e^- \rightarrow (K^+\pi^- \text{ or } K^-\pi^+\pi^+\pi^-)$ + (recoil, strangeness = ± 1)¹ strongly suggests that the long-awaited charmed mesons have been found. The identified $K\pi$ and $K\pi\pi\pi$ systems appear as 6-7 standard deviation enhancements at 1.865 ± 0.010 GeV, while there are somewhat less significant enhancements in the recoil invariant mass at 2.02 and 2.16 GeV. All of this comes from analysis of data taken in the "threshold region", $3.70 \text{ GeV} \lesssim W \lesssim 4.60 \text{ GeV}$, with little or no evidence for the enhancements at $W \gtrsim 5-6 \text{ GeV}$.

Taken at face value, this new data permits resolution of two important issues: (1) The charmed pseudoscalar D^0 lies at 1.865 GeV, below the vector D^{*0} at 2.02 GeV. (2) The rich structure in R observed between 3.7 and 4.5 GeV is completely consistent with the charmonium model, generalized to include coupling to decay channels. Furthermore, we can estimate masses of all other low-lying charmed mesons, the D^* branching ratios, and the exclusive channel contributions to ΔR , the charmed component of R. We propose a number of tests of this "charm interpretation" of the SPEAR results.

Systematics of Charmed Mesons. As we argue shortly, $M_{D^0} = 1.865$ and $M_{D^{*0}} \simeq 2.020$ GeV. From the quark model, $M_{D^+} - M_{D^0} = M_{K^0} - M_{K^+}$ and $M_{F^+} - M_{D^0} = M_{\phi} - M_{K^*}$. Thus, $M_{D^+} = 1.870$, $M_{D^{*+}} = 2.025$, $M_{F^+} \simeq 2.00$, and $M_{F^{*+}} \simeq 2.15$ GeV. A linear potential model calculation² places the center of gravity of the charmed P-states 550 MeV above the S-states. Spin-dependent splittings among the P-states can be taken from the strange meson system (the reduced masses are reasonably close). The estimated P-state masses are: $D_p(1^1P_1) \simeq 2.5$, $D_{p0}(1^3P_0) \simeq 2.4$, $D_{p1}(1^3P_1) \simeq 2.6$, and $D_{p2}(1^3P_2) \simeq 2.6$ GeV.

These considerations set the following thresholds in e^+e^- annihilation below 4.5 GeV: $W_{DD} = 3.73$, $W_{DD^*} = 3.885$, $W_{FF} = 4.00$, $W_{D^*D^*} = 4.04$, $W_{FF^*} = 4.15$,

$W_{F^*F^*} = 4.30$, $W_{DDP} \sim W_{D^*DP_0} \sim 4.4$, and $W_{DDP_1} \sim 4.5$ GeV.

There is no phase space inhibition for the decay modes: $D_P \rightarrow D^*\pi$, $D_{P0} \rightarrow D\pi$, $D_{P1} \rightarrow D^*\pi$, and $D_{P2} \rightarrow D\pi$, $D^*\pi$, $F^*\bar{K}$.³ However, phase space for $D^* \rightarrow D\pi$ is limited, and $D^* \rightarrow D\gamma$ can be competitive. Note that $F^{*+} \rightarrow F^*\gamma$ is the only observable mode of the $C=S=1$ vector. These are sensitive to all relevant mass differences. We computed $\Gamma(D^* \rightarrow D\pi)$ by two quite different methods: (i) Calculation of the amplitude using the model of Ref. 4; (ii) Assuming $SU(4)$ symmetry and relating to $\Gamma(K^* \rightarrow K\pi)$. Good agreement between the two methods establishes insensitivity to dynamical details. Radiative (M1) transitions are computed from the nonrelativistic quark model.^{2,5} Results are listed in Table I.

Charmed Meson Production in e^+e^- Annihilation. Recently we presented a dynamical model for $e^+e^- \rightarrow$ charmed mesons⁴, based on a universal interaction (linear potential) responsible for both quark binding and hadronic decay. The annihilation cross section is the absorptive part of $\sum_{n,m} (e^+e^- \rightarrow \psi_n + \text{charmed meson pair} \rightarrow \psi_m + e^+e^-)$, with ψ_n a 3S_1 or 3D_1 charmonium level.

General features of this model relevant here are: (1) The basic charmed-meson production process is a sequential two-body one. For example, $e^+e^- \rightarrow D^*\bar{D}^* \rightarrow (D+\pi) + (\bar{D}+\pi)$.⁶ (2) The $\psi_n \rightarrow D\bar{D}$ form factor falls rapidly with increasing D momentum. Thus, any exclusive channel is important only for energies near its threshold. (3) $\sigma_D \equiv \sigma(e^+e^- \rightarrow D^+\bar{D}^-) = \sigma(e^+e^- \rightarrow D^0\bar{D}^0)$, and similarly for $\sigma_{D^*} = \sigma(e^+e^- \rightarrow D^{*+}\bar{D}^-)$ and $\sigma_{D^{*0}} = \sigma(e^+e^- \rightarrow D^{*+}\bar{D}^{*0})$. (4) For $M_D = M_{D^*}$, $\sigma_D : \sigma_{D^*} : \sigma_{D^{*0}} = 1:2:7 + 6(P_{D^*}/M_{D^*})^2 + (P_{D^*}/M_{D^*})^4$. This relation holds reasonably well for unequal masses above $W_{D^*D^*}$. The strongest peak in recoil against D or D^* is the $\bar{D}^*$ (for $W \approx 4.4 - 4.5$ GeV), which implies $M_{D^{*0}} = 2.02$ GeV while $M_{D^0} = 1.865$ GeV. (5) The rate for $\psi_n(c\bar{c}) \rightarrow (c\bar{q}) + (\bar{c}q)$ decreases as m_q^{-4} for $m_c \gg m_q \sim .2-.6$ GeV. Thus F -production is a negligible contribution

to ΔR in the threshold region.

The exclusive cross section ratios $R_D = 2\sigma_D/\sigma_\mu$, $R_{DD^*} = 4\sigma_{DD^*}/\sigma_\mu$, and $R_{D^*} = 2\sigma_{D^*}/\sigma_\mu$ are shown in Fig. 1, along with their approximate sum ΔR . Since charmed P-states were not included, $W_{DD} \leq W \leq 4.3$ GeV.

We now interpret the observed structure of R (Fig. 2) in terms of charm production, suggesting several tests which require only moderate statistics. We use our computations of exclusive channel contributions to R , together with the estimated D^* branching ratios, to indicate the expected outcome of these tests.

The invariant mass M_X recoiling against D^0 and D^+ reveals much about the spectrum of charmed mesons as well as details of various exclusive channels (branching fractions, e.g.). M_X will show strong energy dependence in the threshold region and maximum signal to background requires separate analysis of data from several subregions. We discuss each one in turn:

$3.73 \leq W \leq 3.88$. Clean isolation of the lowest charmed mesons, uncontaminated by γ 's and π 's from D^* and D_P decays, is possible only in this region. The only significant DD signal is at the peak of the 1^3D_1 charmonium level, seen in Fig. 1 at 3.77 GeV. Two 2-standard-deviation bumps ($\Delta R \sim 1.5$) of similar shape, at 3.77 and 3.84 GeV, have been reported.^{7,8} Additional running over this region is required to confirm either as 1^3D_1 . We emphasize that fully 25-40% of all e^+e^- reactions at the peak will yield a pure DD final state.

Discovery of D^+ is crucial, and makes it compelling to determine the 1^3D_1 peak, where its production constitutes half of ΔR . An important test of the charm⁹ and sextet enhancement selection rules¹⁰ is that the only probable ($D^+ \rightarrow$ all charged) transitions are $K^-\pi^+\pi^+$ and $K_S^-\pi^+\pi^+$. Finally, a search for single leptons in the recoil against D measures directly its inclusive

semileptonic/nonleptonic branching ratio and, possibly, tests the $\Delta C = \Delta S$ rule. $3.88 \leq W \leq 4.04$. Opening of $D^* \bar{D}^*$ at 3.88 GeV in Fig. 1 agrees well with the rise observed in the data between 3.90 and 3.97 GeV. The subsequent fall-off, from 3.97 to 4.00 GeV in Fig. 2, is due to $\psi_n \rightarrow D\bar{D}$ form factor effects. There next appears in Fig. 2 a sharp rise of $\Delta R \simeq 3$ at $W = 4.01-4.03$. Since the $D^* \bar{D}^*$ channel is not yet open, this must be interpreted as the 3^3S_1 level. The mass, therefore, is 4.03 GeV.¹¹

In addition to $M_X = M_D$, two new effects leading to overlapping enhancements in M_X now appear. The obvious one is $M_X = M_{D^*} = 2.02$ GeV. The second is a kinematic enhancement corresponding to observation of D in $e^+e^- \rightarrow D^* + \bar{D} \rightarrow D + (\pi + \bar{D})$, and is a consequence of the small pion momentum. For $p_\pi = 75$ MeV in the D^* rest frame, $M_X = M_{D\pi^-}$ lies in the range 2.01 to 2.03 GeV (for $W = 3.90$), 2.00 to 2.06 ($W = 3.95$), and 2.00 to 2.09 ($W = 4.05$). Data taken over this region will show a pile-up at $M_X = 2.00-2.01$. The frequency of events in which $\bar{D} + \pi$ recoils against D relative to those in which $\bar{D}^*$ does is $B_{\pi^0}^{D^0} + B_{\pi^+}^{D^+} \simeq 1.1$ if D^0 is observed, and $B_{\pi^-}^{D^0} + B_{\pi^0}^{D^+} \simeq 0.6$ if D^+ is. [Our notation is $B_{\pi^-}^{D^0} = \Gamma(D^{*0} \rightarrow \pi^- D^+)/\Gamma(D^{*0})$, etc.]. Once D^* production becomes important, there will be a substantial increase in the fraction of slow pions, $p_\pi^{\text{lab}} \lesssim 100-150$ MeV and $x = p_\pi^{\text{lab}}/W \lesssim 0.04$.¹²

A method of searching for D^+ in this region is to select D^0 events with $\bar{D}^{0*}$ in recoil. Approximately one-third of these have $\bar{D}^{0*} \rightarrow D^- \pi^+$, with $p_\pi^{\text{lab}} \lesssim 100$ MeV. There should be a D^- signal in the recoil against $D^0 + \text{slow } \pi^+$.

$4.04 \leq W \leq 4.35$. The model calculation shows that $D^* \bar{D}^*$ production, influenced by the nearby 3^3S_1 pole, contributes a large and rapid rise to R . When compared with the rise beginning at ~ 4.05 GeV in Fig. 2, it is clear that the points from there to 4.3 represent the opening and subsequent decay of this channel. The

absence of further clear thresholds in this region is consistent with the quark-mass suppression of F and F^* production mentioned above. The $\bar{D}D_p$ channel, expected to have a strong S-wave threshold, presumably does not open below ~ 4.4 GeV.

A new kinematic enhancement appears at 2.16 GeV corresponding to $\bar{D}^* + \pi$ recoiling against D . For $p_\pi = 75$ MeV in the D^* rest frame, $2.16 \leq M_x \leq 2.21$ at $W = 4.10$ GeV, and $2.16 \leq M_x \leq 2.27$ at $W = 4.30$. For $p_\pi = 50$ MeV, the allowed ranges are 2.16 to 2.19 GeV ($W = 4.10$), and 2.17 to 2.24 ($W = 4.30$). $\bar{D}^* + \gamma$ recoiling against D has a much broader M_x -distribution ($2.12 \leq M_{\bar{D}^*\gamma} \leq 2.22$ at $W = 4.1$) and does not accumulate at any particular energy for data taken over this region.

Measuring the relative strengths of various enhancements not only tests our interpretation of the data, but proves useful in extracting branching ratios and exclusive cross sections. We mention two examples:

(1) The ratio of events with $\bar{D}^* + \pi$ recoiling against D to those with $\bar{D}^*$ in recoil is

$$N(\bar{D}^* \pi \text{ against } D^0)/N(\bar{D}^* \text{ against } D^0) = 2(B_{\pi^0}^0 + B_{\pi^+}^+)R_{D^*}/R_{DD^*}, \quad (1)$$

A similar expression holds for D^+ . Integrated over this region, we find that the relative strength of the two enhancements opposite D^0 is $\sim 3.7:1$. The integrated ratio for recoil against D^+ is $\sim 2.1:1$. The $\bar{D}^* + \pi$ kinematic effect is now quite broad and should not seriously contaminate identification of true $\bar{D}^*$.

(2) If D^0 is observed through its decay mode f , then D^{*+} should be seen in $f + \pi^+$. The expected relative frequencies are

$$\begin{aligned} \rho_+ &\equiv N(D^{*+} \rightarrow \pi^+ + f)/N(D^0 \rightarrow f) \\ &= B_{\pi^+}^+(R_{DD^*}/2 + R_{D^*})/[R_D + R_{DD^*}/2 + (B_{\pi^+}^+ + B_{\pi^0}^0 + B_Y^0)(R_{DD^*}/2 + R_{D^*})] \end{aligned} \quad (2)$$

A similar formula gives $\rho_0 = N(D^{*0} \rightarrow \pi^- + f)/N(D^+ \rightarrow f)$.

Onset and decay of various thresholds give ρ_+ and ρ_0 strong energy dependence. We find $\rho_+ \simeq 0.1$ to 0.2 for $3.9 \lesssim W \lesssim 4.04$, followed by a sharp rise to 0.4 , maintained from 4.04 to 4.35 GeV. Integrated over 3.88 - 4.35 GeV, the ratio of $(D^{*+} + \pi^+ f)$ to $(D^0 + f)$ events is $\simeq 0.37$. ρ_0 jumps from 0.1 below 4.04 GeV to 0.33 above; the integrated ratio of $(D^{*0} + \pi^- f)$ to $(D^+ + f)$ events is 0.30 .

$4.35 \leq W \leq 4.60$. Assignment of 3^3S_1 at 4.03 GeV forces our reinterpretation⁴ of the 4.4 GeV structure¹³ (Fig. 2) as the 4^3S_1 level: (i) 4.41 - $4.03 \simeq 400$ MeV is consistent with the charmonium separation $M(4^3S_1) - M(3^3S_1)$, not with $M(4^3S_1) - M(2^3D_1)$. (ii) $\Gamma_e(4.4) \simeq 0.4$ keV implies $|\psi_{4.4}(0)|/|\psi_{3.1}(0)| \simeq 0.4$, too large for a 3^3D_1 state.¹⁴ Beware that nonrelativistic level designation may be meaningless by now. The important test that this is a charmonium level is a sharp increase in D-production at $\psi(4.4)$.

Charmed P-states, if not very broad, will show in recoil against D, D^* at these higher energies. Further signals are:

- (i) Sudden jumps in ρ_+ and ρ_0 (generalized to include these new channels).
- (ii) The slow-pion effect diminishes as the $D^* \bar{D}^*$ channel does, until $W \gtrsim W_{D^* \bar{D}^*}, W_{D^* \bar{D}^0}$ when slow D^* 's are produced once again.
- (iii) A search for $\bar{D}_p$ opposite D at $\psi(4.4)$ is worthwhile.

The foregoing considerations demonstrate that much remains to be done at SPEAR to determine the nature of the new quantum number and map out the newest spectroscopy.

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3. We assume that P-state widths are not so great as to wash out their threshold effects. If SU(4) symmetry may be used to determine their widths from those of the strange P-states, we get: $\Gamma(D_P) \simeq \Gamma(D_{PD}) \simeq 90$ MeV, $\Gamma(D_{P1}) \simeq 75$ MeV, and $\Gamma(D_{P2}) \simeq 30$ MeV.
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Decays leading to $K^- \pi^+ \pi^+$ are $D^+ \rightarrow \pi^+ \overline{K^{*0}}$, $D^+ \rightarrow \pi^+ \overline{\kappa^0}(1300)$, while
 $D^+ \rightarrow \pi^+ \overline{K^{*0}}(1400) \rightarrow \pi^+ K_S^0 \pi^+ \pi^-$. If sextet enhancement is correct, D^+ has
considerably fewer Cabibbo-favored nonleptonic decay modes than does D^0 .
Consequently, these modes have appreciable branching fractions. We estimate
the ratio of events with D^+ to those with D^0 to be 1.0 for $3.73 \leq W \leq 3.88$,
 ~ 0.75 at $W = 4.03$, and ~ 0.62 for data uniformly taken between 3.73 and
4.30 GeV. It will be difficult to explain a D^+ signal much weaker than D^0 .
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	$D^{*+} \rightarrow D^0 \pi^+ \quad D^+ \pi^0 \quad D^+ \gamma$			$D^{*0} \rightarrow D^+ \pi^- \quad D^0 \pi^0 \quad D^0 \gamma$		
Momentum (MeV)	75	73	149	53	73	149
Rate (keV)	182	84	4.5	64	84	54
Branching Ratio	.67	.31	.02	.32	.42	.27

Table I. Final particle momenta, decay rates, and branching ratios for D^* decays, calculated with the model of Ref. 4. Branching fractions obtained from the SU(4) assumption are: .66, .31, and .03 for D^{*+} ; .27, .36, and .37 for D^{*0} . $\Gamma(F^{*+} \rightarrow F^+ + \gamma) = 1.6$ keV.

Figure Captions

- Fig. 1. Charm component ΔR (heavy solid line) for $W \leq 4.3$ GeV, and its dominant exclusive contributions: R_D (small dashed), R_{D^*} (large dashed), and R_{D^*} (light solid). Parameters for this model calculation are given in Ref. 4.
- Fig. 2. SLAC/LBL data for R from Ref. 7.

Figure 1

Figure 2