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Semileptonic decays of charmed mesons produced in electron-positron annihilation*

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In this paper we study a few models for the inclusive semileptonic decays as well as a few exclusive decays of the charmed meson $D(1865)$, recently discovered at SPEAR. We calculate the electron distributions for the sequence $e^+ + e^- \to \bar{D}^* + D \to \bar{D} + \pi + D$ followed by $D \to e + \nu + \cdots$, at the center-of-mass energy 4.1 GeV. The results are compared with the recent findings of a DESY experiment carried out at center-of-mass energies between 4.0 and 4.2 GeV by Braunschweig *et al*. We conclude that $D \to e + \nu + K^*$ is most likely the dominant semileptonic decay mode of the D meson. Furthermore, the decay structure for $D \to e + \nu + K^*$ favors a *phenomenological* $(V + A)(V - A)$ form, as is dictated by an underlying charm scheme. This may be viewed as an indirect, and another partial confirmation of the weak-interaction scheme of charm. We also present results for dilepton production, for the afore-mentioned sequence of production and decay. The lepton distributions for the sequence of $e^+ + e^- \to D^+ + D^-$ followed by $D \to e + \nu + K^*$ (or K), at the center-of-mass energy 3.9 GeV, is also calculated.

I. INTRODUCTION

The newly discovered weakly decaying hadrons[1,2] fit very well with predicted spectroscopy of the charm scheme.[3] However, urgently needed is the experimental verification of the weak-interaction properties and, in particular, the semileptonic decay properties of the charm scheme. Also needed is an understanding of the *inclusive* semileptonic decays and the identification of dominant semileptonic decay modes of the charmed hadrons.

Since charmed hadrons are most likely to be the source of the multileptonic events observed in high-energy neutrino and muon scattering processes,[4] information can be derived from these events concerning the decay properties of the charmed hadrons. Recently, evidence was reported by Braunschweig *et al.*[5] of semileptonic decays of the charmed meson $D(1965)$ produced in e^+e^- annihilation. Since the production of D in e^+e^- annihilation, slightly beyond threshold, is a simple mechanism theoretically, the lepton events observed in e^+e^- annihilation should in principle provide a better chance for a clean analysis of the semileptonic decay modes of the charmed D meson.

In this paper we study the semileptonic decays of $D(1865)$. We consider two models for the inclusive semileptonic decay

$$D \to e(\mu) + \nu + X \tag{1}$$

as well as the *exclusive* semileptonic decays

$$D \to e(\mu) + \nu + K, \tag{2}$$

and

$$D \to e(\mu) + \nu + K^*. \tag{3}$$

To compare with the recent DESY result of Braunschweig *et al.*,[5] we have calculated the electron energy spectrum, for these decays, in the process

$$\begin{array}{l} e^+ + e^- \to \bar{D}^* + D \\ \qquad\qquad\quad D \to e(\mu) + \nu + \cdots \\ \qquad \bar{D}^* \to \bar{D} + \pi \text{ (or } \gamma) \\ \qquad\qquad \bar{D} \to e(\mu) + \nu + \cdots \end{array} \tag{4}$$

for the e^+e^- center-of-mass energy at 4.1 GeV. Our result suggests that $D \to e + \nu + K^*$ *is the dominant semileptonic decay mode of D, and that the structure of the decay matrix element is in accord with the underlying weak-current structure*[6] *of the charm scheme.*

In Sec. II we present the models for the inclusive semileptonic decays of D. In Sec. III we consider $D \to e + \nu + K$, and in Sec. IV, $D \to e + \nu + K^*$. We discuss the production of D and D^* in e^+e^- annihilation in Sec. V. Numerical results for single-lepton and dilepton distributions for the process (4) are presented in Sec. VI. In Sec. VII, we present the results for

$$\begin{array}{l} e^+ + e^- \to \bar{D} + D \\ \qquad\qquad D \to e(\mu) + \nu + \cdots \\ \qquad\quad \bar{D} \to e(\mu) + \nu + \cdots \end{array} \tag{5}$$

at center-of-mass energy 3.9 GeV. Some discussions are given in Sec. VIII.

II. MODELS FOR INCLUSIVE SEMILEPTONIC DECAYS OF D

Models A and A′

The simplest model for the inclusive semileptonic decays of D corresponds to the decay of the underlying charmed quark according to the charm scheme,[6]

$$\bar{c} \to \bar{\lambda} + e^-(\mu^-) + \bar{\nu}\,,$$

with, however, the quark masses for $\bar{c}$ and $\bar{\lambda}$ taken to be the physical masses M_D and M_K, respectively. According to the charm scheme, the effective Lagrangian for the two decays

$$\mu^- \to \nu_\mu + e^- + \bar{\nu}_e$$

and

$$\lambda \to c + e^- + \bar{\nu}_e$$

is given by

$$\mathcal{L}_{\text{eff}} = (G/\sqrt{2})[\bar{\nu}_\mu \gamma^\alpha (1-\gamma_5)\mu + \cos\theta_C \bar{c}\gamma^\alpha(1-\gamma_5)\lambda] \times \bar{e}\gamma_\alpha(1-\gamma_5)\nu_e\,, \qquad (6)$$

which can also be written, in terms of the charge conjugates c^c and λ^c,

$$\mathcal{L}_{\text{eff}} = (G/\sqrt{2})[\bar{\nu}_\mu \gamma^\alpha (1-\gamma_5)\mu - \cos\theta_C \bar{\lambda}^c \gamma^\alpha(1+\gamma_5)c^c] \times \bar{e}\gamma_\alpha(1-\gamma_5)\nu_e\,. \qquad (6')$$

It is clear from (6′) that the effective coupling for the decay $\bar{c} \to \bar{\lambda} + e^- + \bar{\nu}$ is of a $(V+A)(V-A)$ structure, corresponding to a Michel parameter of $\frac{1}{2}$, instead of $\frac{3}{4}$ as for muon decay, for the electron momentum spectrum.

In this model, the lepton spectrum for the inclusive process

$$D(P_D) \to e(p_e) + \nu + X \qquad (1')$$

is thus given by (model A)

$$E_e \frac{d\Gamma}{d^3p_e} = \frac{G^2\cos^2\theta_C}{16\pi^4 E_D}(M_D{}^2 - Q^2)\frac{(Q^2 - M_K{}^2)^2}{Q^2}\,,$$

where

$$Q^2 = M_D{}^2 - 2(P_D\cdot p_e)\,.$$

For completeness, the width Γ is given below:

$$\Gamma = \frac{G^2\cos^2\theta_C}{16\pi^4 E_D} F\,, \qquad (7)$$

where

$$F = 16\pi M_D{}^6\left\{\left(\frac{M_D{}^2 - 2M_K{}^2}{6M_D{}^2}\right)\left(\frac{M_D{}^2 - M_K{}^2}{2M_D{}^2}\right)^3 - \frac{1}{4}\left(\frac{M_D{}^2 - M_K{}^2}{2M_D{}^2}\right) - \left(\frac{M_K{}^2}{2M_D{}^2}\right)^2\left[\frac{3}{8} + \frac{1}{4}\ln\frac{M_K{}^2}{M_D{}^2} - \frac{M_K{}^2}{2M_D{}^2} + \frac{1}{2}\left(\frac{M_K{}^2}{2M_D{}^2}\right)^2\right]\right\}. \qquad (8)$$

To contrast with the "effective" $(V+A)/(V-A)$ structure implied by the charm scheme,[6] we also give the formula for the $(V-A)(V-A)$ structure in the following (model A′):

$$E_e \frac{d}{d^3p_e} = \frac{G^2\cos^2\theta_C}{16\pi^4 E_D}\,\frac{1}{6}\left(\frac{Q^2 - M_K{}^2}{Q^2}\right) \times\left[(Q^2 - M_K{}^2)(M_D{}^2 - Q^2) + \left(\frac{Q^2 + 2M_K{}^2}{Q^2}\right)(M_D{}^4 - Q^4)\right],$$

where again $Q^2 = M_D{}^2 - 2(P_D\cdot p_e)$. The corresponding width Γ is identical to (7).

We remark that the spectrum (A), as compared with the spectrum (A′), contains more low-energy electrons. We also remark that according to the numerical results to be presented in Sec. VI both (A) and (A′) contain excessive high-energy electrons as compared with the DESY results, and are, therefore, not good models for the inclusive process $D \to e + \nu + X$.

Models B and B′

In models A and A′, we have essentially assumed that the invariant mass M_X of the final hadrons in $D \to e + \nu + X$ is fixed at M_K. This is definitely a simple-minded assumption. Excessive high-energy electrons contained in these models, as compared with experiment (to be discussed Sec. VI), means that this simple-minded assumption is physically not a good one. To improve on this, we allow for a spectrum of the final-hadron invariant mass. Let $\rho(m^2)$ be the spectral weight. Then the electron distribution is given, in the effective $(V+A)(V-A)$ case, by (model B)

$$E_e \frac{d\Gamma}{d^3p_e} = \frac{G^2\cos^2\theta_C}{16\pi^4 E_D} \times\int_{M_K{}^2}^{Q^2}(M_D{}^2 - Q^2)\frac{(Q^2 - m^2)^2}{Q^2}\rho(m^2)dm^2$$

and, in the case of effective $(V-A)(V-A)$, by (model B′)

$$E_e \frac{d\Gamma}{d^3p_e} = \frac{G^2\cos^2\theta_C}{16\pi^4 E_D}\int_{M_K^2}^{Q^2}\frac{1}{6}\left(\frac{Q^2-m^2}{Q^2}\right)^2\left[(Q^2-m^2)(M_D^2-Q^2)+\left(\frac{Q^2+2m^2}{Q^2}\right)(M_D^4-Q^4)\right]\rho(m^2)dm^2 .$$

where

$$Q^2 = M_D^2 - 2(P_D\cdot p_e).$$

The spectral function $\rho(m^2)$ according to our definition has the dimension of (mass)$^{-2}$. In the spirit of scaling, we assume

$$\rho(m^2)\propto m^{-2}. \tag{9}$$

With this assumption, the m^2 integration can be carried out in (B) and (B′). However, the results will not be presented.

With the incorporation of the final-hadron mass spectrum, the agreement with DESY results,[5] as will be seen in Sec. VI, becomes improved. Again, the effective $(V+A)(V-A)$ structure offers better agreement than $(V-A)(V-A)$, although the agreement is still not too good.

III. $D\to e+\nu+K$

The decays $D\to e+\nu+K$ are similar to $K\to e+\nu+\pi$. Simple SU(4) consideration[7] leads to, according to the charm scheme, the following ratios of the decay coupling constants:

$$(K^+\to\pi^0):(D^0\to K^-):(D^+\to\bar{K}^0) = \sin\theta_C/\sqrt{2}:\cos\theta_C:\cos\theta_C. \tag{10}$$

The matrix elements for both D decays are identical. With the momentum variables as indicated in

$$D(P)\to e(p)+\nu(p')+K(k), \tag{11}$$

the matrix element is of the form

$$(D\to K) = \cos\theta_C(G/\sqrt{2})f(q^2)(P+k)^\mu l_\mu , \tag{12}$$

where l_μ represents the lepton current, and $f(q^2)$ represents the form factor, which we choose to be

$$f(q^2) = (1-q^2/M_{F^*}^2)^{-1}, \quad M_{F^*}\sim 2.2\text{ GeV}. \tag{13}$$

We remark that we have neglected a $(P-k)$ term in the matrix element, which gives rise to a contribution proportional to the lepton mass.

In the rest frame of D, the double energy spectrum is given by

$$\frac{d\Gamma}{dE_e\,dE_k} = \cos^2\theta_C(G/\sqrt{2})^2(4\pi^3)^{-1}f^2(q^2) \times M_D[4E_e(M_D-E_e-E_K)-q^2]. \tag{14}$$

where

$$q^2 = M_D^2 + M_K^2 - 2M_D E_K .$$

The limits for the energy variables are the following:

$$\frac{(M_D-2E_e)^2+M_K^2}{2(M_D-2E_e)} \le E_K \le \frac{M_D^2+M_K^2}{2M_D}, \tag{15}$$

$$0\le E_e \le (M_D^2-M_K^2)/(2M_D). \tag{16}$$

The energy spectra will be presented in Sec. VI, with the production distribution of D taken into account. We report here only that numerical computation yields the following decay width:

$$\Gamma(D^0\to e^+K^-) = (0.19)\cos^2\theta_C G^2 M_D^5/(192\pi^3) \sim 9.5\times 10^{-11}\text{ MeV}. \tag{17}$$

For comparison, we have also calculated $D\to e+\nu+\pi$. We only report the total width here. Using $f(g^2) = (1-q^2/M_{D^*}^2)^{-1}$ with $M_{D^*}=2$ GeV, we obtain the following numerical result, according to the charm scheme:

$$\Gamma(D^0\to e^+\nu\pi^-) = (0.39)\sin^2\theta_C G^2 M_D^5/(192\pi^3) \sim 9.4\times 10^{-12}\text{ MeV}. \tag{18}$$

The phase space favors the rate of $D^0\to e^+\nu\pi^-$ over $D^0\to e^+\nu K^-$ by a factor of $(0.39)/(0.19) = 2.05$.

IV. $D\to e+\nu+K^*$

Of all the semileptonic decays of D, this is probably the most important one. The arguments are the following: (i) In the e^+e^- annihilation experiment,[1] in which the charmed meson D is discovered, it is found that the production of $\bar{D}D^*$ dominates over the production of $\bar{D}D$. This means that the $\bar{D}D^*$ coupling is much stronger than $\bar{D}D$. We therefore expect that the weak vertices would behave likewise. That is, $D\to e\nu K^*$ should be much more important than $D\to e\nu K$. (ii) There is the theoretical argument,[8] based on current-algebra and soft-pion hypotheses, suggesting that $(D\to e\nu K+\pi\text{'s})$ is not important. (iii) Although there is no theoretical indication concerning the strength of the weak $D\to K^{**}$ (1420) transition, one may expect a suppression of the rate because of the small phase space. (iv) Phenomenologically, as we shall see in Sec. VI, the observed electron energy spectrum of Braunschweig *et al.*[5] agrees well with the calculated spectrum for $D\to e+\nu+K^*$, if the transition matrix element is chosen in accordance with the underlying charm scheme.

As we have pointed out in Sec. II, according to the charm scheme[6] the quark decay $\bar{c}\to\bar{\lambda}+e^-+\bar{\nu}$ has an effective $(V+A)(V-A)$ structure. At the phenomenological level, this should be reflected in the decays of the charmed hadrons. That is, the charm scheme predicts a $(V+A)$, or a right-handed current structure for the weak transition $D\to K^*$. We shall in the following refer to this as "normal," and the $(V-A)$ or the left-handed combination as "anomalous."

For the two decays

$$D^-(\bar{D}^0)\to e^- + \bar{\nu} + K^{*0}(K^{*+}) \tag{19}$$

the matrix elements are identical. With the momentum variables as indicated in (and ϵ_μ the polarization vector K^*)

$$D(P)\to e^-(p) + \bar{\nu}(p') + K^*(k)\,, \tag{20}$$

the matrix element we write in the form

$$\mathfrak{M}(D\to K^*) = \cos\theta_C(G/\sqrt{2}) \times a[f_V(g^2)\tilde{K}^{\mu\nu} + f_A(q^2)K^{\mu\nu}]q_\nu l_\mu\,, \tag{21}$$

where $q=P-k$, l_μ is the leptonic current, and

$$\begin{aligned} K^{\mu\nu} &= k^\mu\epsilon^\nu - k^\nu\epsilon^\mu\,,\\ \tilde{K}^{\mu\nu} &= (2i)^{-1}\epsilon^{\mu\nu\lambda\rho}K_{\lambda\rho}\,. \end{aligned} \tag{22}$$

For a discussion of the matrix element, see Appendix A. We shall neglect the symmetry-breaking and renormalization effects, and note the following correspondence:

$$f_A = \begin{cases} f_V\,, & \text{right-handed (normal)} \\ -f_V, & \text{left-handed (anomalous)}\,. \end{cases} \tag{23}$$

This correspondence we shall explicitly illustrate in Appendix B.

We shall take, with $M_{F^*}=2.2$ GeV,

$$f_V(q^2) = |f_A(q^2)| = (1-q^2/M_{F^*}{}^2)^{-1}\,. \tag{24}$$

The parameter a in (21) can be estimated by relating, through SU(4), to $\Gamma(\omega\to\pi\gamma)$. We thus obtain

$$a \sim 6\ \text{GeV}^{-1}. \tag{25}$$

The differential decay spectrum, in the rest frame of D, is given by

$$d\Gamma(D\to K^*) = \frac{1}{2M_D}\sum_{\text{spins}}|\mathfrak{M}(D\to K^*)|^2 \frac{d^3p}{2E_e(2\pi)^3}\frac{d^3p'}{2E_\nu(2\pi)^3}\frac{d^3k}{2E_{K^*}(2\pi)^3}(2\pi)^4\delta^4(P-p-p'-k)\,, \tag{26}$$

where

$$\begin{aligned} \sum_{\text{spins}}|\mathfrak{M}(D\to K^*)|^2 &= \cos^2\theta_C G^2(8a^2)\{f_V{}^2(q^2)[2(k\cdot p')(k\cdot q)(p\cdot q) + 2(k\cdot p)(k\cdot q)(p'\cdot q) - 2(k\cdot p)(k\cdot p')q^2 - 2M_{K^*}{}^2(p\cdot q)(p'\cdot q)] \\ &\quad + f_A{}^2(q^2)[2(k\cdot p')(k\cdot q)(p\cdot q) + 2(k\cdot p)(k\cdot q)(p'\cdot q) - 2(k\cdot p)(k\cdot p')q^2 + M_{K^*}{}^2(p\cdot p')q^2] \\ &\quad + 4f_V(q^2)f_A(q^2)[(k\cdot p)(k\cdot q)(p'\cdot q) - (k\cdot p')(k\cdot q)(p\cdot q)]\}\,, \end{aligned} \tag{27}$$

The total decay width is given in the rest frame of D, for both $f_A=f_V$ and $f_A=-f_V$, by

$$\Gamma(D\to e\nu K^*) \simeq 3.2\times10^{-3}\cos^2\theta_C(aM_D)^2[G^2M_D{}^5/(192\pi^3)] \simeq (aM_D)^2\times1.6\times10^{-12}\ \text{MeV}. \tag{28}$$

If we use the estimated value $a\sim 6$ GeV^{-1} given in (25), the calculated width is $\sim2\times10^{-10}$ MeV. Recall that, according to (17), $\Gamma(D^-\to e^-\bar{\nu}K^0)\sim10^{-10}$ MeV. There is some room for adjusting the parameter a (see, however, Appendix A).

V. PRODUCTION OF D AND D^* IN e^+e^- ANNIHILATION

The mass of the charmed pseudoscalar meson D is 1.86 GeV, and the mass of the charmed vector meson D^* is 2.0 GeV. The DESY experiment[5] is carried out at the center-of-mass energies between 4.0 to 4.2 GeV. The conceivable charm-producing channels are $\bar{D}D, \bar{D}^*D, \bar{D}^*D^*$, and the emission of accompanying pions. From the results of a SLAC experiment, run at similar energies, it seems that DD^* is the most prominent production channel. We will therefore assume the dominance[9] of the D^*D production channel in the DESY e^+e^- annihilation experiment, the energy range for which is from 4.0 to 4.2 GeV, and calculate the following sequence of reactions[10]:

$$\begin{aligned} & e^+ + e^- \to \bar{D}^* + D\,, \quad D \to e+\nu+\circ\circ\circ \\ & \bar{D}^* \to \bar{D}+\pi\ (\text{or } \gamma)\,, \quad \bar{D} \to e+\nu+\cdots\,. \end{aligned} \tag{29}$$

For simplicity, we will only give the numerical result for a fixed center-of-mass energy 4.1 GeV, to be shown in Sec. VI, and assume that it is representative of the (4.0–4.2)-GeV range.

With the $\gamma\bar{D}^*D$ vertex described by

$$\mathcal{L}_{\text{eff}} = g\epsilon^{\mu\nu\lambda\rho}F_{\mu\nu}D^*_{\lambda\rho}D\,,$$

the production cross section can be easily calculated. It is given by

$$\frac{d\sigma}{d\Omega}(e^+e^- \to \bar{D}^*D) = \frac{2}{\pi}\alpha g^2\beta^3(1+\cos^2\theta), \qquad (30)$$

where, with s representing (center-of-mass energy)^2,

$$\beta^2 = [s-(M_{D^*}+M_D)^2][s-(M_{D^*}-M_D)^2]/s^2. \qquad (31)$$

In the following, we also give the expression for $e^+e^- \to D^+D^-$:

$$\frac{d\sigma}{d\Omega}(e^+e^- \to D^+D^-) = \frac{\alpha^2}{2}\beta^3\sin^2\theta, \qquad (32)$$

where the corresponding β is $(E^2-M_D{}^2)^{1/2}/E$.

In order to study the decay properties of D, it is desirable to have an *exclusive* production channel for which the production mechanism is firmly understood and there is no contamination from other production channels. The production of D^+D^- at center-of-mass energies less than $2M_D+M = 3.87$ GeV is such a case. We will present the numerical result, in Sec. VII, for

$$\begin{aligned} e^+ + e^- &\to \bar{D} + D \\ &\qquad\quad \searrow e(\mu) + \nu + \cdots \\ &\searrow e(\mu) + \nu + \cdots . \end{aligned} \qquad (33)$$

VI. PRODUCTION OF $\bar{D}^*D$ AND SUBSEQUENT DECAYS

The results of the last few sections can be easily combined[11] to yield the single-lepton and dilepton distribution for

$$\begin{aligned} e^+ + e^- &\to \bar{D}^* + D \\ &\qquad\quad \searrow e(\mu) + \nu + \cdots \\ &\searrow \bar{D} + \pi \text{ (or } \gamma) \\ &\qquad \searrow e(\mu) + \nu + \cdots . \end{aligned} \qquad (34)$$

As has been discussed in Sec. V, we assume the dominance of the production channel $\bar{D}^*D$ for the energy range 4.0–4.2 GeV of the DESY experiment.[5] We have chosen 4.1 GeV as a representative energy, and present numerical results in the e^+e^- center-of-mass frame for the various models and decays discussed in Secs. II–IV. In the numerical computation, we have also imposed an angular cut, $|\cos\theta| \leq 0.6$, corresponding to the angular acceptance of the DESY experiment.[5]

In Fig. 1 is shown the calculated electron spectrum[12] for the two inclusive decay models A and B given in Sec. II. Both of these models have the normal $(V+A)(V-A)$ structure. The data points are taken from Braunschweig *et al.*[5] It is seen that the agreement is not good. The experimental spectrum peaks toward the low-energy region.

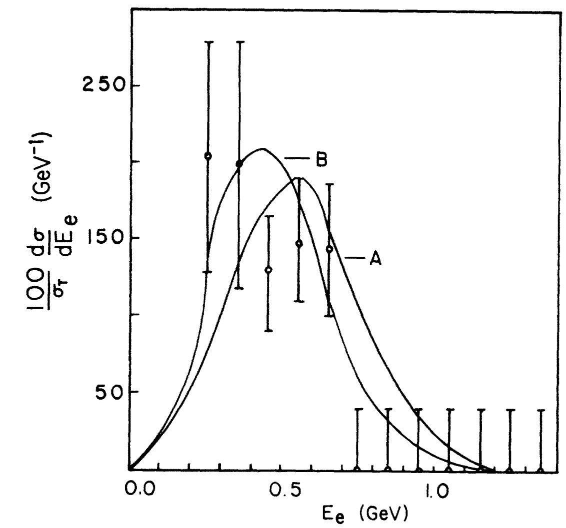

FIG. 1. Electron energy spectrum in the semileptonic decay of D (or $\bar{D}$). The data points are taken from Ref. 5. The two curves A and B correspond to the inclusive decay models A and B, respectively, considered in Sec. II, for the D or $\bar{D}$ mesons produced in $e^+ + e^- \to \bar{D} + D^* \to \bar{D} + D + \pi$ with the beam energy at 2.05 GeV. Normalization of data points is arbitrary.

We have also computed the spectrum for the models A′ and B′, both of which have an anomalous $(V-A)(V-A)$ structure. The calculated spectra are more energetic than the corresponding normal $(V+A)(V-A)$ spectra. Their agreement with the measured spectrum is worse. We have not presented the numerical results for these anomalous models A′ and B′.

In Fig. 2 is shown the calculated electron spectrum[12] resulting from the exclusive decay $D \to e + \nu + K$, which we presented in Sec. III. As expected, its agreement with experiment is not good.

We present the results[12] for the exclusive decay $D \to e + \nu + K^*$ in Fig. 3. The two curves correspond to the two choices, the normal $(V+A)(V-A)$ structure and the anomalous $(V-A)(V-A)$ structure. The spectrum corresponding to the normal structure peaks more toward the low-energy end and is seen to agree very well with the measured expectrum toward the lower energy. In contrast, the spectrum corresponding to the anomalous structure peaks at higher energy and disagrees with the experimental spectrum. The structure around 0.6 GeV is conceivably due to $D \to e + \nu + K$.

In Fig. 4 we superimpose $D \to e + \nu + K^*$ and $D \to e + \nu + K$ with a relative branching ratio of 3:1. The data seem to be well represented by this combination.

We have calculated the angular distribution of the electron[12] for $D \to e + \nu + K^*$ in (34). The dis-

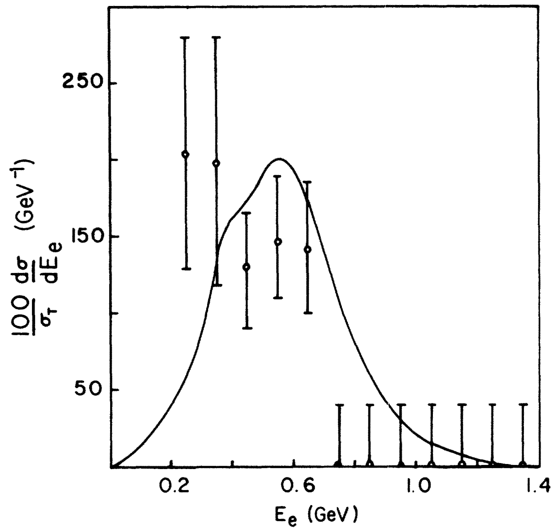

FIG. 2. Calculated electron energy spectrum for $D \to e + \nu + K$, where the charmed mesons are produced in $e^+ + e^- \to \bar{D} + D^* \to \bar{D} + D + \pi$, with the beam energy at 2.05 GeV. The data points are taken from Ref. 5.

tribution is essentially flat in $\cos\theta$, consistent with the experimental finding. It is shown in Fig. 5.

It thus seems that $D \to e + \nu + K^*$ is likely to be the dominant semileptonic decay mode of D. There is

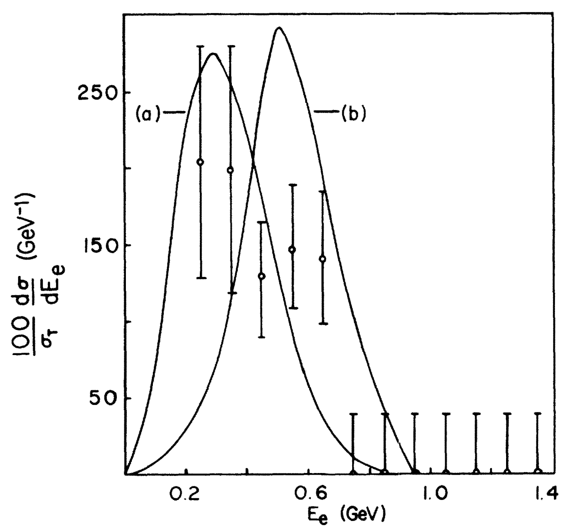

FIG. 3. Calculated electron energy spectrum for $D \to e + \nu + K^*$, where the charmed mesons are produced in $e^+ + e^- \to \bar{D} + D^* \to \bar{D} + D + \pi$, with the beam energy at 2.05 GeV. Curve (a) corresponds to the normal, i.e., effective $(V+A)(V-A)$, structure. Curve (b) corresponds to the anomalous, i.e., effective $(V-A)(V-A)$, structure. The data points are taken from Ref. 5, normalization being arbitrary.

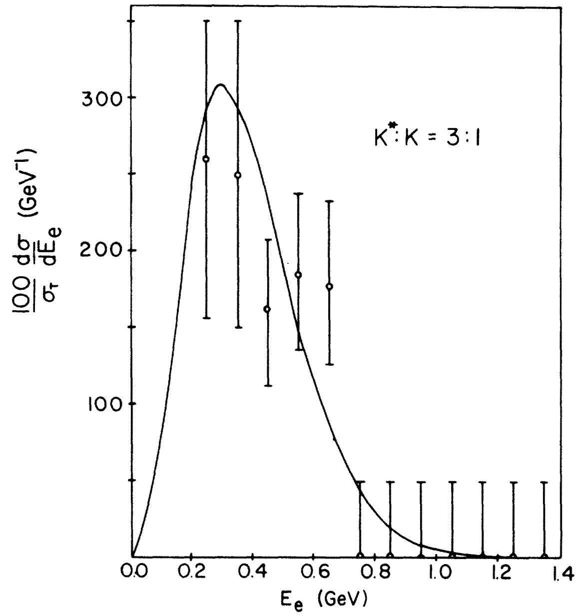

FIG. 4. Calculated electron spectrum for $D \to e\nu K^*$ and $D \to e\nu K$ with a relative branching ratio 3:1. Only the normal couplings are considered. Data points are taken from Ref. 5, normalization being arbitrary.

other available experimental information that also supports this assertion, namely, the hadronic multiplicity distribution given by Braunschweig *et al.*[5] For one of the D mesons in (34) to decay into $e + \nu + K^*$, while the other D is decaying, most likely, into $K\pi$, $K\pi\pi$, and $K\pi\pi$ channels, the final hadron multiplicity in (34) should be 5 or 6 (with K^* counting for 2). The experimental distribution is shown in Fig. 6. The measured hadron multiplicity indeed peaks at 5, in good agreement.

We have calculated the dilepton correlation for

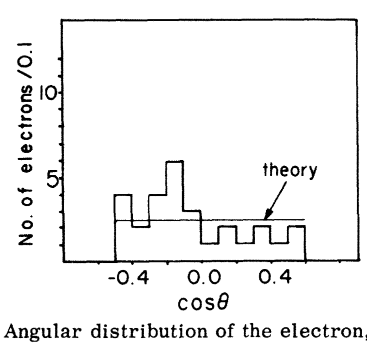

FIG. 5. Angular distribution of the electron, calculated for $D \to e + \nu + K^*$, where the charmed mesons are produced in $e^+ + e^- \to \bar{D} + D^* \to \bar{D} + D + \pi$ with the beam energy at 2.05 GeV. The coupling for the decay is the normal, i.e., effective $(V+A)(V-A)$. The histogram is taken from Ref. 5.

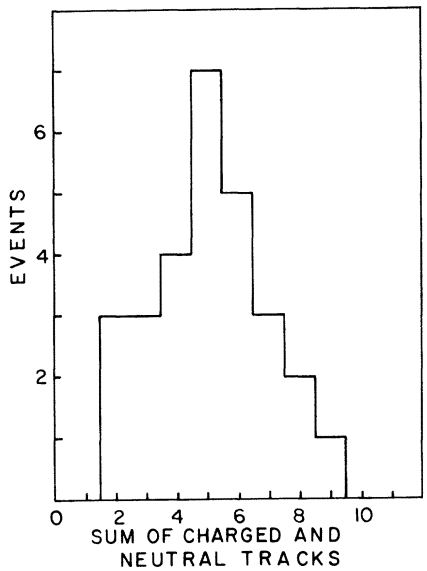

FIG. 6. Multiplicity distribution taken from Ref. 5.

$$
\begin{aligned}
&e^+ + e^- \to \bar{D}^* + D \\
&\qquad\qquad\quad \searrow \mu(e) + \nu + K^* \\
&\quad \searrow \bar{D} + \pi \text{ (or } \gamma) \\
&\qquad \searrow e(\mu) + \nu + K^* .
\end{aligned}
\tag{35}
$$

The distribution in the collinear angle, defined by

$$\cos\theta_{\text{coll}} = -\frac{\vec{p}_e \cdot \vec{p}_\mu}{|\vec{p}_e|\,|\vec{p}_\mu|} \tag{36}$$

is given in Fig. 7. The angular acceptance $|\cos\theta| \leq 0.6$ has been imposed.

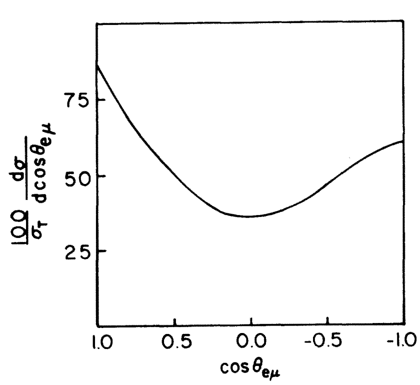

FIG. 7. Angular correlations between e and μ, which are due to the production and subsequent decay of the charmed mesons: $e^+ + e^- \to \bar{D} + D^*$, followed by $D \to e + \nu + K^*$ and $\bar{D} \to \mu + \nu + K^*$. The beam energy is taken to be 2.05 GeV.

VII. PRODUCTION OF D^+D^- AND SUBSEQUENT DECAYS

As has been discussed in Sec. V, the *exclusive* production of D^+D^- at center-of-mass energies less than $2M_D + M_\pi = 3.87$ GeV offers a clear setting for studying the decay properties of D. We have therefore calculated the lepton distributions, at center-of-mass energy 3.9 GeV, for

$$e^+ + e^- \to D^+ + D^-$$

followed by

$$D \to e(\mu) + \nu + \begin{cases} K^* \\ K \end{cases} .$$

In Fig. 8 we present the numerical result, which also incorporates the angular acceptance $|\cos\theta| \leq 0.6$, for the lepton spectrum. The calculated dilepton angular distribution is shown in Fig. 9 (for the K^* mode). The collinear angle θ_{coll} is defined by (36).

VIII. DISCUSSIONS

From our study we are reasonably convinced that $D \to e + \nu + K^*$ is likely to be the dominant semileptonic decay mode. Several arguments are given in Sec. IV in support of this assertion. The most important support is, of course, the agreement between the calculated and observed distributions, presented in Sec. VI.

Also significant from our study is that the decay structure for $D^- \to e^- + \bar{\nu} + K^*$ favors, quite convinc-

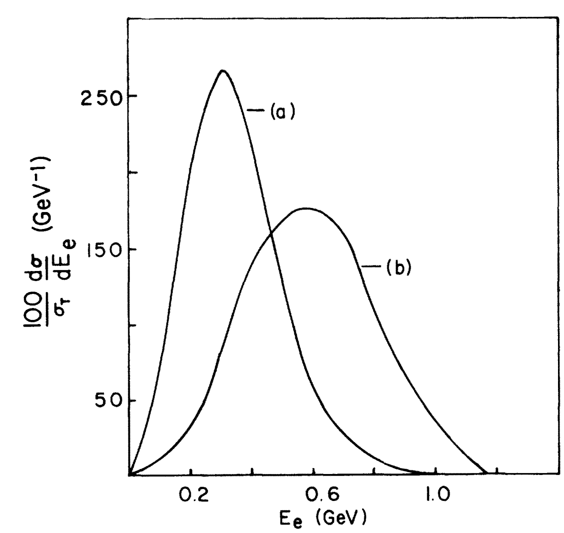

FIG. 8. (a) Calculated electron spectrum for $D \to e + \nu + K^*$, where the charmed mesons are produced in $e^+ + e^- \to \bar{D} + D$, with the beam energy at 1.95 GeV. (b) Calculated electron energy spectrum for $D \to e + \nu + K$, under the same conditions.

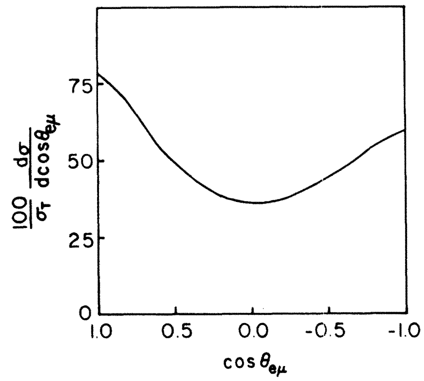

FIG. 9. Angular correlations between e and μ, which are due to the production and subsequent decay of charmed mesons: $e^+ + e^- \to D + D$, followed by $D \to e + \nu + K^*$ and $D \to \mu + \nu + K^*$. The beam energy is taken to be 1.95 GeV.

ingly, the phenomenological $(V+A)(V-A)$, as is dictated by the underlying charm scheme. This may be viewed as an indirect confirmation of this scheme.

In Sec. VII we have presented the calculation of the exclusive production of D^+D^- and their subsequent semileptonic decays. It seems to us that this offers a clean setting for studying the weak-decay properties of the D meson.

We have also presented results for dilepton production, which will be studied in a forthcoming experiment now being prepared at SPEAR.

Based on the DESY result[5]

$$\sigma(e^+e^- \to e + \text{hadrons}) > 1 \text{ nb},$$

and that the upper bound of the D production cross section is estimated to be given by

$$\sigma(e^+e^- \to D + \text{hadrons}) < (5 - 2.5 - 1)\sigma(e^+e^- \to \mu^+\mu^-),$$

which is, at $2E = 4.1$ GeV, roughly 8 nb, the branching ratio for semileptonic decays of D is

$$B(D \to e + \nu + \text{hadrons}) > \tfrac{1}{2} \times \tfrac{1}{8} \sim 6\%.$$

We conclude by making a remark about the strange and charmed meson F in the charm scheme. The F meson is believed to have a mass of about 2 GeV, and therefore should have been produced, in pairs, in the DESY experiment. Based on our study on D, we expect that the dominant semileptonic decay mode of F is likely to be

$$F \to e(\mu) + \nu + \phi.$$

The decay characteristics, however, would be quite similar to those due to the D decay in the DESY experiment, offering no great hope for unraveling the F meson from a study of the lepton distributions.

During the preparation of the present paper, we learned of similar works done by Ali and Yang,[13] and by Barger, Gottschalk, and Phillips.[14] We thank J. Smith for bringing the last work to our attention.

APPENDIX A

We consider the decay $D^- \to e^- + \bar{\nu} + K^*$ in Sec. IV. The form of the matrix element (21) we adopted is not the most general one. In this appendix we present a more general discussion of the matrix element.

For the transition

$$D(P) \to K^*(k, \epsilon^\mu), \tag{A1}$$

the matrix element of the vector current is unique, and is of the form

$$\tilde{K}^{\mu\nu} q_\nu, \tag{A2}$$

where $\tilde{K}^{\mu\nu}$ is defined in (22) and $q = P - k$. This form of the matrix element, incidentally, corresponds to a conserved vector current.

The most general form of the transition matrix element of the axial-vector current is a linear combination of ϵ^μ, $\epsilon^\nu P_\nu k^\mu$, and $\epsilon^\nu P_\nu q^\mu$. However, for obvious reasons, we restrict ourselves to a less general form of the matrix element, which we require to correspond to a partially conserved axial-vector current. By partially conserved axial-vector current we mean that the axial-vector current is conserved in the limit of zero masses. We are thus limited to the form

$$K^{\mu\nu}(q_\nu + bP_\nu). \tag{A3}$$

where $K^{\mu\nu} = k^\mu\epsilon^\nu - k^\nu\epsilon^\mu$. We note that the q term in (A3) corresponds to a conserved axial-vector current, while the b term corresponds to a partially conserved axial-vector current ($M_{K^*} \to 0$).

The matrix element for $D \to K^*$ transition is a linear combination of (A2) and (A3). To make contact with the underlying structure of the weak current, we shall further restrict the form of the matrix element so that it has definite helicity projections in the massless limit. As we shall explicitly illustrate in Appendix B, $\tilde{K}^{\mu\nu} \pm K^{\mu\nu}$ are the right-handed (+) and left-handed (–) helicity projections for K^*, provided K^* is massless. Noting that

$$\tilde{K}^{\mu\nu}(q_\nu + bP_\nu) = (b+1)\tilde{K}^{\mu\nu} q_\nu,$$

we will adopt the following matrix element for $D^-(P) \to e^-(p) + \bar{\nu}(p') + K^*(k, \epsilon^\mu)$:

$$\cos\theta_C (G/\sqrt{2}) a [f_V(q^2)\tilde{K}^{\mu\nu} + f_A(q^2) K^{\mu\nu}](q_\nu + bP_\nu), \tag{A4}$$

where the leptonic matrix element is given by

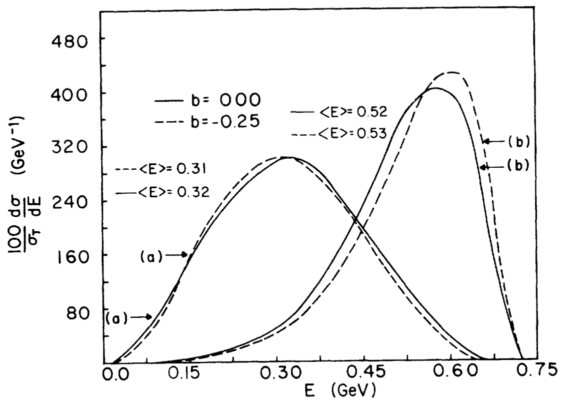

FIG. 10. Electron energy spectrum from $D^- \to e^- \bar{\nu} K^*$ for D at rest, for two values of the parameter $b=0$ and -0.25. Curves (a) correspond to normal coupling, and curves (b) to abnormal coupling.

$$l_\mu = \bar{u}(p)\gamma_\mu(1-\gamma_5)v(p')$$

and

$$f_A = \pm f_V .$$

As to the parameter b, we do not know exactly what value it should take. However, we can estimate its value by making the assumption, which we believe is reasonable, that the vector and axial-vector currents have roughly equal contributions to the total decay rate. By actual computation, we find this limits b to be small and negative. Equal contributions from vector and axial-vector currents correspond to

$$b \sim -0.25 .$$

Over this range of b values, we also find that the peaking characteristics of the electron spectrum, for $f_A = \pm f_V$, are essentially the same. We show in Fig. 10 the electron spectra, for D decaying at rest, for $b=0$ and -0.25. Since the peaking characteristics are our prime interest in this paper, we will for simplicity assume $b=0$. For $b=-0.25$, the rate becomes

$$\Gamma(D \to e\nu K^*) = (a\, M_D)^2 0.63 \times 10^{-12} \text{ MeV} ,$$

which is to be compared with (28) for $b=0$.

APPENDIX B

In this appendix we explicitly demonstrate the handedness of $K^{\mu\nu} \pm \tilde{K}^{\mu\nu}$ for the transition $D \to K^*$, which we have considered in Sec. IV. Denoting by k^μ and ϵ^μ the 4-momentum and the polarization vector of K^*, respectively, we have defined in Sec. IV

$$K^{\mu\nu} = k^\mu \epsilon^\nu - k^\nu \epsilon^\mu ,$$

$$\tilde{K}^{\mu\nu} = (2i)^{-1} \epsilon^{\mu\nu\lambda\rho} K_{\lambda\rho} .$$

We shall explicitly demonstrate that $K^{\mu\nu} + \tilde{K}^{\mu\nu}$ contains only right-handed K^*, while $K^{\mu\nu} - \tilde{K}^{\mu\nu}$ contains only left-handed K^*, if K^* is *massless*:

$$K^{\mu\nu} \pm \tilde{K}^{\mu\nu} : \begin{cases} \text{right-handed } (+) \\ \text{left-handed } (-) . \end{cases}$$

The spin-1 matrices S_j are given by

$$(S_j)_{ik} = i\epsilon_{ijk} ,$$

which satisfy

$$[S_i, S_j] = i\epsilon_{ijk} S_k .$$

For a massless vector particle, or in the high-energy approximation of neglecting the mass, the 4-momentum k^μ can be chosen to be

$$k^\mu = (k^0, k^1, k^2, k^3) = E(1,0,0,1) .$$

The helicity operator is

$$\vec{k} \cdot \vec{S} / |\vec{k}| = S_3 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} .$$

It can be easily checked that the helicity $+1$ (right-handed) and helicity -1 (left-handed) polarization vectors are

$$\epsilon_{(\pm)} = \frac{1}{\sqrt{2}} (0, 1, \pm i, 0) .$$

Corresponding to these polarization vectors $\epsilon^\mu_{(\pm)}$, $K^{\mu\nu} + \tilde{K}^{\mu\nu}$ is given by

$$\frac{\sqrt{2}}{E}(K^{\mu\nu} + \tilde{K}^{\mu\nu}) = \begin{pmatrix} 0 & 1 \pm 1 & \mp i - i & 0 \\ -1 \mp 1 & 0 & 0 & -1 \mp 1 \\ \pm i + i & 0 & 0 & \pm i + i \\ 0 & 1 \pm 1 & \mp i - i & 0 \end{pmatrix}$$

That is, $K^{\mu\nu} + \tilde{K}^{\mu\nu}$ is zero for $\epsilon^\mu_{(-)}$ and, therefore, a right-handed combination.

Simiarly, $K^{\mu\nu} - \tilde{K}^{\mu\nu}$ can be easily demonstrated to be a left-handed combination.

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[1]G. Goldhaber *et al.*, Phys. Rev. Lett. 37, 252 (1976); I. Peruzzi *et al.*, *ibid.* 37, 569 (1976).
[2]B. Knapp *et al.*, Phys. Rev. Lett. 37, 882 (1976).
[3]A. De Rújula *et al.*, Phys. Rev. D 12, 147 (1975).
[4]Experimental and theoretical references can be found

in F. Bletzacker *et al.*, Phys. Rev. Lett. 37, 1316 (1976).

[5]W. Braunschweig *et al.*, Phys. Lett. 63B, 471 (1976).

[6]Y. Hara, Phys. Rev. 134, B701 (1964); J. D. Bjorken and S. L. Glashow, Phys. Lett. 11, 255 (1964); S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[7]Invoking the Ademollo-Gatto theorem on symmetry-breaking effect, we do not expect large SU(4)-symmetry breaking for the matrix elements of the weak vector currents.

[8]M. K. Gaillard *et al.*, Rev. Mod. Phys. 47, 277 (1975).

[9]The $\bar{D}^*D^*$ channel could conceivably be important at energies higher than the DESY experiment (Ref. 5). We have carried out the calculation for $e^+ + e^- \rightarrow \bar{D}^* + D^*$ followed by $D^* \rightarrow D + \pi$ and $D \rightarrow e + \nu + \cdots$. The results differ very little, actually, from the $\bar{D}^*D$ case.

[10]There is experimental indication that $D^* \rightarrow D\gamma$ is comparable to $D^* \rightarrow D\pi$. Since both are two-body decays, and the pion mass is negligibly small compared to M_D, essentially the same kinematics applies to both cases in (29).

[11]Correlation effect due to the spin of D^* is neglected.

[12]We average over the two final electrons in (34).

[13]A. Ali and T. C. Yang, Phys. Lett. 65B, 295 (1976).

[14]V. Barger, T. Gottschalk, and R. J. N. Phillips, University of Wisconsin report (unpublished).