Charmed-meson production in electron-positron annihilation*

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Charmed-meson production is analyzed in a free-quark model. Arguments are given for the predominance of electromagnetic c-quark pair creation with subsequent q-quark association. F-meson production is not suppressed. Experimental tests of these findings are suggested in regions with and without resonances.

I. INTRODUCTION

The recently discovered narrow states with energies near 2 GeV (Ref. 1) in the final-state channels $K\pi$, $K2\pi$, $K3\pi$ in e^+e^--initiated reactions are commonly interpreted as bound states of a charmed quark (c) and a lighter nonstrange quark (u or d, which we refer to generically as q quarks).[2]

The experiments[1] reveal a new neutral state with mass 1865 ± 15 MeV/c^2 which decays into $K\pi$ and $K3\pi$ channels. In charm spectroscopy it is identified with the s-wave singlet state $D^0 \equiv (c\bar{u})$.[2] More recent data also give clear evidence for a peak at 1876 ± 15 MeV/c^2 in the charged $K2\pi$ channels corresponding to the expected charmed mesons with charge $D^+ \equiv (c\bar{d})$ and $D^- \equiv (\bar{c}d)$. In addition, the recoil spectra indicate that the D's are produced predominantly in association with higher-mass states around 2.0–2.2 GeV/c^2, which have been identified in charm spectroscopy[2] with the anticipated charmed vector mesons D^* corresponding to s-wave spin-triplet states.

The experimental results and a number of their consequences have been discussed recently by De Rújula, Georgi, and Glashow[3] and by Lane and Eichten.[4] Of particular interest is the striking predominance of the associated production of D^* over D evident in the experimental data. Both groups of authors in Refs. 3 and 4 qualitatively account for the D^* predominance by assuming a sequential production of quark pairs in which the more massive $c\bar{c}$ combination is produced initially through the virtual photon, and subsequently an uncorrelated pair of lighter quarks is produced having no direct interaction with the photon. The ratios of cross sections $D\bar{D}:(D\bar{D}^* + \bar{D}D^*):D^*\bar{D}^* = 1:4:7$ for both neutral and charged cases are then obtained using the above assumptions, angular momentum conservation, and the traditional method of counting statistical weights of the allowed final angular momentum states. An implicit assumption is also

made that the electromagnetic coupling to each allowed spin state is equivalent.

In this paper we investigate the charmed-meson production process in a relativistic free-quark model (Fig. 1) which considers the general nature of the electromagnetic interactions with the quarks, but retains the simplifying assumptions of free constituents. We assume electromagnetic c-quark creation and subsequent q-quark association out of the vacuum (and vice versa) by the intermediary of an "object" which is exchanged between the c quark and the q quark. This model permits determination of the form of the current amplitudes as well as investigation of the relative size of the form factors F_c and F_q. We propose experimental tests to determine whether diagram (b) in Fig. 1 contributes as much as diagram (a); they may also be used to separate the electric and magnetic (and even electric quadrupole[5]) form factors and permit consistency checks. A resonance in the vicinity of 4.03 GeV has a distorted shape if there is a substantial nonresonating contribution. It will enhance the $D\bar{D}^*$ contribution below the resonance if there is positive resonance background interference and suppress it if there is negative interference; the opposite effect for the $D^*\bar{D}^*$ channel above the resonance is expected.

II. FREE-QUARK MODEL

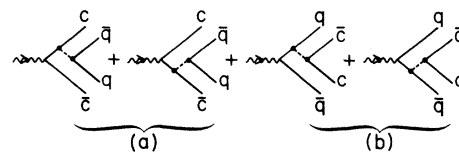The pseudoscalar D mesons are assumed to be represented by s-wave spin-singlet states,

FIG. 1. D-pair production in e^+e^- annihilation in the free-quark model with (a) the photon coupling to the c quarks and (b) to the q quarks.

$$D^+ \equiv \frac{1}{\sqrt{2}} \left[|c, -\tfrac{1}{2}\rangle |\bar{d}, +\tfrac{1}{2}\rangle - |c, +\tfrac{1}{2}\rangle |\bar{d}, -\tfrac{1}{2}\rangle \right] , \quad (1)$$

$$D^0 \equiv \frac{1}{\sqrt{2}} \left[|c, -\tfrac{1}{2}\rangle |\bar{u}, +\tfrac{1}{2}\rangle - |c, +\tfrac{1}{2}\rangle |\bar{u}, -\tfrac{1}{2}\rangle \right] , \quad (2)$$

where $\pm\tfrac{1}{2}$ corresponds to the quark helicities and the $c, \bar{d}$ labels represent the internal quark quantum numbers. Similarly, the vector D^* mesons are assumed to be s-wave spin-triplet states

$$D^{+*}_{\lambda = +1} \equiv |c, \pm\tfrac{1}{2}\rangle |\bar{d}, \pm\tfrac{1}{2}\rangle , \quad (3)$$

$$D^{+*}_{\lambda = 0} \equiv \frac{1}{\sqrt{2}} \left[|c, -\tfrac{1}{2}\rangle |\bar{d}, +\tfrac{1}{2}\rangle + |c, +\tfrac{1}{2}\rangle |\bar{d}, -\tfrac{1}{2}\rangle \right], \quad (4)$$

where λ is the meson helicity.

The meson electric current operator in configuration space is given in terms of the quark fields by

$$J^\mu = ie(Q_c \bar{\psi}_c \gamma^\mu \psi_c + Q_q \bar{\psi}_q \gamma^\mu \psi_q) , \quad (5)$$

where Q_c (Q_q) are the charges of the charmed (light) quarks in units of e.

Since the masses of the quarks are different we assume that both the c and q quarks in a given D or D^* have the velocity of the meson center of mass. This implies for the c- and q-quark momenta k_c and k_q

$$k_c = k_D \frac{m_c}{m_D} , \quad k_q = k_D \frac{m_q}{m_D} , \quad (6)$$

where k_D is the momentum of the charmed-meson center of mass and $m_D = m_{D*} = m_c + m_q$ is assumed throughout. This connection is appropriate since it yields the proper form for the mesonic electric current expected classically in terms of the quark charges, velocities, and Dirac magnetic dipole moments.

With the above assumptions the meson current matrix elements are given by

$$\langle D\bar{D}| J^\mu |0\rangle = \hat{z}_\mu k_D (Q_c F_c^{(E)} + Q_{\bar{q}} F_q^{(E)}) , \quad (7)$$

where $\hat{z}_\mu \equiv (0, 0, 0, 1)$ is the four-vector in the z direction (chosen along the D-meson momentum) and the lighter-quark charge Q_q and mass m_q are determined by whether the $D\bar{D}$ is in the neutral or charged mode. Similarly for $D\bar{D}^*$ we obtain for the nonvanishing matrix elements with D^* helicity $\lambda = \pm 1$

$$\langle D\bar{D}^*_{\lambda = \pm 1}| J^\mu |0\rangle = \frac{(\hat{x} \mp i\hat{y})_\mu}{\sqrt{2}} k_D E_D (Q_c F_c^{(M)} - Q_{\bar{q}} F_q^{(M)}) , \quad (8)$$

where E_c and E_q are the quark energies. In the $D^*\bar{D}^*$ case we have for the nonvanishing matrix elements corresponding to the meson helicity states

$$\langle D^*_{\lambda = \pm 1}, \bar{D}^*_{\lambda = 0}| J^\mu |0\rangle = \frac{(\hat{x} \pm i\hat{y})_\mu}{\sqrt{2}} k_D E_D (Q_c F_c^{(M)} + Q_{\bar{q}} F_q^{(M)}) , \quad (9)$$

$$\langle D^*_{\lambda = \pm 1}, \bar{D}^*_{\lambda = \pm 1}| J^\mu |0\rangle = \hat{z}_\mu k_D (Q_c F_c^{(E)} + Q_{\bar{q}} F_q^{(E)})$$
$$= \langle D^*_{\lambda = 0}, \bar{D}^*_{\lambda = 0}| J^\mu |0\rangle . \quad (10)$$

From the explicit form of the meson electromagnetic currents we observe the following features:

(1) The proper threshold behavior is ensured by the D-meson momentum factor.

(2) In the nonrelativistic limit

$$\frac{k_D}{m_D} \sim v_D = v_c = v_{\bar{q}} , \quad (11)$$

and we observe that the currents represented in Eqs. (7) and (10) reduce to the form

$$\langle D\bar{D}| J^\mu |0\rangle = \langle D^*_{\lambda = \pm 1} \bar{D}^*_{\lambda = \pm 1}| J^\mu |0\rangle \Rightarrow \sum_i Q_i \vec{v}_i \quad (12)$$

and therefore correspond to purely electric currents.

(3) Similarly the currents represented by Eqs. (8) and (9) can be seen to correspond to the magnetic part of the current arising from the Dirac magnetic dipole moments.

(4) The resulting form factors for photon c-quark coupling behave like

$$F_c^{(E)} \propto \frac{4m_D^2 m_c + q^2 m_q}{q^2 \frac{m_q}{m_D} \left(q^2 \frac{m_q^2}{m_D^2} - m_0^2 \right)} ,$$

$$F_c^{(M)} \propto \frac{1}{q^2 \frac{m_q}{m_D} \left(q^2 \frac{m_q^2}{m_D^2} - m_0^2 \right)} . \quad (13)$$

The analogous form factors for the q quarks, $F_q^{(E)}$ and $F_q^{(M)}$, are obtained by the interchange $m_q \rightarrow m_c$; the result indicates that they are suppressed like m_q/m_c, at least, with respect to the c-quark form factors.

(5) The above currents are in the form expected for the electromagnetic coupling of D and D^* mesons. The invariant expansions for electromagnetic $D\bar{D}$, $D\bar{D}^*$, and $D^*\bar{D}^*$ production as well as the differential cross sections as functions of the form factors are given in Ref. 6. With the matrix elements given in Eqs. (7)–(10) one easily determines the ratios of the integrated cross sections:

$$\sigma_{D\bar{D}} : \sigma_{D\bar{D}^* + \bar{D}D^*} : \sigma_{D^*\bar{D}^*}$$
$$= (Q_c F_c^{(E)} + Q_{\bar{q}} F_q^{(E)})^2 : 4 \left(\frac{E_D}{m_D} \right)^2 (Q_c F_c^{(M)} - Q_{\bar{q}} F_q^{(M)})^2 : 3 (Q_c F_c^{(E)} + Q_{\bar{q}} F_q^{(E)})^2 + 4 \left(\frac{E_D}{m_D} \right)^2 (Q_c F_c^{(M)} + Q_{\bar{q}} F_q^{(M)})^2 , \quad (14)$$

where kinematical factors due to phase space (with identical forms in all three processes) have been ignored here. Equation (14) implies that the cross-section ratios are fixed by numerical factors due to spin and the square of the sum and difference of the quark charges times form factors. If $F_c^{(E)}$ $\equiv F_c^{(M)}$ is assumed and all q-quark contributions are ignored we are back at the 1:4:7 ratio of Refs. 3 and 4. In the extreme case of $F_c^{(E, M)}$ and $F_q^{(E, M)}$ equal to the same function of q^2, we would find the ratios

$$\sigma_{D^0 \bar{D}^0} : \sigma_{D^0 \bar{D}^{0*} + \bar{D}^0 D^{0*}} : \sigma_{D^{0*} \bar{D}^{0*}} = 0 : \tfrac{64}{9} : 0 , \tag{15}$$

$$\sigma_{D^+ D^-} : \sigma_{D^+ D^{-*} + D^{+*} D^-} : \sigma_{D^{+*} D^{-*}} = 1 : \tfrac{4}{9} : 7 \tag{16}$$

for q^2 around $(2m_D)^2$. Note that in this model of quasifree quarks the quadrupole form factor vanishes.

III. FORM-FACTOR SIZE

The model presented above does not exhibit the full quark-mass dependence of the form factors since the dimension of an amplitude describing four-fermion production is different from the dimension of an amplitude describing two-boson production. Furthermore, the study of different types of quark interactions is not practical. We therefore investigate the dependence of the form factors on the c-quark and q-quark masses in the model of Fig. 2. Such a picture is motivated by the Zweig-rule-violating decay of $\psi \to$ hadrons (Fig. 3); the interaction between c and q quarks is thought to be mediated by gluons,[7] and their effect has been phenomenologically described by the sequential pole model.[8] In the framework of these ideas we investigate the consequences of the exchange of an "object" whose different spin-parity assignments we vary. The current amplitude reads

$$\langle D's | J^\mu | 0 \rangle = \text{const} \times \int_{-\infty}^{+\infty} \frac{d^4 l_1}{(2\pi)^4} \frac{d^4 l_2}{(2\pi)^4} \frac{\text{Tr}^\mu}{\prod_{i=1}^{6} (l_i^2 - m_i^2)} , \tag{17}$$
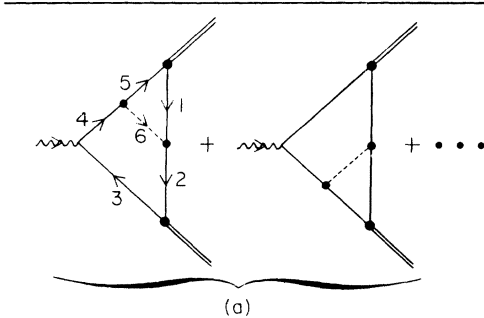
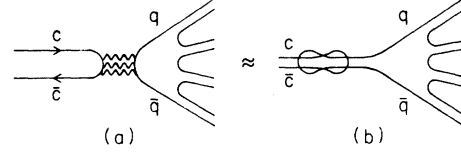FIG. 2. c-quark and q-quark interactions in the free-quark model.

FIG. 3. The decay of ψ into hadrons using the sequential pole description of the charmonium picture.

where the l_i are defined in Fig. 2 and Tr^μ abbreviates the trace of the loop fermions. By imposing the mass-shell constraint on the q-quark (c-quark) lines 1 and 2 (3 and 5), e.g.,

$$\frac{1}{l_i^2 - m_i^2} \to \delta^+(l_i^2 - m_i^2) ,$$

we find

$$\langle D's | J^\mu | 0 \rangle = \text{const} \times \int_{-\infty}^{+\infty} \frac{d\vec{l}_1}{(2\pi)^2} \frac{d\vec{l}_2}{(2\pi)^2} \frac{\phi(\vec{l}_1)}{\eta(\vec{l}_1)} \frac{\phi(\vec{l}_2)}{\eta(\vec{l}_2)}$$

$$\times \frac{\text{Tr}^\mu}{(l_4^2 - m_c^2)(l_6^2 - M_0^2)} , \tag{18}$$

where

$$\eta(\vec{l}) \equiv \left[\left(\frac{m_D^2 + m_q^2 - m_c^2}{2} \right) - m_D^2 (\vec{l}^2 + m_q^2) \right]^{1/2}$$

and $\vec{l} \equiv (l_x, l_y)$ is the momentum vector in the transverse plane (with respect to the D-meson c.m. momentum). If we now demand that the transverse momentum be cut off—this means we set simply $(\vec{l}_1, \vec{l}_2) = 0$—we recover the earlier result in Eqs. (6).

Evaluation of the trace for a scalar object being exchanged gives the form factors

$$F_c^{(E)} = \text{const} \times \frac{M^4}{\eta^2} \frac{m_q^2 m_c^2}{m_D} \frac{\left[m_c + m_q \left(\frac{q^2}{4 m_D^2} \right) \right]}{q^2 \frac{m_q}{m_D} \left(q^2 \frac{m_q^2}{m_D^2} - m_0^2 \right)} , \tag{19}$$

$$F_c^{(M)} = \text{const} \times \frac{M^4}{\eta^2} \frac{m_q^2 m_c^2}{m_D} \frac{1}{q^2 \frac{m_q}{m_D} \left(q^2 \frac{m_q^2}{m_D^2} - m_0^2 \right)} . \tag{20}$$

These results were obtained by using $m_{D*} = m_D = m_c + m_q$ except in $\eta(\vec{l})$, where m_D has to be different in order to prevent divergence of the integrand in Eq. (18). In order to study the influence of the spin we have determined the changes if a vector or pseudoscalar object is exchanged. Calculations with a vector object give almost the same results,

$$F_c^{(E)} = \text{const} \times \frac{M^4}{\eta^2} \frac{m_q{}^2 m_c{}^2}{m_D} \frac{\left[m_c + 2m_q \left(\frac{q^2}{4m_D{}^2} \right) \right]}{q^2 \frac{m_q}{m_D} \left(q^2 \frac{m_q{}^2}{m_D{}^2} - m_0{}^2 \right)} \ ,$$

$$(21)$$

whereas the exchange of a pseudoscalar object leads to a slightly different form. Here we have

$$F_c^{(E)} = \text{const} \times \frac{M^4}{\eta^2} \frac{m_c{}^2 m_q{}^2}{m_D{}^2} \frac{1}{\left(q^2 \frac{m_q{}^2}{m_D{}^2} - m_0{}^2 \right)} \ ,$$

$$(22)$$

$$F_c^{(M)} = 0 \ .$$

The main conclusions we draw from this simple picture are as follows:

(i) In the region $q^2 \cong 4m_D{}^2$ the q-quark form factor is substantially smaller than the c-quark form factor with $F_q/F_c \lesssim (m_q/m_c)$. This result is mainly due to the off-shell propagator of one of the quarks coupled directly to the photon. In the region $q^2 \gg 4m_D{}^2$, F_q is less suppressed in comparison to F_c.

(ii) Application of this model to F, F^* production shows little change; in particular, we find no $(1/m_q)^4$ behavior[4] and therefore predict F production at similar rates as D production.

Phenomenology also teaches us that the production of particles comprised of more massive strange quarks is less likely in comparison to production of (u, d)-quark mesons. The assumption of a vanishing F_q then leads to the conclusion that the production ratios should be identical for charged and neutral channels. This seems to be at variance with the experimental results.

IV. MOMENTUM DEPENDENCE

In the following we assume that all channels share the same form factors $F_c(k_D)$ and $F_q(k_D)$. These are strongly dependent on the charmed-meson momentum k_D which in turn is a function of q^2 and the charmed-meson masses m_D and m_{D*}. This feature does not emerge from our simple model presented above, but becomes immediately obvious if more complicated diagrams are studied and/or our simplifying assumptions are dropped. This property is also indicated by the experimental cross-section ratio $R(q^2) \equiv \sigma_h/\sigma_\mu$, which in the region 3.8–4.2 GeV can be fitted by resonances and a sum of terms[3,9]:

$$R(q^2) \propto k_D{}^{3/2} \exp(-k_D{}^2/\Gamma) \ ,$$

$$k_D = \left\{ \frac{[q^2 - (m_1 + m_2)^2][q^2 - (m_1 - m_2)^2]}{4q^2} \right\}^{1/2} \ .$$

$$(23)$$

Note that k_D depends sensitively on the charmed-

meson masses m_1 and m_2. In order to fit the bumps at 3.9 and 4.1 GeV simultaneously, assuming that they are due to $D\bar{D}^*$ and $D^*\bar{D}^*$ threshold onsets with subsequent form-factor damping, the value $\Gamma \sim 0.125$ GeV^2 is needed.[9] We stress that it is therefore not adequate to write the form factor as simply $F(q^2)$ since the charmed-meson masses are ignored and the form factor varies strongly with changing momentum values $k_D(q^2)$.[10] The q^2 dependence of the momenta for the final-state channels $D\bar{D}$, $D\bar{D}^*$, and $D^*\bar{D}^*$ are plotted in Fig. 4. At a fixed q^2 value the actual values of k_D vary according to the respective meson masses and therefore no comparison between different channels is possible.

V. FORM-FACTOR TESTS

However, a comparison of the production cross sections at equal k_D values permits interesting experimental tests. In this case the cross sections for common k_D are compared at their corresponding center-of-mass energies

$$\sigma_{D\bar{D}}(s_1), \quad \sigma_{D\bar{D}*}(s_2), \quad \sigma_{D*\bar{D}*}(s_3) \quad (24)$$

(Fig. 4). The above assumption $F_q \ll F_c$ may now be investigated by considering the combination

$$\sigma_{D*\bar{D}*}(s_3) - \sigma_{D\bar{D}*}(s_2) - 3\sigma_{D\bar{D}}(s_1) \propto F_c \cdot F_q \sim 0 \ ,$$

$$(25)$$

which should be small for any momentum value. This relation might even be used to predict the
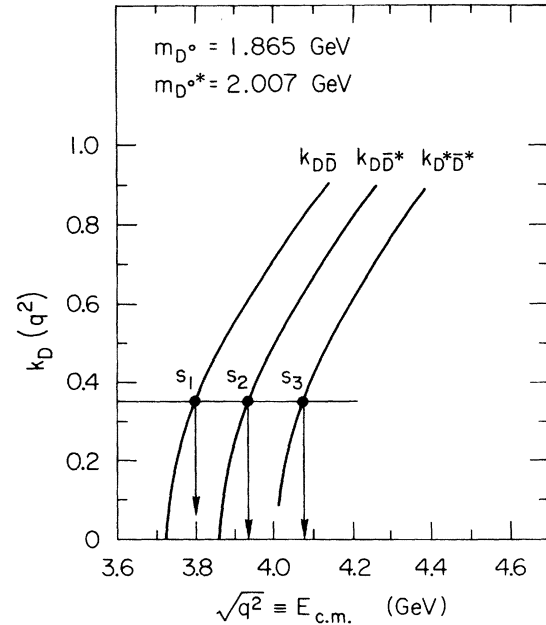
FIG. 4. D-meson momenta as a function of the c.m. energy.

cross-section shape of one of the three channels if the s dependence of the other two channels is known. Note that this method can be applied to neutral-and charged-D production separately and therefore permits checks of consistency of our assumptions. One should, however, keep in mind that the quadrupole form factor is ignored in our model, and thus an experimentally nonvanishing value has to be either due to $F_q \sim F_c$ or $F^{(Q)} \neq 0$ which would signal non-negligible binding forces between the c and the q quark. Another test of the above assumption is to compare the cross section for charged- and neutral-D production. For example,

$$\frac{\sigma_{D^0 D^0*}(s_2)}{\sigma_{D^+ D^-*}(s_2')} = \frac{\frac{2}{3}F_c + \frac{2}{3}F_u}{\frac{2}{3}F_c - \frac{1}{3}F_d} \approx 1 + \frac{F_u + F_d}{F_c} \qquad (26)$$

is expected to deviate from unity if the q-quark creation with subsequent c-quark association is substantial. Again the cross-section values are determined at energies s_2 and s_2' where the momenta k_D of the two channels are equal. Further tests can be thought of along this line of reasoning.

We now assume that the c-quark contribution dominates and diagrams (b) in Fig. 1 can be ignored. We noticed earlier that there are electric, magnetic dipole, and electric quadrupole couplings which we describe by the form factors $F_c^{(E)}$, $F_c^{(M)}$, and $F_c^{(Q)}$. In the free-quark model the electric quadrupole contribution vanishes and we here assume that it is small even in the realistic case of interacting quarks. With this assumption, we may determine the ratio of the magnetic to electric form factors by considering the combination

$$\frac{\sigma_{D^* \bar{D}*}(s_3)}{\sigma_{D\bar{D}}(s_1)} - 3 \propto 4 \left| \frac{F_c^{(M)}}{F_c^{(E)}} \right|^2 \left(\frac{E_c}{m_c} \right)^2 , \qquad (27)$$

where the shape of $F_c^{(M)}(k_D)$ is determined by $\sigma_{D\bar{D}*}$; again this method can be applied to the charged and neutral cases separately. It is obvious that a number of further relations can be constructed to extract form-factor information in this manner.[10] Note that these methods are only applicable if the following assumptions are satisfied:

(i) No resonance may be present in the energy range where the sizes of the form factors are determined.

(ii) The electric quadrupole coupling must be negligible.

VI. RESONANCES

So far we have not taken into account the possibility that the electromagnetically produced $c\bar{c}$ pair can form resonances at specific energies which subsequently decay into charmed mesons; we therefore have to consider contributions of the

type shown in Fig. 5. In the form factors they lead to a resonance part R_c in addition to the background parts B_c and B_q (Fig. 2):

$$F_c = R_c + B_c , \quad F_q = B_q . \qquad (28)$$

If B_q is non-negligible, the sum of the background contributions changes substantially as we go to different channels. This manifests itself in a different interference pattern between the resonance and the background. If B_q is negligible, the resonance shape is unaffected. A strong negative background contribution $B \equiv Q_c B_c + Q_q^- B_q$ suppresses the resonance shape at its lower end and enhances it at its upper end whereas the effect is reversed if B gives a strong positive contribution. This behavior is illustrated by the diagrams in Fig. 6. Figure 6(a) shows the threshold onset of the $D\bar{D}$, $D\bar{D}*$, and $D^*\bar{D}*$ channels due to a nonresonating background [Fig. 1(a)] with a subsequent universal form-factor damping of the form $\exp(-k_D^2/\Gamma)$. Figure 6(b) gives the cross-section behavior with a resonance at 4.03 GeV (width ~ 30 MeV) and no background. In Figs. 6(c) and 6(d) the interference pattern appears clearly, with a destructive interference at the lower end of the resonance [Fig. 6(c)] due to a strong negative background and a constructive interference at its upper end. In Fig. 6(d) the background contribution is strongly positive and therefore gives the opposite effect. The momentum dependence of the resonance residue and the background are assumed to be universal as given above. Our numerical calculations show the following results:

(1) Assuming an equal form-factor damping for all channels, one cannot reproduce the equal size of the recoil bumps due to the $D\bar{D}*$ and $D^*\bar{D}*$ channels[9] (see below).

(2) If the q-quark contribution is substantial, the resonance shape in charged- and neutral-D pair production appears with different distortions at its lower or upper ends.[11]

(3) In the resonance region, the cross sections for different D-production channels are more favorably compared at fixed q^2 values (instead of k_D) keeping, however, in mind that a strong k_D dependence of the resonance residue functions might substantially influence the results.
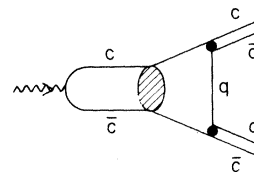

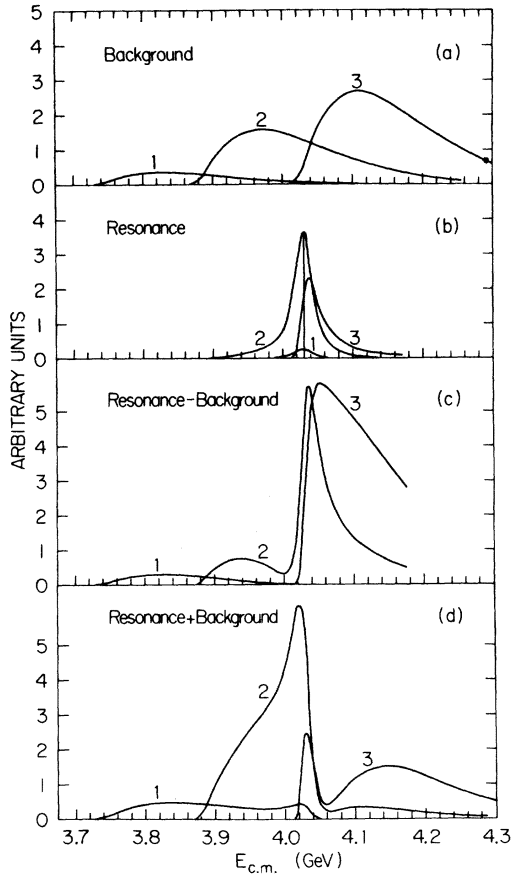FIG. 5. D-pair production via a resonating $c\bar{c}$ pair.

FIG. 6. D-pair production in e^+e^- annihilation supposing (a) a nonresonating back-ground, (b) a resonance at 4.03 GeV, and their possible interference (c) and (d).

VII. RECOIL SPECTRA

Analysis of the recoil spectra using the momentum dependence of the form factor in Sec. IV reveals

$$R_{D^0 \bar{D}^0} : R_{D^0 \bar{D}^{0*} + \bar{D}^0 D^{0*}} : R_{D^{0*} \bar{D}^{0*}} = 1:4.5:0.7 \ .$$

The $D\bar{D}^*$ mode clearly outweighs the $D^*\bar{D}^*$ mode by a factor 6 at $E_{c.m.} = 4.028$ GeV, which is in disagreement with the experimental D^0 recoil spectrum; it predicts equal amounts of $D^*\bar{D}^*$ and $D\bar{D}^*$ production, roughly. Several explanations for this discrepancy have been suggested[9]; we mention the onset of the $D\bar{D}^{**}$ threshold,[11] the uncertainty of the D-meson masses, and others. Model calculations[4] using nonrelativistic Bethe-Salpeter approximations have shown that at small k_D values the form factors vary substantially with changing momentum k_D, and it is therefore of no surprise that data show such behavior.

We would like to add a brief comment on the widths of the bumps in the recoil spectrum. As the c.m. energy increases the recoil bumps, due

to reflection, become broader; their lower boundaries vary relatively little, whereas their upper boundaries increase. The amount of broadening depends on the exact masses of D and D^* (see Fig. 7), in particular at larger values of $E_{c.m.}$. The widths of the recoil peaks thus provide further checks.

VIII. CONCLUSIONS

In this paper we have investigated the size of the c- and q-quark form factors in a free-quark model and found theoretical arguments for the suppression of F_q in comparison to F_c. We indicated experimental tests for this finding which also could be used to determine the electric, magnetic dipole, and electric quadrupole form factors. A resonance at 4.03 GeV is distorted in its shape if a non-negligible background contribution exists; the distortion differs for different D-pair production channels if the background is mainly due to the q quarks.

While this work was completed we learned of the papers in Refs 5 and 11. The authors in Ref. 11 assume the most general invariant expansion for the current amplitudes of $D\bar{D}$, $D\bar{D}^*$, and $D^*\bar{D}^*$ production and attempt a fit of the abnormally large $D^*\bar{D}^*$ recoil spectrum by a resonance a-
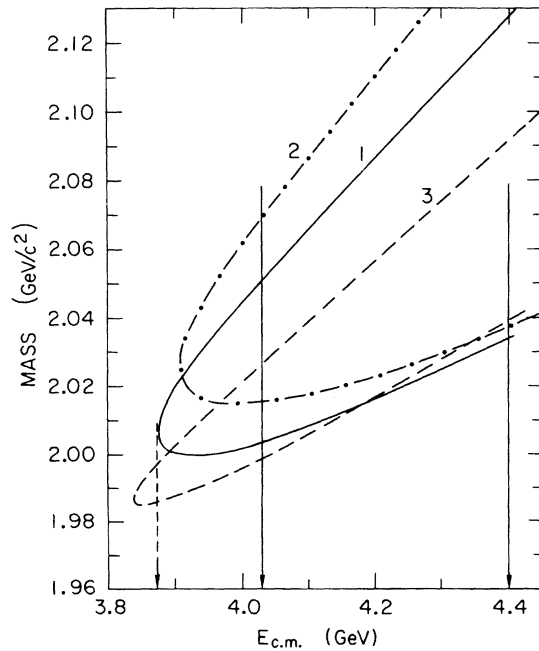

FIG. 7. Kinematical upper and lower limits of the reflection bumps in the invariant-mass spectrum as a function of the c.m. energy and the D-meson masses. Curve 1: $m_{D^0} = 1.865$ GeV, $m_{D^0*} = 2.007$. Curve 2: $m_{D^0} = 1.880$ GeV, $m_{D^0*} = 2.027$. Curve 3: $m_{D^0} = 1.850$ GeV, $m_{D^0*} = 1.987$.

round 4.03 GeV. They assume equal contribution of all light-quark form factors which slowly vary as q^2 increases and parametrize the form factors of the charmed quarks by a Breit-Wigner ansatz without any momentum dependence; there is no interplay between a term describing the threshold onset with subsequent momentum-dependent fall-off and a resonance term.

The paper in Ref. 5 presents an analysis of the amplitudes for $D\overline{D}$, $D\overline{D}^*$, and $D^*\overline{D}^*$ using the helicity formalism and relates the helicity amplitudes to the form factors; the paper ignores the strong momentum dependence of the form factors as stressed in Sec. IV of this paper.

After completion of this work a number of related papers appeared. In Ref. 12 the helicity formalism is used to determine the d-wave con-tribution of the charmed-quark pair which in this work is ignored since we consider quasifree $(c\overline{q})$ mesons.

The substantial enhancement of the $D\overline{D}^*$ channel around 4.03 GeV has been speculated as being due to four-quark molecules[13]; however, the experimental results do not support such a hypothesis.

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