CHARMED MESON PRODUCTION IN A FREE QUARK MODEL*

By B. Humpert

Stanford Linear Accelerator Center, Stanford University**

and R. B. Clark†

Department of Physics, Texas A & M University, College Station***

(Received July 16, 1977)

Production of charmed mesons D and D* in e^+e^- annihilation is analyzed. Experimental tests are proposed for the extraction of form factor information from the cross section ratios.

The recently discovered narrow states with energies near 2 GeV [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 experimental results and a number of their consequences have been discussed recently by DeRujula, Georgi and Glashow [3] and by Lane and Eichten [4].

In this paper we supplement these discoveries by a number of experimental tests [5] which can give substantial information on the form factors and in turn on the bound state nature of the cq-systems.

Cross section ratios. Assuming invariant expansions for the currents describing $D\overline{D}$, $D\overline{D}^*$, $D^*\overline{D}^*$ production [6]

$$j^{\mu}_{D} = j^{\mu}_{c}+j^{\mu}_{q}, \tag{1}$$

where $j^{\mu}_{c(q)}$ stands for the electromagnetic current resulting from $c\bar{c}$ ($q\bar{q}$) creation by the photon and subsequent $q\bar{q}$ ($c\bar{c}$) association out of the vacuum, the ratio of integrated

* Work supported in part by the Energy Research and Development Administration.

† Work supported in part by Associated Western Universities, Inc. under a contract from the Energy Research and Development Administration.

** Address: SLAC, Stanford University, Stanford, CA 94305, USA.

*** Address: Dept. of Physics, Texas A & M University, College Station, TX 77843, USA.

cross sections is

$$\sigma_{D\bar{D}} : \sigma_{D\bar{D}^* + \bar{D}D^*} : \sigma_{D^*\bar{D}^*} = (Q_c F_c^{(E)} + Q_{\bar{q}} F_q^{(E)})^2$$

$$4\left(\frac{E_D}{m_D}\right)^2 (Q_c F_c^{(M)} - Q_{\bar{q}} F_q^{(M)})^2 : 3(Q_c F_c^{(E)} + Q_{\bar{q}} F_q^{(E)})^2 + 4\left(\frac{E_D}{m_D}\right)^2 (Q_c F_c^{(M)} + Q_{\bar{q}} F_q^{(M)})^2; \tag{2}$$

kinematical factors due to phase space (with identical forms in all three processes) have been ignored here. $F^{(E,M,Q)}$ are the electric, magnetic dipole and electric quadrupole form factors [7]. Equation (2) 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, 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:

$$\sigma_{D^0\bar{D}^0} : \sigma_{D^0\bar{D}^{0*} + \bar{D}^0 D^{0*}} : \sigma_{D^{0*}\bar{D}^{0*}} = 0 : \tfrac{64}{9} : 0, \tag{3}$$

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

for q^2 around $(2m_D)^2$.

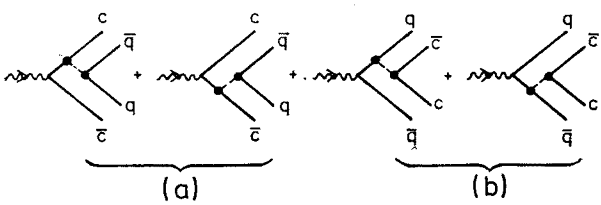

Fig. 1. D-pair production in e⁺e⁻ annihilation in the free quark model with (a) the photon coupling to the c-quarks and (b) to the q-quarks

Free quark model. The behavior of the form factors is analyzed in the free quark model; the c-quark q-quark interaction is mediated by the exchange of gluons (Fig. 1). In its most simple form, such picture leads to

$$F_c^{(E)} \propto \frac{m_q^2 m_c^2}{m_D} \frac{\left[m_c + m_q\left(\frac{q^2}{4m_D^2}\right)\right]}{q^2 \frac{m_q}{m_D}\left(q^2 \cdot \frac{m_q^2}{m_D^2} - m_0^2\right)}, \quad F_q^{(E)} = (c \to q), \tag{5}$$

$$F_c^{(M)} \propto \frac{m_q^2 m_c^2}{m_D} \frac{1}{q^2 \frac{m_q}{m_D}\left(q^2 \cdot \frac{m_q^2}{m_D^2} - m_0^2\right)}, \quad F_q^{(M)} = (c \to q), \tag{6}$$

$$F_c^{(Q)} \propto 0. \tag{7}$$

The main conclusions are:

(*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 $F_q/F_c \leqslant (m_q/m_c)$. 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 to F, F*-production shows little change; in particular *we find no* $(l/m_q)^4$ *behavior* [4] and therefore predict F-production at similar rates as D-production.

(*iii*) $F^{(E)} \gg F^{(M)}$, $F^{(Q)} \equiv 0$.

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]

$$R(q^2) \equiv \sigma_D/\sigma_\mu \propto k_D^{3/2} \exp(-k_D^2/\Gamma), \quad k_D = \sqrt{\frac{[q^2-(m_1+m_2)^2]\,[q^2-(m_1-m_2)^2]}{4q^2}}. \tag{8}$$

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 GeV 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 $\Gamma \sim 0.125\ \text{GeV}^2$ is needed [9]. *We stress: it is not adequate to write the form factor simply as* $F(q^2)$ *since the charmed meson masses are ignored and the form factors (and common kinematical factors) vary strongly with changing momentum* $k_D(q^2)$ [5]. The q^2-dependence of the momenta for the final state channels $D\bar{D}$, $D\bar{D}^*$ and $D^*\bar{D}^*$ is given in Ref. [9]. 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.

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

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

The above assumption $F_q \gg F_c$ may now be investigated by considering the combination

$$\sigma_{D^*\bar{D}^*}(s_3) - \sigma_{D\bar{D}^*}(s_2) - 3\sigma_{D\bar{D}}(s_1) \propto F_c F_q \sim 0 \tag{9}$$

which should be small for any momentum value. This relation might even be used to predict the 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 consistency checks. Other tests result from combining the cross sections for charged and neutral D-production. For example

$$\frac{\sigma_{D^0 D^{0*}}(s_2)}{\sigma_{D^+ D^{-*}}(s_2')} = \frac{\frac{2}{3} F_c + \frac{2}{3} F_u}{\frac{2}{3} F_c - \frac{1}{3} F_d} \approx 1 + \frac{F_u + F_d}{F_c}, \tag{10}$$

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.

We assume that j_c^μ dominates. We then may determine the ratio of magnetic to electric form factors by considering the combination

$$\frac{\sigma_{D^*\bar{D}^*}(s_3)}{\sigma_{D\bar{D}}(s_1)} - 3 \propto 4 \left| \frac{F_c^{(M)}}{F_c^{(E)}} \right|^2 \left(\frac{E_D}{m_D} \right)^2, \tag{11}$$

where the shape of $F_c^{(M)}(k_D)$ is determined by $\sigma_{D\bar{D}^*}$; again this reasoning can be applied to the charged and neutral cases separately. These methods are however only applicable under the following restrictions:

(*i*) No resonance is present in the energy range where the size of the form factors are determined.

(*ii*) The electric quadrupole coupling must be negligible.

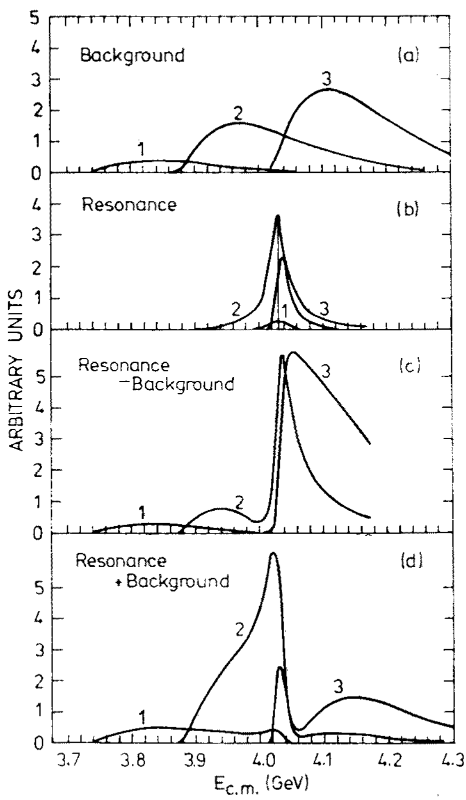

Fig. 2. D-pair production in e⁺e⁻ annihilation supposing (a) a nonresonating background, (b) a resonance at 4.03 GeV and their possible interference (c) and (d)

Resonances. The electromagnetically produced $c\bar{c}$-pair can form ψ-resonances at specific energies which subsequently decay into charmed mesons; this leads to a resonance part R_c in addition to the background parts B_c and B_q

$$F_c = R_c + B_c, \quad F_q = B_q. \tag{12}$$

If B_q is nonnegligible, 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 $B \equiv Q_c \cdot B_c + Q_{\bar{q}} \cdot B_q$ 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. 2.

Our results are summarized:

1) Assuming an equal 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].

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 [10].

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.

One of the authors (B.H.) would like to thank Fred Gilman, Dick Blankenbecler and M. Suzuki for discussions and he wishes to express his gratitude for the warm hospitality of Professor S. D. Drell and SLAC.

REFERENCES

[1] G. Goldhaber et al., *Phys. Rev. Lett.* **37**, 255 (1976); I. Peruzzi et al., *Phys. Rev. Lett.* **37**, 56 (1976); G. Goldhaber, Lawrence Berkeley Laboratory preprint LBL-4883, 1976; G. Goldhaber SLAC Summer Institute, 1976.

[2] M. K. Gaillard, B. W. Lee, J. L. Rosner, *Rev. Mod. Phys.* **47**, 277 (1975); see also: B. Humpert, *Dynamical Concepts on Scaling Violation and the New Particles in e^+e^- Annihilation, Lecture Notes in Physics*, No. 45 Springer-Verlag, Berlin 1976.

[3] A. DeRujula, H. Georgi, S. L. Glashow, *Phys. Rev. Lett.* **37**, 398 (1976).

[4] K. Lane, E. Eichten, *Phys. Rev. Lett.* **37**, 477 (1976).

[5] Similar ideas have also been proposed in Ref. [8] where however the strong momentum dependence of form factors has been ignored.

[6] N. Cabibbo, R. Gatto, *Phys. Rev.* **124**, 1577 (1961); Y. S. Tsai, *Phys. Rev.* **D12**, 3533 (1975).

[7] In order to present the essential ideas as clear as possible we refrain from complete generality and ignore the form factor $F^{(Q)}$ (which is expected to be small from the experience with noncharmed hadrons) and do not allow for a $^3D_1$ component in D*.

[8] F. E. Close, Rutherford Laboratory preprint RL 76 112, 1976.

[9] B. Humpert, *Phys. Rev.* **D16**, 1327 (1977).

[10] Similar ideas have also been pursued by M. Suzuki, W. Wada, Lawrence Berkeley Laboratory preprint LBL-5377, 1976.