Two kinds of the mass of the charmed quark

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It is argued that when a pair of a charmed quark and a charmed antiquark is produced via one photon, the mass of the charmed quark is to be light, i.e., roughly 500 MeV, quite contrary to the heavy mass usually assumed. It is thus proposed that we have to discriminate between, at least, two kinds of the mass of the charmed quark that are exhibited in different situations.

The spectroscopy of the ψ/J particle and the charmed particle can be well described by a picture in which they are nonrelativistic composite states of a quark and an antiquark bound together by a confinement potential. In this picture, the mass, or what will be called the *effective mass,* of the charmed quark is assumed to be about 1.5 GeV.[1] In this paper we will analyze the jet structure and conclude that the data suggest that when a pair consisting of a charmed quark and a charmed antiquark is produced via one photon, the mass of the charmed quark, to be defined by Eq. (3), is not so heavy as 1.5 GeV. This mass will hereafter be called the *mechanical mass.* Such a result enables us to propose that for the charmed quark there are, at least, two kinds of mass which are exhibited in different situations. We also propose methods for establishing experimentally the existence of the two kinds of mass.

The phenomenon with which we shall mainly be concerned here is the jet structure[2] in e^+e^- annihilation with $\alpha = 0.97 \pm 0.14$. Here α is defined by[2]

$$\alpha = \frac{\sigma_T - \sigma_L}{\sigma_T + \sigma_L} , \qquad (1)$$

and it is experimentally determined by analyzing the azimuthal angular dependence of the jet axis. According to G. Hanson[2] the most recent value of α is given by

$$\alpha = 0.97 \pm 0.14 . \qquad (2)$$

In the quark-parton model, on the other hand, this value depends on the mass m of the produced quark:

$$\alpha = \frac{E^2 - m^2}{E^2 + m^2} , \qquad (3)$$

where E is the energy of the produced quark. The fundamental assumption made in deriving Eq. (3) is that the orientation of the jet axis is identical with that of the quark. Here it is also assumed, as usual, that the quark is a Dirac particle with the minimal electromagnetic interaction. We de-

fine the *mechanical mass* of the quark by Eq. (3).

At $E_{\text{c.m.}} = 7.4$ GeV, where the experiment was done, the charmed quark as well as the ordinary quarks (u, d, s) are produced. The production of a heavy lepton will be taken into account later. The ratio of the production rate of the charmed quark to that of the ordinary quarks is $(\frac{2}{3})^2 : (\frac{2}{3})^2 + (\frac{1}{3})^2 + (\frac{1}{3})^2 = 4 : 6$. Assuming that

$$m_u = m_d = 300{-}400 \text{ MeV} ,$$
$$m_s = 500 \text{ MeV} , \qquad (4)$$

we obtain the following from Eq. (3):

$$\alpha_{\text{ordinary}} = 0.97{-}0.98 , \qquad (5)$$

which is the value of α to be taken for the case of the production of only the ordinary quarks.

Thus taking into account the above ratio $4 : 6$, we find from Eqs. (2) and (5) that

$$\alpha_{\text{charm}} = 0.97{-}0.96 \quad (\pm 0.14), \text{[3]} \qquad (6)$$

which, together with Eq. (3), leads to

$$m_c = 400{-}500 \text{ MeV} \quad (\sim 1160 \text{ MeV}) . \qquad (7)$$

That is, if the mean value of Eq. (2) is adopted, the mechanical mass of the charmed quark is determined to be much lighter than the effective mass, 1.5 GeV, and to be approximately equal to that of the ordinary quarks. In view of the large experimental error, however, the above numerical value of m_c is not to be taken seriously. In fact, in the case of the largest experimental error, the value $m_c = 1160$ MeV is obtained. However, we may take the result of the above analysis as an indication that the mechanical mass is much lighter than the effective mass.

Even when $m_u = m_d = m_s = 0$ is assumed instead of Eq. (4), the mean value of Eq. (2) gives us $m_c = 700$ MeV. When the existence of the heavy lepton[4] with a mass about 2.0 GeV is assumed, the corresponding mechanical mass m_c turns out to be smaller than Eq. (7), irrespective of any detailed assumptions. Thus we may say the existence of the heavy

lepton strengthens the possibility of the lighter mechanical mass.

How can we then test the possibility of the light mechanical mass of the charmed quark? One method is to measure the α with smaller experimental errors (e.g., by 4π detector). Another method is to measure the azimuthal angular dependence (or the polar angular dependence) of the inclusive charmed-meson production, thereby determining the α versus the Feyman variable x. At the center-of-mass energy 7.4 GeV, the α will approach the limiting value as x goes to unity:

$$\alpha \to 0.97 \quad \text{for} \quad m_c = 0.5 \text{ GeV} ,$$

$$\alpha \to 0.72 \quad \text{for} \quad m_c = 1.5 \text{ GeV} . \tag{8}$$

Thus the limiting value of the α will discriminate between the light and heavy mechanical masses.

The third method is to measure the ratios of the pair productions of the charmed mesons,[5] and the fourth method to measure the angular distribution of $D^*\overline{D}^*$ production. Here we need to assume that the quark-parton model can be applied to exclusive production. By counting the number of spin states, De Rújula, Georgi, and Glashow[6] derived the following ratios for the pair productions:

$$(D\overline{D} : D\overline{D}^* + D^*\overline{D} : D^*\overline{D}^*)_{\text{spin}} = 1 : 4 : 7 . \tag{9}$$

Lane and Eichten[6] obtained a similar result but with additional momentum dependent factors in the $D^*\overline{D}^*$ production rate.

If the mechanical mass of the charmed quark is light, the ratios, Eq. (9), will be modified significantly. As shown by Close[7], the ratios of the pair productions of the charmed mesons by a transverse photon and by a longitudinal photon are given, respectively, by

$$D\overline{D} : D\overline{D}^* + D^*\overline{D} : D^*\overline{D}^* = 0 : 4 : 4 \ (T) ,$$

and $\hspace{11cm}$ (10)

$$D\overline{D} : D\overline{D}^* + D^*\overline{D} : D^*\overline{D}^* = 1 : 0 : 3 \ (L) .$$

Equations (1) and (3) lead to

$$\sigma_L / \sigma_T = m^2 / E^2 . \tag{11}$$

Thus from Eqs. (10) and (11) the ratios of the pair productions of the charmed mesons are found to be[8]

$$D\overline{D} : D\overline{D}^* + D^*\overline{D} : D^*\overline{D}^* = 1 : 4E^2/m^2 : 3 + 4E^2/m^2 . \tag{12}$$

If we put $E = m$, the ratios turn out to be $1 : 4 : 7$, as derived in Ref. 6. In the cases $m_c = 1.5$, 1.0, and 0.5 GeV, we obtain, e.g., at $E_{\text{c.m.}} = 4$ GeV, the following results:

$$D\overline{D} : D\overline{D}^* + D^*\overline{D} : D^*\overline{D}^*$$

$$= 9 : 64 : 91 \quad \text{for} \ m_c = 1.5 \text{ GeV} ,$$

$$= 1 : 16 : 19 \quad \text{for} \ m_c = 1.0 \text{ GeV} ,$$

$$= 1 : 64 : 67 \quad \text{for} \ m_c = 0.5 \text{ GeV} . \tag{13}$$

Most of the data available at present[5] have been taken at $E_{\text{c.m.}} = 4.028$ GeV, where the threshold effect is significant.[9] If we assume[5] $m_{D^0} = 1864$ MeV and $M_{D^{0*}} = 2005$ MeV, the ratios of the available phase space are given by

$$(D\overline{D} : D\overline{D}^* + D^*\overline{D} : D^*\overline{D}^*)_{\text{phase space}} = 65 : 25 : 1 . \tag{14}$$

The data cannot be fitted by combining Eqs. (13) with (14) unless an ad hoc form factor is introduced. We interpret this result as a reflection of the structure[10] of the resonance, since the energy $E_{\text{c.m.}} = 4.028$ GeV lies at the peak of the resonance. The data off the resonance will indicate what value is taken by the mechanical mass of the charmed quark.

Let us now turn to the fourth test. The angular distributions for the cases of a transverse photon and of a longitudinal photon are given, respectively, by

$$\tfrac{1}{2}(1 + \cos^2\theta) \ (T) ,$$

and $\hspace{11cm}$ (15)

$$(1 - \cos^2\theta) \ (L) .$$

Equations (11) and (15) then give the following angular distribution[8] of $D^*\overline{D}^*$ production:

$$2(1 + \cos^2\theta) + (3m_c^2/E^2)(1 - \cos^2\theta) . \tag{16}$$

For $E_{\text{c.m.}} = 4$ GeV, Eq. (16) gives

$$1 + \tfrac{5}{59}\cos^2\theta \quad \text{for} \ m_c = 1.5 \text{ GeV} ,$$

$$1 + \tfrac{5}{11}\cos^2\theta \quad \text{for} \ m_c = 1.0 \text{ GeV} , \tag{17}$$

$$1 + \tfrac{29}{35}\cos^2\theta \quad \text{for} \ m_c = 0.5 \text{ GeV} .$$

We hope that it is possible to discriminate experimentally between at least the two cases $m_c = 1.5$ GeV and $m_c = 0.5$ GeV by the present method.

If it can really be established that the mechanical mass is different from the effective mass, 1.5 GeV, how do we interpret such a result? One possible explanation is as follows: In hadrons, quarks are attached to a string and the effective mass of a quark includes the kinematic energy of the string (or gluons) as well. On the other hand when a pair consisting of a quark and an antiquark is produced via one photon the quark is free from such a string at the instant of production (e.g., as in the asymptotic free theory), thereby obtaining the lighter mass.

The mechanical mass will be different from the effective mass even in the cases of the ordinary

quarks. However, since the effective mass itself is light for the ordinary quark, it will be difficult to discriminate experimentally between the mechanical and the effective masses. If the difference between the two is experimentally established in such cases, it will provide a very important clue to understanding the structure of hadrons and also

to answering the question of why the effective mass of the charmed quark is heavy. In view of this it is highly desirable to try such experimental tests as suggested in the above discussion.

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[1]See, e.g., E. Eichten, K. Gottfried, T. Kinoshita, J. Kogut, K. D. Lane, and T.-M. Yan, Phys. Rev. Lett. 34, 369 (1975).

[2]G. Hanson, in *Proceedings of the XVIII International Conference on High Energy Physics, Tbilisi, 1976,* edited by N. N. Bogolubov *et al.* (JINR, Dubna, U.S.S.R., 1977); see also G. Hanson *et al.,* Phys. Rev. Lett. 35, 1609 (1975).

[3]We have assumed that the experimental error in the case of charm production is the same as in the case of ordinary-meson production. Since some models of charmed-quark decay suggest it will give fewer particles at large x than the three ordinary quarks, the experimental errors in the case of charm production might be larger than ordinary-meson production. In this case the upper value 1160 MeV in Eq. (7) will become larger, although the mean value 400–500 MeV

does not change. However, the following discussion does not depend strongly on the value 1160 MeV.

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