REMARKS ON NEW MESON STATES

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We discuss some of the phenomenological consequences of the assumption that the new meson seen in e^+e^- and hadron collisions is the lowest spin one state containing a charmed quark and the corresponding antiquark.

There has been much recent interest in the possibility of new hadronic degrees of freedom associated with extensions of the quark model – e.g. to SU(4) [1,2] or to SU(3) × SU(3)′ [3] symmetries. The new quantum numbers are charm and color, respectively. There exists a body of phenomenology concerning the new hadronic states associated with these enlarged quark models [1–7].

In this paper we shall discuss the production of charmed mesons in e^+e^- collisions, attempting to avoid overlap with the extensive work of Gaillard, Lee and Rosner, to which we refer the reader for material not covered here [6]. The SU(4) quark model is fixed by adding a fourth $Q = 2/3, I = S = 0$ "charmed" quark to the usual set q = u, d, s [1–7]. One can add components $i = 1, 2, 3$ to each quark so as to take or der 3 parastatistics into account (sometimes called color) [3,9]. Besides the usual $q\bar{q}$ states, there are new pseudoscalars $D^+ = c\bar{d}$, $D^o = c\bar{u}$, $F^+ = c\bar{s}$, $\eta_c = c\bar{c}$ as well as D^-, D^o, F^-, completing a **15** + **1** of SU(4) [1, 7]. There is a similar set D^*, F^*, $\bar{D}^*$, $\bar{F}^*$ of vector mesons as well as scalars D_s, F_s, ϵ_c. In the usual quark model classification these are $^1S_0$, $^3S_1$ and $^3P_0$ states; higher ones should exist as well.

We shall discuss the new meson states; when we require masses we shall assume that the new state seen in $pp \to e^+e^- + X$ and $e^+e^- \to$ hadrons, $\mu^+\mu^-$ is the ϕ_c [‡1], $m_{\phi_c} = 3.1$ GeV.

I. The ϕ_c (3.10 GeV): This state has a γ-ϕ_c coupling $f_{\phi c} = (3/2\sqrt{2}) f_\rho$ where $f_\rho^2/4\pi \sim 2$. Then $\Gamma(\phi_c \to e^+e^-) \approx 26$ keV; this can only be an estimate, since SU(4) is badly broken in masses, and perhaps in couplings. If a $c\bar{c}$ state did not mix at all with $q\bar{q}$ via strong interactions, then $\Gamma(\phi_c \to \text{hadrons})/\Gamma(\phi_c \to e^+e^-)$ should be of order R where $R = \sigma(e^+e^- \to \text{hadrons}) \times (\sigma(e^+e^- \to \mu^+\mu^-))^{-1}$. A larger ratio would suggest $q\bar{q} \leftrightarrow c\bar{c}$ mixing (fig. 1). If the ϕ_c is produced singly in hadronic processes then it must mix with $q\bar{q}$, but it may do so very weakly. Such mixing is very small for $s\bar{s} \leftrightarrow (u\bar{u}, d\bar{d})$ and may be much smaller for $c\bar{c} \leftrightarrow q\bar{q}$ [‡2]. A very small $\Gamma(\phi_c \to \text{hadrons})$ need not contradict the charm origin of the ϕ_c.

The ϕ_c is an SU(3) singlet, so if the $c\bar{c} \leftrightarrow q\bar{q}$ mixing conserves isospin the final states with an even number of pions are disallowed ($\pi^+\pi^-, \pi^+\pi^-\pi^+\pi^-$, etc.), but K^+K^- is allowed. Absence of 4π state would prove $I_{\phi c} = 0$ and that $c\bar{c} \leftrightarrow q\bar{q}$ conserved I. We also have

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‡1 H. Schopper (public communication) and MIT and SLAC preprints (submitted to Phys. Rev. Lett.). If the ϕ_c is a $c\bar{c}$ state the quadratic mass formula in refs. [6,7] gives the masses cited in the text. The baryon masses all lie above 4.5 GeV. We presume that the ϕ_c is a $J = 1$ hadronic state. The alternatives available at present are c = color and c = charm. We discuss charm. The two possibilities are distinguished by their multiplet structure and their decays (c ≠ 0 states decay weakly and colored states electromagnetically [8]). The ϕ_c might in the color case be a degenerate pair of states in an SU(3) × SU(3)′ (1, 8) representation. There is now rumored evidence for states above 3.1 GeV in e^+e^- annihilation..

‡2 It would be the same if SU(4) were exact and the mixing an SU(4) singlet [6]. Suppression of Γ(Had) compared to the estimate of ref. [6] might indicate SU(4) breaking for couplings. The suppression of Γ_{had} and $\Gamma_{e\bar{e}}$ indicated by the experiments of footnote ‡1 might arise naturally in case (i) discussed in the text, which implies via duality that $f_{\phi c}/m_{\phi c}$ and not $f_{\phi c}$ should approximately obey SU(4) symmetry.

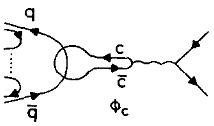

Fig. 1. Production and $c\bar{c} \leftrightarrow q\bar{q}$ mixing decay of the ϕ_c.

$\sigma(\bar{K}^o \overset{*}{K}{}^o) = \sigma(K^+\overset{*}{K}{}^-) = \sigma(\pi^+\rho^-)$ if the mixing preserves SU(3). In many pion final states, $\langle n(\pi^o)\rangle = \langle n(\pi^+)\rangle$ and the charged pions carry off 2/3 of the CM energy. If the hadronic decay proceeds as in fig. 1, then we expect the final state to look like that in $e^+e^- \to$ hadrons at a nearby energy – apart from the fact that 1/3 of the events should have a $K\bar{K}$ pair, versus 1/6 for $e^+e^- \to$ hadrons nearby. Multiplicities and momentum distributions should look similar. Apart from the $K\bar{K}$ fraction, this would hold also for electromagnetic mixing. It might even hold for a color ϕ_c if the decay were by mixing and not via γ emission. For the charm case, the ratio $\Gamma(K^+K^-)/\Gamma(\text{Had})$ should be, in order of magnitude only $\sim |F_K(S = m^2_{\phi c})|^2 \sim 10^{-2} - 10^{-3}$.

A vital question concerns $J = 1$ (daughter) recurrences of the ϕ_c. The mass formula can read

$$m^2_{\phi c(k)} = m^2_{\phi c} + \mathcal{M}^2 k \qquad (1)$$

with (i) $\mathcal{M}^2 \approx (\alpha')^{-1} \approx 1$ GeV^2 and (ii) $\mathcal{M}^2 \approx m^2_{\phi c}$ as extremes. The fact that normal and strange particles seem to lie on parallel trajectories speaks for the former. For the latter: if the higher (radially excited) ϕ_c average in some sense the charm contribution to $R = 10/3 - 2 = 4/3$, then this is roughly $|2\pi^2 m^2_{\phi c}/f^2_{\phi c} \times \mathcal{M}^{-2}$ is the spacing. For $f_{\phi c} \sim f_\rho$ this implies $\mathcal{M}^2 \sim m^2_{\phi c}$; a $c\bar{c}$ potential of radius $\sim m^{-1}_{\phi c}$ would also lead to a spacing $\mathcal{M}^2 \sim m^2_{\phi c}$ [‡3]. In case (i) there would be a $\phi_c(k)$ every ~200 MeV above 3.1 GeV. In the latter case, the states are at 4.4 GeV and 5.3 GeV, etc. It may be that the odd k states are missing [10]. We should remark that the radially excited states may have very small production cross sections in hadronic reactions. They (unlike the ϕ_c) should decay strongly to charmed hadrons if $m_{\phi c(k)} \gtrsim 4.3$ GeV; otherwise they are narrow. They might even remain narrow above the charm threshold, since high radial excitations may nearly decouple from the low D and F states. This feature might also hold for a colored ϕ_c.

We also expect $J = 2$ $c\bar{c}$ states (analogous to $f' = s\bar{s}$) which can be produced in $\gamma\gamma$ collisions or as one of a pair (e.g. $\phi_c f_c$ $(J = 2)$) in e^+e^- annihilation. These $J = 2$ states may have substantial branching ratios to $\gamma\gamma$ if m_{fc} is below the charm threshold. The $\gamma\gamma$ collision cross sections are hard to estimate, and we prefer to go on to

II. The η_c (3.01 GeV): We assume that this $I = 0$ pseudoscalar is pure $c\bar{c}$. The relation to the states of Gaillard et al. [6] is

$$\begin{aligned} \eta' &= \eta' \cos\theta + \eta_c \sin\theta \\ \eta_c &= -\eta' \sin\theta + \eta_c \cos\theta \end{aligned} \qquad \theta = 30^\circ. \qquad (2)$$

The assumption of a pure $\eta_c = c\bar{c}$ means that the SU(3) singlet η' has $\Gamma(\eta' \to \gamma\gamma) \approx 6$ keV; the SU(4) singlet η' chosen in ref. [6] would have a $\gamma\gamma$ width $(5/3)^2$ times larger. In the Han-Nambu model the factor is 4 [11], even for the usual SU(3) singlet η'. We have assumed here that the ratios of the matrix elements to $\pi^o \to \gamma\gamma$ are given by quark charge counting. If we do the same for $\eta_c = c\bar{c}$, $\Gamma(\eta_c \to \gamma\gamma) \approx 300$ keV and this leads to $\gamma\gamma$ production cross sections $\sigma(e^+e^- \to e^+e^-\eta_c) \sim 0.5$ nb at $\sqrt{s} = 8$ GeV. If $c\bar{c} \leftrightarrow q\bar{q}$ is small, a major decay mode could be $\eta_c \to \gamma\gamma$ and the state could be found in the $\gamma\gamma$ mass distribution for $\sigma(e^+e^- \to \gamma + \gamma + \text{missing energy})$. The η_c could also be produced via $\phi_c \to \eta_c\gamma \to 3\gamma$ [‡4]; we estimate $\Gamma(\phi_c \to \eta_c\gamma) \sim 30$ eV. The state could also be produced in e^+e^- annihilation at higher energies – especially through $\eta_c\gamma$ decay of the $\phi_c(k)$ states – where phase space is less critical. For the η' of ref. [6], the branching ratios of the $\phi_c(k)$ to $\eta'\gamma$ may be substantial.

Amusingly, there may be a 0^+ ϵ_c state at 3.1 GeV which could also be produced by (and decay into) $\gamma\gamma$. This can be separated from the η_c by measuring $\sigma_\| - \sigma_\perp$ [12] in $\gamma\gamma$ collisions, since even (odd) normality states contribute positively (negatively) to $\sigma_\| - \sigma_\perp$. This ϵ_c state can also be produced via $e^+e^- \to \phi_c(k) \to \epsilon_c\gamma$.

Some of these remarks may even hold for the case of colored ϕ_c, η_c, ϵ_c. The disadvantage here is our ignorance of the expected spectroscopy.

‡3 This has also been noted by M. Krammer (private communication).

‡4 Suggested by H. Joos.

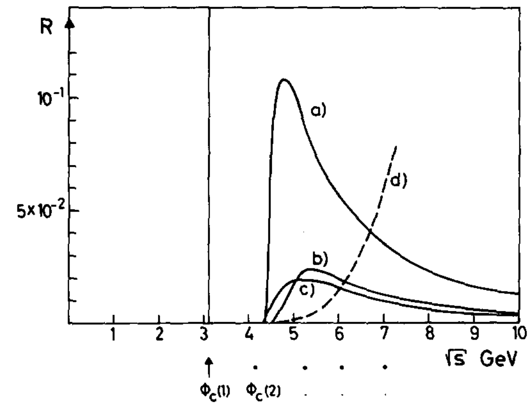

Fig. 2. R_{AB} for (a) AB = $F\bar{F}^* + F^*\bar{F} + D\bar{D}^* + \bar{D}D^*$, (b) AB = $F^*\bar{F}^* + D^*\bar{D}^*$, (c) AB = $F\bar{F} + D\bar{D}$, (d) A guess at the multibody cross section.

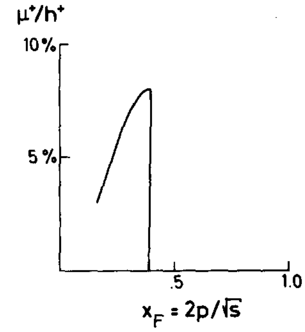

Fig. 3. μ^+/h^+ ratio as a function of $x_F = 2p/\sqrt{s}$ assuming 40% of all events have charmed particles with nonleptonic branching ratio 10%. The charmed particles are taken to be at rest, and we have assumed that $s\, d\sigma^h/dx_F$ scales for $x_F \gtrsim 0.2$. We choose $\sqrt{s} = 5.5$ GeV.

III. D(2.13 GeV), F(2.18 GeV), D*(2.26 GeV), F*(2.30 GeV): These states can be pair produced in e^+e^- annihilation: D^+D^-, $D^o\bar{D}^o$, F^+F^-, F^+F^- ..., $F^{*+}F^-$, etc. The thresholds are close together for all these states. Well above threshold a gap in rapidity will develop between the charmed pairs; this gap will be filled by multibody states containing ordinary mesons and the two body channels will decrease rapidly in importance.

It seems worthwhile to attempt a crude estimate of the cross sections for these two body states near threshold. Besides the importance of multibody states far above threshold, higher $\phi_c(k)$ would lead to gigantic enhancements. These may be localized unless $\Gamma(\phi_c(k) \to D\bar{D}\ ...)$ are large. For a threshold estimate we neglect the higher ϕ_c and assume dominance of the form factors by ρ, ω, ϕ, ϕ_c. If we assume that SU(4) can be used for the couplings f_V, $g_{VD\bar{D}}$, etc. – i.e. that the major breaking of SU(4) is in masses – then we find that the cross sections depend mainly on the contribution of the ϕ_c to the form factors and writing $R_{AB} = \sigma(e^+e^- \to AB)/\sigma(e^+e^- \to \mu^+\mu^-)$ we have

$$R_{F^+F^-} = R_{D^+D^-} = R_{D^o\bar{D}^o} =$$

$$= \tfrac{1}{4}(\tfrac{2}{3})^2 \left(1 - \frac{4m^2}{s}\right)^{3/2} \left(\frac{m_{\phi_c}^2}{s - m_{\phi_c}^2}\right)^2 . \qquad (3)$$

For exact SU(4), $R_{D^o\bar{D}^o} = 0$ [6]. We can now do the same for the pseudoscalar-vector and vector-vector states. For the former we take the dimensionless couplings equal to $g_{\rho\omega\pi}/m_\rho$ times SU(4) factors and for the latter we use VDM for the charge form factors, arbitrarily setting $F_M = F_Q = 0$ [13]. The results are shown on fig. 2.

If our estimate is at least correct as to order of magnitude, the contribution of charmed states to R away from $s = m^2_{\phi c(k)}$ may be small until well above threshold. In this connection we might remark that the whole energy scale involved in the production of charmed states may be stretched by a factor $\sim m^2_{\phi c}/m^2_\rho$ over that familiar from low energy e^+e^- annihilation (case (ii) mentioned above).

Of course, the best place to look for these charmed mesons is at $s = m^2_{\phi c(k)}$ provided $m_{\phi c(k)} > 2m_{\rm charm}$. From the mechanism of fig. 1 we expect in general for such states that $\Gamma(D^o + \chi) = \Gamma(D^+ + \chi) = \Gamma(F^+ + \chi)$, and similarly for the other $C \neq 0$ mesons in $\phi_c(k)$ decay.

If we take the optimistic view that not too far above threshold the charmed states occur in about 40% of the events, then several comments become appropriate. First, about half the events would contain $K\bar{K}$ pairs (this is well known [6]) and, second, the inclusive direct μ^+/h^+ ratio offers a distinctive signature for charmed particles. If we assume that the semileptonic and leptonic branching ratios amount to ≈10% averaged over D and F mesons (D^*, $F^* \to \gamma D$, γF should dominate), then the rapid rise of the μ-spectrum with energy and the so far observed rapid drop of the charged hadron spectrum lead to a dramatic increase of the μ/h or e/h ratio with particle momentum. See fig. (3), obtained under the simplifying assumptions that the charmed hadrons are at rest and that $s\, d\sigma^h/dx_F$ scales for $x_F \geqslant 0.2$. Lastly, there is a small (0.4%) probability for the final state to contain a μe pair. All these features should be enhanced at a high mass $\phi_c(k)$.

This discussion leaves a number of problems untouched, mostly unrelated to e^+e^- annihilation. However, we should remark that the experimental behavior of R below the charm threshold at 4.3 GeV is unexplained [14]. Neither is the observed monotonous behavior of the K/π ratio up to 4.8 GeV, unless charm production really is small. The $\phi_c(k)$ can contribute to R away from $s = m^2_{\phi c(k)}$ via $e^+e^- \to \phi_c(k) + \gamma$. Whether this is related to the missing energy problem and the rise in R is unclear, as the $\phi_c + \gamma$ contribution depends sensitively on $f_{\phi c(k)}$. For $f_{\phi c(k)} \sim f_\rho$ the effects are substantial.

If the ϕ_c is invoked as a source of large p_T, μ and e, the problem of its production in the case of a small $q\bar{q} \leftrightarrow c\bar{c}$ mixing is acute. In taking the μ/π ratio at large p_T, the mixing cancels between production cross section and $\mu^+\mu^-$ branching ratio. It then seems as if each $\phi_c(k)$ contribution to the μ/π ratio is comparable to, say, the ϕ-contribution.

An interesting effect may occur in $e + p \to e' + \phi_c + X$ and $\nu(\bar{\nu}) + p \to \nu(\bar{\nu}) + \phi_c + X$. For deep inelastic ep scattering, we estimate the ϕ_c fraction to be

$$\frac{\sigma_T(\phi_c + X)}{\sigma_T(\text{tot})} \sim 0.01 \left(1 + \frac{Q^2}{m_0^2}\right)\left(1 + \frac{Q^2}{m^2_{\phi_c}}\right)^{-2} \qquad (4)$$

where $\sigma_T^{\text{tot}}(Q^2) \approx \sigma_T^{\text{tot}}(Q^2 = 0)(1 + Q^2/m_0^2)^{-1}$, $m_0^2 \approx 0.4\ \text{GeV}^2$ (4) is obtained from photoproduction estimates of ϕ_c production [4] [‡5]. The ϕ_c fraction thus *increases* with Q^2 for $Q^2 \lesssim m^2_{\phi c}$. The same rough estimate should hold for the ϕ_c fraction in neutral current events if the weak neutral current has a significant vector contribution. The fraction of $\mu^+\mu^-$ in neutral current events is just the above fraction times the $\mu^+\mu^-$ branching ratio. The above estimate is consistent with the observed dimuon fraction for a branching ratio of a few percent [15].

Lastly, we emphasize that the observation of a ϕ_c does not by itself tell one whether c = charm or c = color; observation of the other states is essential. Some of what we have said about the ϕ_c, η_c, ϵ_c may hold if c = color. Of course, it may be that something totally unexpected occurs, with the companions of the ϕ_c and its radial excitations unrelated either to color or charm.

For similar duality considerations and further references thereto, see ref. [16].

Stimulated by rumor, we note that for the charm model, decays like $\phi_c(k) \to \phi_c(k') + \text{hadrons}\,(k' < k)$ should have widths of the same order of magnitude as $\phi_c(k) \to$ hadrons via the mechanism of fig. 1, since a similar disconnected duality diagram is involved. The (uncharmed) hadrons in such a chain decay form a SU(3) singlet. Note further that via Zweig $\phi_c(k) \not\to \phi_c(k') + \eta'$ unless the η' of ref. [6] is chosen, in which case this is a strong decay. By contrast to the case of pure $c\bar{c}$ states, the $C \neq 0$ higher excitations should all be broad.

‡5 This estimate is based on $f_{\phi c} \sim f_\rho$; moreover $q\bar{q} \leftrightarrow c\bar{c}$ coupling suppressed with respect to $u\bar{u} \leftrightarrow s\bar{s}$ could lead to a suppression of the pomeron-ϕ_c coupling beyond that in ref. [4].

References

[1] Z. Maki, Prog. Theor. Phys. 31 (1964) 331, 333;
Y. Hara, Phys. Rev. 134 (1964) B701;
J.D. Bjorken and S. Glashow, Phys. Lett. 11 (1964) 255.
[2] S.L. Glashow, J. Illiopoulos and L. Maiani, Phys. Rev. D2 (1970) 1285, and many more cited in ref. [6].
[3] Y. Nambu and M.Y. Han, Phys. Rev. 10D (1974) 674.
[4] C.E. Carlson and P.G.O. Freund, Phys. Lett. 39B (1972) 349.
[5] G. Snow, Nucl. Phys. B55 (1973) 445.
[6] M.K. Gaillard, B.W. Lee and J.L. Rosner, Fermilab 74/86 THY.
[7] M. Nakagawa and H. Nitto, Prog. Theor. Phys. 49 (1973) 1322;
M. Kobayashi, M. Nakagawa and H. Nitto, Prog. Theor. Phys. 47 (1972) 982;
T. Hayashi, E. Kawai, M. Matsuda, S. Ogawa and S. Shige-eda, Prog. Theor. Phys. 47 (1972) 280, 1998. These papers are based on the Niu particle, whose mass implies $m_{\phi c} \sim 3$ GeV! See K. Niu, E. Mikumo and Y. Y. Maeda, Prog. Theor. Phys. 46 (1971) 1644.
[8] R.N. Cahn and J. Ellis, SLAC-PUB-1334.
[9] M. Gell-Mann, in Proc. XVI Intern. Conf. on High High energy physics, Chicago-Batavia, 1972.
[10] M. Böhm, H. Joos and M. Krammer, submitted to Phys. Lett. B.

[11] H. Suura, T.F. Walsh and B.L. Young, Lett. Nuovo Cim. 4 (1972) 505.
[12] H. Terazawa, Rev. Mod. Phys. 45 (1973) 615.
[13] G. Kramer and T.F. Walsh, Z. Physik 263 (1973) 361.
[14] B. Richter, plenary session talk at London Conf. 1974.
[15] D. Cline, Intern. Conf. on Neutrino physics, April 1974.
[16] D. Schildknecht and F. Steiner, DESY 74/55.