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Remarks on New Meson States

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S. Kitakado, S. Orito and T. F. Walsh
Deutsches Elektronen-Synchrotron DESY, Hamburg

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) x 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 $Q = 2/3$, $I = S = o$ "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 order 3 parastatistics into account (sometimes called color) (3),(8). 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 $\underset{\sim}{15} + \underset{\sim}{1}$ of SU(4) (1),(7). There is a similar set $D^*, F^*, \bar{D}^*, \bar{F}^*, \phi_c$ of vector mesons as well as scalars D_s, F_s, ϵ_c. In the usual quark model classification these are ${}^1S_o$, ${}^3S_1$ and ${}^3P_o$ 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 $f_{\phi_c} = \frac{3}{2\sqrt{2}} f_\rho$ where $f_\rho^2/4\pi \sim 2$. Then $\Gamma(\phi_c \to e^+e^-) \simeq 26$ 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 the 4π state would prove $I_{\phi_c} = 0$ and that $c\bar{c} \leftrightarrow q\bar{q}$ conserved I. We also have $\sigma(\bar{K}^0 K^0) = \sigma(K^+ K^-) = \sigma(\pi^+\rho^-)$ if the mixing preserves SU(3). In many pion final states, $\langle n(\pi^0)\rangle = \langle n(\pi^+)\rangle$ 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, vs $^1/_6$ 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 $\sim |F_K(s = m_{\phi_c}^2)|^2 \sim 10^{-2}$.

A vital question concerns J = 1 (daughter) recurrences of the ϕ_c .

The mass formula can read

$$m^2_{\phi_c(k)} = m^2_{\phi_c} + \mathcal{M}^2 k \tag{1}$$

with (i) $\mathcal{M}^2 \simeq (\alpha')^{-1} \simeq 1\ \mathrm{GeV}^2$ and (ii) $\mathcal{M}^2 \simeq m^2_{\phi_c}$ 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 $12\pi^2\, m^2_{\phi_c}/f^2_{\phi_c} \times \mathcal{M}^{-2}$ where $\mathcal{M}^2$ 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 $\sim$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(9). 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_{f_c} 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 = o pseudoscalar is pure $c\bar{c}$. The relation to the states of Gaillard et al. (6) is

$$\eta' = \eta' \cos\theta + \eta_c \sin\theta$$
$$\theta = 30^\circ \qquad (2)$$
$$\eta_c = -\eta' \sin\theta + \eta_c \cos\theta$$

The assumption of a pure $\eta_c = c\bar{c}$ means that the SU(3) singlet η' has $\Gamma(\eta' \to \gamma\gamma) \simeq 6$ 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 (10), even for the usual SU(3) singlet η'. We have assumed here that the ratios of the matrix elements to $\pi^0 \to \gamma\gamma$ are given by quark charge counting. If we do the same for $\eta_c = c\bar{c}$, $\Gamma(\eta_c \to \gamma\gamma) \simeq 300$ 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 $\sigma(e^+e^- \to \gamma + \gamma$ + missing energy). The η_c could also be produced via $\phi_c \to \eta_c\gamma \to 3\gamma$ /4/; we estimate $\Gamma(\phi_c \to \eta_c\gamma) < 1$ keV. 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.

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 $\sigma_{\parallel} - \sigma_{\perp}$ (11) in $\gamma\gamma$ collisions, since even (odd)normality states contribute positively (negatively) to $\sigma_{\parallel} - \sigma_{\perp}$. 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.

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 $\Gamma(\phi_c(k) \to D\bar{D} \cdots)$ are large. For a threshold estimate we neglect the higher ϕ_c and assume dominance of the form factors by $\rho, \omega, \phi, \phi_c$. 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

$$R_{F^+F^-} = R_{D^+D^-} = R_{D^o\bar{D}^o} = \frac{1}{4}\left(\frac{2}{3}\right)^2\left(1 - \frac{4m^2}{s}\right)^{3/2}\left(\frac{m^2_{\phi_c}}{s - m^2_{\phi_c}}\right)^2 \qquad (3)$$

For exact SU(4), $R_{D^o\bar{D}^o} = 0$ (6). We can now do the same for the pseudo-scalar-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 $F_M = F_Q = 0$[12]. 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 streched 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 $m_{\phi_c(k)} > 2\, m_{charm}$

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 semi-leptonic and leptonic branching ratios amount to $\simeq$ 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 $x_F \gtrsim .2$. 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 [13]. 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

$$\frac{\sigma_T(\phi_c + X)}{\sigma_T(tot)} \sim .01 \left(1 + \frac{Q^2}{m_0^2}\right)\left(1 + \frac{Q^2}{m^2_{\phi_c}}\right)^{-2} \qquad (4)$$

where $\sigma_T^{tot}(Q^2) \cong \sigma_T^{tot}(Q^2=0)(1 + Q^2/m_0^2)^{-1}$, $m_0^2 \simeq 0.4\ GeV^2$
(4) is obtained from photoproduction estimates of ϕ_c production[4] /5/.

The ϕ_c fraction thus <u>increases</u> 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 per cent [14].

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 $\phi_c, \eta_c, \epsilon_c$ 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.

Footnotes

/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) and (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 ($c \neq o$ 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) x SU(3)' $(\underset{\sim}{1},\underset{\sim}{8})$ representation.

/2/ It would be the same if SU(4) were exact and the mixing an SU(4) singlet [6]. Suppression of $\Gamma(\mathrm{Had})$ compared to the estimate of Ref. (6) might indicate SU(4) breaking for couplings.

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

/4/ Suggested by H. Joos

/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).

Figure Captions

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

Fig. (2) R_{AB} for (a) $AB = F\overline{F^*} + F^*\bar{F} + D\overline{D^*} + \bar{D}D^*$

(b) $AB = F^*\overline{F^*} + D^*\overline{D^*}$ (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 $x_F \gtrsim .2$

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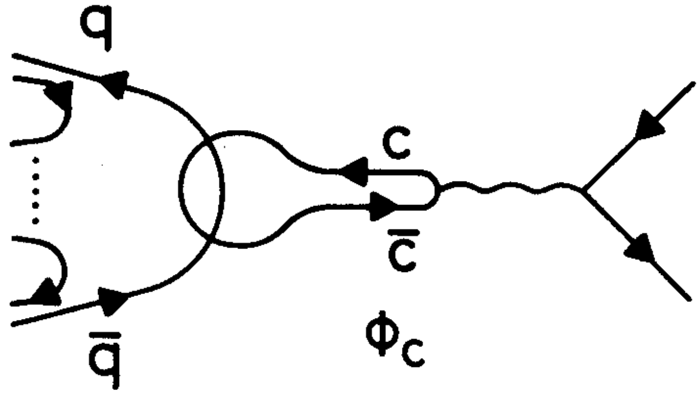

Fig. 1

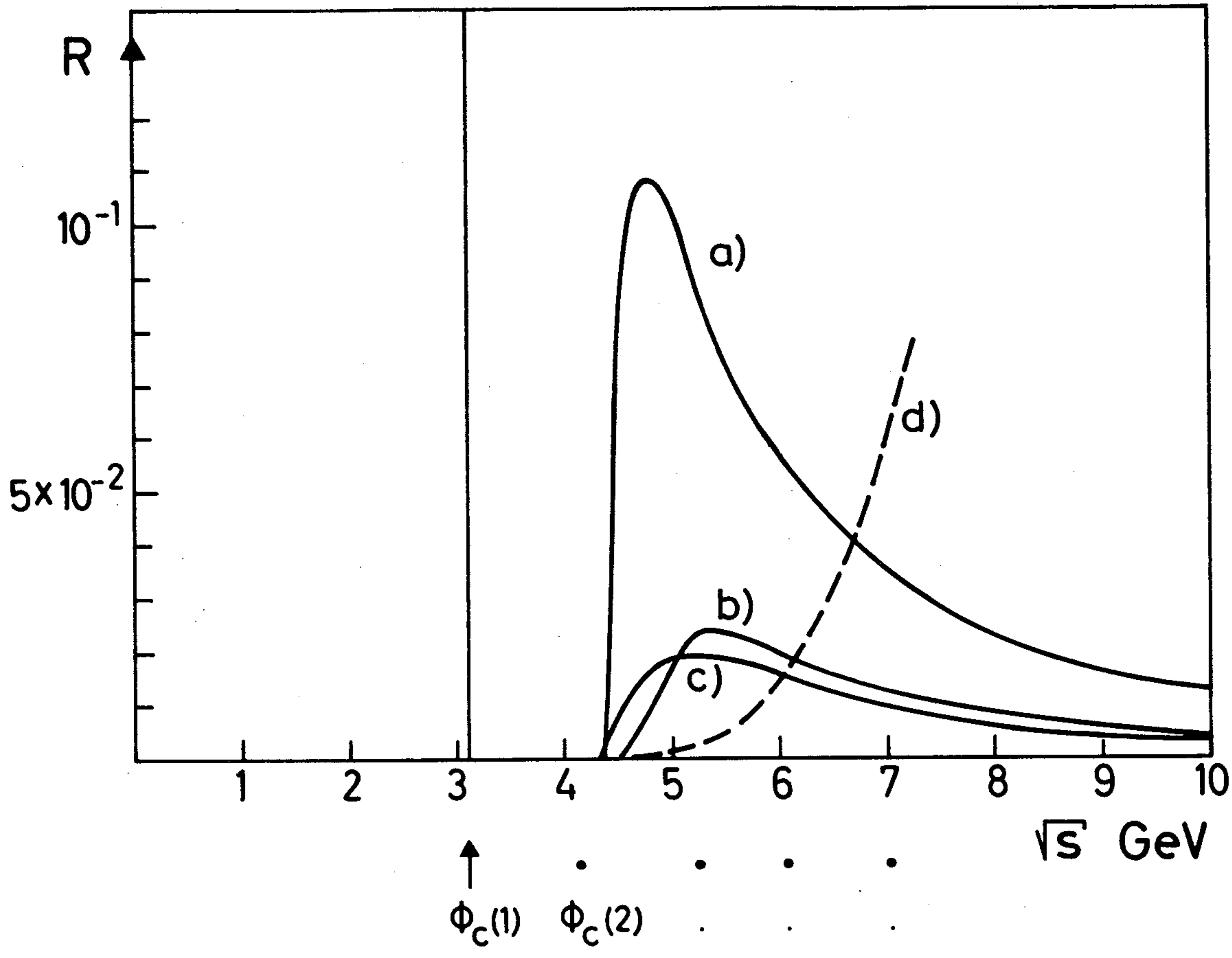

Fig. 2

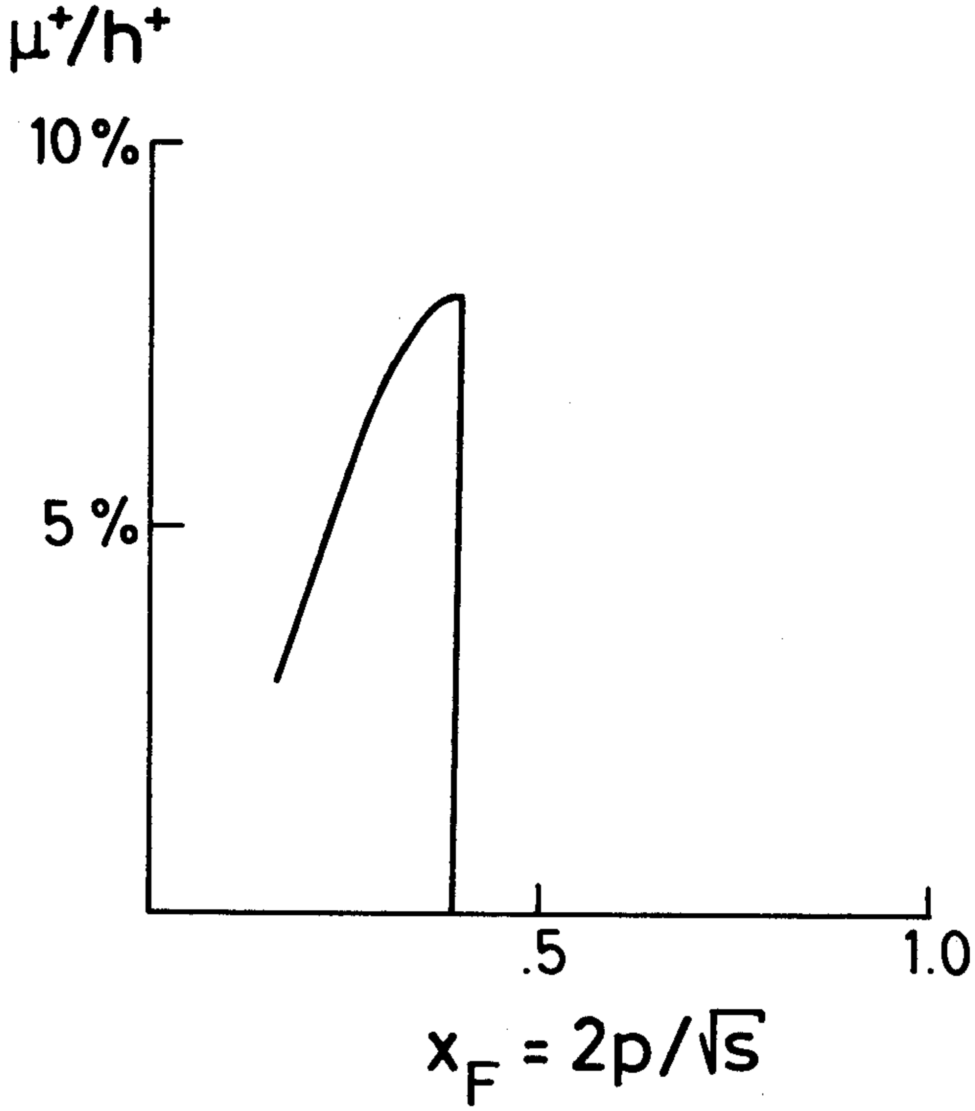

Fig. 3