A Possible Model for New Resonances

—Exotics and Hidden Charm—

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We assign $\psi(3695)$ to an exotic meson $cc(p\bar{p}+n\bar{n})$ and $\phi(3105)$ to a vector meson $cc$, respectively. Then we can explain naturally two facts: 1) $\psi(3695)$ decays strongly to $\phi(3105)+2\pi$ and 2) there is very little $\psi(3695)$ production compared with $\phi(3105)$ production in $pN$ scattering at Brookhaven. In this model we expect two broad resonances at $3.7\sim4.1$ GeV and at $\sim4.1$ GeV. We also predict another resonance at $\sim6.2$ GeV, which will be a sharp resonance if the mass is smaller than twice the mass of the lowest mass state of $cc$.

We can explain the small branching ratio of the decay $\rho'(1600)\rightarrow 2\pi$, assigning $\rho'(1600)$ to an exotic meson $(p\bar{p}+n\bar{n})(p\bar{p}+n\bar{n})$. We make some speculations on the decays of $\psi(3695)$ and other exotic mesons.

After the discovery of $J(3105)^1,^2,^3$ [or $\phi(3105)$], the second new sharp resonance $\psi(3695)$ has been observed at SLAC.\textsuperscript{4} [We shall refer to the resonance at 3105 MeV as the $\psi$ particle and the resonance at 3695 MeV as the $\psi'$ particle.] Very recently a broad bump at 4.15 GeV with width 250$\sim$300 MeV has also been observed.\textsuperscript{5}a) The tentative experimtal results are as follows:

\[ \Gamma(\psi\rightarrow all)\sim100 \text{ keV}, \]  
\[ \Gamma(\psi\rightarrow e^+e^-)\sim\Gamma(\psi\rightarrow \mu^+\mu^-)\sim\text{5 keV}, \]  
\[ \Gamma(\psi'\rightarrow all)\sim350 \text{ keV}, \]  
\[ \Gamma(\psi'\rightarrow e^+e^-)\sim\Gamma(\psi'\rightarrow \mu^+\mu^-)\sim\text{2.5 keV}, \]  
\[ \Gamma(\psi'\rightarrow 2\pi)\sim0.45\Gamma(\psi'\rightarrow all). \]

A yield of $\psi$ at BNL [assuming $d\sigma/dp_x \propto \exp(-6p_t)$, independent of $p_t$] which subsequently decays to $e^+e^-$ is approximately $10^{-34}\text{cm}^2$. However, to a level of 1% of $\psi$ yield, and with 90% confidence, no heavier particles were found in the region $3.2\sim4.0$ GeV.\textsuperscript{6} This means

\[ \sigma(pN\rightarrow \psi X)\sim2.5\times10^{-33}\text{ cm}^2 \]
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\[ \sigma(pN \to \psi'X) < 0.01 \frac{\text{B.R.}(\psi \to e^+e^-)}{\text{B.R.}(\psi' \to e^+e^-)} \sigma(pN \to \psi X) \]  \tag{7}

at \( E_L \sim 30 \text{ GeV} \).

Assuming that \( \psi \) and \( \psi' \) are produced via one photon in \( e^+e^- \) annihilation, we obtain \( J^{PC}=1^{--} \) for both. Since the decay \( \psi' \to \psi + 2\pi \) is due to the strong interaction [see below], the G-parities are the same for \( \psi \) and \( \psi' \). Thus the isospins are also the same. We assume \( I=0 \).

In previous work\(^6\) we investigated the possibility\(^7\) that \( \psi \) is the vector meson which is composed of the fourth-quark\(^6\) and fourth anti-quark \( c\bar{c} \). In Ref. 6) we made a prediction that the yield of \( \psi \) in \( pp \) scattering will begin to grow at \( p_L=40 \sim 60 \text{ GeV} \) and that at energies of NAL and ISR, it will be as high as, roughly, \( 10^{4\sim 5} \) times that reported at BNL. The experimental check of this prediction will be a clear test for the assumption that the quark-duality-diagram-constraint or the Okubo-Zweig-Iizuka rule\(^9\) [hereafter we refer to this rule as the OZI rule] is the mechanism to suppress the decay width of \( \psi \).

In this paper we propose a model that \( \psi' \) is an exotic state\(^{**} \) including a pair of charmed quark and anti-quark as well as a pair of ordinary quark and anti-quark \( c\bar{c} (p\bar{p} + n\bar{n}) \) [hereafter we call this model Model E]. We use the terminology 'exotics' for states whose configurations are not simply \( qq \) or \( qq \) [e.g., \( q\bar{q}q\bar{q} \)], even if their quantum numbers are allowed by the simple configuration \( qq \) or \( q\bar{q} \) [e.g., \( I=0 \)].

Our strong motive to consider exotic resonances is as follows: The fact that the OZI rule is well satisfied suggests, for example, a string picture\(^10\) of hadrons. If we consider a string picture of baryons as well as duality, we have to include exotic states.\(^11\) An exotic state can be shown as in Fig. 1(a). Although we do not necessarily restrict ourselves to this particular picture, we will use it hereafter as a guide to get some qualitative conclusions.

Before going into detail, we recapitulate some results in Ref. 11), to make this paper reasonably self-contained. Those who are familiar with Ref. 11) can skip this part since there are no new results.

![Fig. 1. An exotic state, a meson and a baryon.](https://academic.oup.com/ptp/article-abstract/54/2/492/1831244/7654249216831244)
A string picture of hadrons\textsuperscript{(10,11)}

A meson is a string with a quark at one end and an anti-quark at the other end [Fig. 1(b)] and a baryon is made of three strings joining at a point, carrying quarks at their free ends [Fig. 1(c)]. The string is supposed to be neutral except at the end, but oriented (to avoid strings with two quarks or two anti-quarks).

In our 4-dimensional space-time, strings sweep out 2-dimensional surfaces called "world sheets". Duality diagrams are topological drawings of these world sheets. By studying the topology of the world sheets, we find eight basic interactions [Fig. 2]. We can fix the power of the coupling constant of these basic interactions, from the requirement that each world sheet should be associated with the definite power of the coupling constant, independently from the channel (e.g., s-channel or t-channel) where we view the flow of the time. Let $\lambda$ be the coupling constant associated with interaction $a$. Then the results are given as in the right column.
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Fig. 3. Allowed transitions and a forbidden transition.

of Fig. 2. Some of the interactions are found to be associated with inverse powers of $\lambda$.

To draw duality diagrams in this scheme we need exotic states.

**Generalized OZI rule**

We propose that the transitions shown in Figs. 3(a) and 3(b) are allowed ones, while the transition from an exotic meson to an ordinary one, shown in Fig. 3(c), is a suppressed one. This rule is an extension of the OZI rule.

It was usually assumed that an exotic meson cannot couple with ordinary mesons [see the second reference in Ref. 11]. In our model there is no reason to suppress the transition 3(b); the interaction 2(d) is an allowed one, since it is associated with the same coupling constant as the interaction 2(a).

A more general rule may be that the interactions with negative powers of the coupling constant $\lambda$ [2(c), 2(f), 2(g), and 2(h)] are suppressed. Perhaps this rule might be too simple. For example, the interaction 2(c) seems to be suppressed only at low energies as will be discussed later.

Now we will derive some conclusions from the Model E and will compare them with those derived from another model [Model O/R] where $\psi'$ is considered as a radial excitation or an orbital excitation of $\psi$.

$$\psi' \rightarrow \psi + 2\pi$$

The branching ratio of the decay $\psi' \rightarrow \psi + 2\pi$ is about 45% of the total decay and $I'(\psi' \rightarrow \psi + 2\pi) \gtrsim 150$ keV. Jackson's analysis\textsuperscript{12b} shows that if we take the effec-
tive interaction

\[ H_{\text{int}} = g \phi_{\lambda} \phi_{\lambda} \phi_{\pm} \phi_{\mp} \, , \]  

then

\[ \Gamma_{(\phi' \to \phi + 2 \pi)} = 0.0204 \left( \frac{g^2}{4\pi} \right) \text{MeV} . \]  

Thus we obtain

\[ \frac{g^2}{4\pi} \gtrsim 7.4 . \]  

This number is reasonable if we assume that the decay \( \phi' \to \phi + 2\pi \) is due to the (unsuppressed) strong interaction in spite of its small width. The reason for its smallness is that the phase space is small for the final three bodies.

Here we have compared the magnitude of the coupling constant with those of \( \pi\pi\pi\pi \) (scattering at low energies) and \( \gamma\gamma\pi\pi \) (decay). The order of the magnitude of the coupling constant for the decay \( (\phi' \to \phi\pi\pi) \) is the same as those of these two interactions. We obtain, however, \( f^2/4\pi \sim 800^{+} \) for the decay \( (\rho' \to \rho\pi\pi) \), if we take the effective interaction \( f\rho'_{\lambda} \rho_{\pi\pi} \). This value is exceptionally large. We conjecture that \( \rho' (1600) \) may not be a single resonance.

![Diagram](https://example.com/diagram.png)

**Fig. 4.** The decay \( \phi' \to \phi + 2\pi \) in the Model E.

In the Model E, this decay is an allowed transition [see Fig. 4.] Thus the Model E explains naturally the fact that the decay width is reasonable with the assumption that the decay \( \phi' \to \phi + 2\pi \) is due to the strong interaction.

On the other hand, in the model O/R this decay should be suppressed by the OZI rule. So we have to assume, ad hoc, that in the channel \( f^{pe} = 0^{++} \) we need not take into account the OZI rule, or that because the invariant mass of the \( 2\pi \) channel is small, we can neglect the OZI rule on the assumption that the breaking of the OZI rule depends on the invariant mass of the disconnected channel. Another possible way to explain the decay width may be to assume, as the quark-duality-diagram-constraint, "pair productions or annihilations are forbidden in the same hadron" instead of "transitions corresponding to disconnected diagrams.

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* Addendum to Ref. 12.

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are forbidden". Then the diagram a) is allowed, while the diagram b) is forbidden in Fig. 5. The diagrams a) and b) are, however, equivalent topologically in the sense of the quark duality diagram. Furthermore, the decay width depends crucially on whether we regard the 2π system as a resonance ε, or not. Thus without introducing more assumptions or modifying the rule, it is hard to explain the decay width of the decay (ψ' → ψ2π) in the Model O/R.

Production of the ψ particle at Brookhaven

First we remark that the ψ particle is not produced only via the one-photon state in p Be scattering. Further the yield of ψ by other mechanisms which we will identify with the breaking of the OZI rule is roughly 20−25 times as much as that by the e. m. interaction.

We will show it by two methods as follows:

i) Define the signal-to-noise ratio\(^{(b)}\) as

\[ R = \frac{\text{cross-section integrated over the peak}}{\text{background under the peak}} \]  

and let us compute two ratios\(^*)\) defined in Fig. 6. If ψ is produced only via one photon, then \(R_1 = R_2\). We obtain from the data

\[ R_1 = \frac{242}{5/25[\text{MeV}]} \approx 1200 \text{ MeV} \]  

and

\[ R_2 = \frac{10^4(\text{nb} \times \text{MeV}) \times \text{B.R.}(\psi \rightarrow \mu^+ \mu^-)}{10(\text{nb})} \approx 50 \text{ MeV}. \]

\(^*)\) Note the difference between our \(R_1\) and \(R_2\) in Ref. 13.

Fig. 5. The decays ψ'→ψ+2π in the Model O/R.

Fig. 6. The definition of \(R_1\) and \(R_2\).
[We use rough numbers to estimate $R_2$.] From Eqs. (12) and (13),
\[ R_1/R_2 = 24. \] (14)

Since in $e^+e^-$ collision the $\phi$ particle is produced via the one-photon state, at BNL the $\phi$ particle is produced by other mechanisms 24 times as much as by the e.m. interaction.

ii) The background of $e^+e^-$ mass spectrum in $p$ Be scattering is the upper limit of the mass spectrum of $e^+e^-$ which are produced via the one-photon state. We can estimate the yield of $\phi$ via one photon, since we know the yield of $e^+e^-$ via one photon. [We assume that the background is only due to the one photon intermediate state.] The ratio of the yield of $e^+e^-$ via one photon to that via the $\phi$ particle (produced by the e.m. interaction) is given by
\[ \frac{1}{q^2} \cdot \frac{(e^2)}{f_\phi^2} \cdot \frac{1}{(q^2-M_\phi^2+\Gamma_\phi^2/M_\phi^2)^2}, \] (15)
where $q^2$ is the invariant mass of $e^+e^-$, $\langle 0|j_\mu^\alpha(0)|\phi(p)\rangle = M_\phi^2/f_\phi \times A_\alpha^\mu(p)$ and $M_\phi$ is the mass of $\phi$. From Eq. (15) we obtain the relation
\[ R_3 = \frac{\text{number of events integrated over the peak}}{\text{number of events of the background within } \Delta E} \]
\[ = \frac{(4\pi\alpha)^2}{f_\phi^2} \pi M_\phi^2 \frac{2\Gamma_\phi}{\Delta E}. \] (15')

Using $4\pi\alpha^2 M_\phi/(3f_\phi^2) = \Gamma(\phi \rightarrow l^+l^-) = 5$ keV, we obtain the r.h.s. of Eq. (15)' as 2.5 for $\Delta E = 25$ MeV. On the other hand the l.h.s. of Eq. (15)' = 242/5 = 50. Thus the yield of $\phi$ is roughly $50/2.5 = 20$ times as much as that estimated from the assumption of taking only the e.m. interaction.

By two estimates we conclude that the $\phi$ particle is produced in $pN$ scattering 20~25 times as much as that estimated from the e.m. interaction.

As stressed in Ref. 6), the $\phi$ particle cannot be produced at $E_L \sim 30$ GeV, satisfying the OZI rule. The $\phi$ particle is produced by the breaking of the OZI rule. We repeat some results in Ref. 6) since we need them here. We define two regions, the copious region and the non-copious region for a given particle production; the copious region where the particle can be produced, satisfying the OZI rule and the non-copious region where the particle can be produced if and only if we neglect the OZI rule. The copious region for the $\phi$ production in $pN$ scattering is $E_L > 34 \sim 46$ GeV, while the non-copious region is $34 \sim 46$ GeV $> E_L > 12$ GeV. In the non-copious region the $\phi$ particle can be produced by two mechanisms; 1) electromagnetic production via one photon and 2) breaking of the OZI rule. Now we know that the production by the mechanism 2) is 20~25 times as much as that by the mechanism 1).

We assumed in Ref. 6) a suppression factor $10^{-4}$ by the OZI rule to explain the small width $\Gamma_\phi \sim 100$ keV. So a yield of a particle with mass 3.1 GeV is
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expected to be $10^4$ times of Eq. (6), $2.5 \times 10^{-30}$ cm$^2$, if the particle can be produced without any constraint by the OZI rule. This number supports the argument$^{40}$ that for a production of a particle with mass $M$, the mass-suppression factor may be $(m_s/M)^2$ instead of $(M/m_s)^3 \exp(-8M/7m_s)$.

Production of the $\psi'$ particle at Broodhaven

From Eq. (7) we obtain

$$\sigma(pN\rightarrow\psi'X) < 0.07\sigma(pN\rightarrow\psi X), \quad (16)$$

at $E_L \sim 30$ GeV. From the above analysis this means that the production of the $\psi'$ particle by the breaking of the OZI rule should be less than 7% of that of the $\psi$ particle.

The question is why the $\psi'$ particle cannot be produced by the breaking of the OZI rule in an analogous way as the $\psi$ particle. We can answer this question in the Model E. In this model the $\psi'$ particle is an exotic meson $c\bar{c}(p\bar{p} + n\bar{n})$ which can be mixed with exotic mesons without charmed quarks $(p\bar{p} + n\bar{n})$ and $\lambda\bar{\lambda}(p\bar{p} + n\bar{n})$. This mixing is caused by the breaking of the generalized OZI rule. The mixing with ordinary mesons $\phi$ and $\omega$ may be completely neglected, since it can be caused by, at least, twice the breaking of the generalized OZI rule.

The topology of the world sheet which corresponds to the production of an exotic meson, e.g., $(p\bar{p} + n\bar{n})$, is quite different from that corresponding to the production of an ordinary meson, e.g., $\phi$ or $\omega$. To produce an exotic meson we need the interaction "creation of a loop on a string" [Fig. 2(c)]. We assume that this interaction is suppressed at low energies (e.g., $E_L \leq 30$ GeV in $pp$ scattering).

From this assumption we can explain the small ratio $p/k^-$ at $\lesssim 30$ GeV in $pp$ scattering, since to produce $\bar{p}$ we need the interaction 2(c). By the same assumption we can understand the little production of $\psi'$ at 30 GeV.

Since the ratio $p/k^-$ goes up to about 1/2 at $E_L = 200 \sim 300$ GeV, the interaction 2(c) becomes significant at very high energies. Thus the yield of $\psi'$ will increase at a certain very high energy, but it will grow much slower than the yield of $\psi$. Furthermore the energy where the interaction 2(c) becomes significant may be higher than that in the case of the $\bar{p}$ production, since the mass of $\psi'$ is about twice the mass of a pair of $p\bar{p}$.

In the Model O/R, on the other hand, the $\psi'$ particle could be produced by the breaking of the OZI rule in a similar way as $\psi$, since there is no qualitative difference between $\psi$ and $\psi'$ in this respect. Roughly speaking, the ratio of the productions may be estimated by

$$R_{\psi'} = \frac{|\phi_{\psi'}(0)|^2}{|\phi_{\psi}(0)|^2} \times \frac{F(M_{\psi})}{F(M_{\psi'})}, \quad (17)$$

where $\phi_{\psi'}$ and $\phi_{\psi}$ are the wave functions of $c\bar{c}$ and $F(M)$ is the mass-suppression
factor. We have implicitly assumed that the mixing with orbital or radial excitations of $\phi$ and $\omega$ in the case of $\psi'$ is similar to the mixing with $\phi$ and $\omega$ in the case of $\psi$. The ratio $\frac{|\phi_{\psi'}(0)|^2}{|\phi_{\psi}(0)|^2}$ is roughly 1/2, since

$$
\frac{M_{\psi'} f_{\psi'}^2}{M_{\psi} f_{\psi}^2} = \frac{\Gamma(\psi' \rightarrow e^+e^-)}{\Gamma(\psi \rightarrow e^+e^-)} \sim \frac{1}{2}.
$$

(18)

If we take $F(M) \sim (m_\pi/M)^2$ which is consistent with the analysis made in the part “Production of the $\phi$ particle at Brookhaven”, we obtain $R_c \sim 0.35$. Although the data in Eqs. (1)~(4) are tentative and our analysis is crude, these numbers derived are larger than the experimental upper limit 0.07 [shown in Eq. (16)].

Future experiments on productions of $\psi$ and $\psi'$ in $p\bar{p}$ scattering will clarify which model is better.

Coupling with the photon

From the decay widths to lepton pairs, Eqs. (2) and (4), we have obtained Eq. (18):

$$
\frac{f_{\psi'}^2}{f_{\psi}^2} = \frac{1}{2} \frac{M_{\psi'}}{M_{\psi}} \sim 0.4,
$$

(18')

which means the coupling of the $\psi'$ particle with the photon is of the same order of magnitude as compared with that of the $\psi$ particle. This means in the Model O/R, $|\varphi_{\psi'}(0)|^2 \sim 0.5 |\varphi_{\psi}(0)|^2$. If we assign the $\psi'$ particle to an orbital excitation ($L=2$), we obtain $|\varphi_{\psi'}(0)|^2 \sim 0$. Thus the non-relativistic quark model where the $\psi'$ particle is assigned to an orbitally excited state ($L=2$) is ruled out.

Other exotic mesons with hidden charm

We expect at least three exotic mesons with hidden charm, $c\bar{c}(p\bar{p} \rightarrow n\bar{n})$ [between 3.7~4.1 GeV], $c\bar{c}\lambda\lambda$ [~4.1 GeV] and $c\bar{c}c\bar{c}$ [~6.2 GeV], to which we refer as $\psi_{p}, \psi_{\pi}$ and $\psi_{p}$, respectively. [We may refer to $\psi'$ as $\psi_{p}'$.] We assume that the masses of the $p$ and $n$ quarks are 300~400 MeV, that of the $\lambda$ quark is 500 MeV and that of the $c$ quark is 1500 MeV, and we take the sum of the masses of the quarks to estimate the masses of the exotic mesons. The total widths of the exotic mesons $\psi_{p}$ and $\psi_{\pi}$ are expected to be broad [see “Decays”]. The structure of the cross section in $e^+e^-$ annihilation between 3.8 GeV and 4.6 GeV seems not to be a simple Breit-Wigner type plus the background. We expect that the structure is due to two broad resonances as well as the threshold effect of the pair production of charmed hadrons plus the background. Whether the exotics $\psi_{p}$ is a sharp resonance or not depends crucially on its mass. If the mass is lower than twice that of the lowest state of $c\bar{c}$ [probably, the pseudo-scalar $\chi$], the $\psi_{p}$ particle will be a sharp resonance.

Exotics without the charmed quarks

We expect a lot of exotic hadrons, but none of hadrons are identified definitely
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as exotics, though there are several candidates. This may seem to be a difficulty in the Model E. We do not, however, consider this as a difficulty for two reasons: i) Some of hadrons which have not been identified as exotic hadrons are, in fact, exotic [e.g., \( \rho' (1600) \)] and ii) it is difficult to observe some of them because of too large widths and/or because of many-body final states.

![Diagram of \( \rho' (1600) \) and its decay]

Fig. 7. \( \rho' (1600) \) and the decay of \( \rho' (1600) \).

Usually \( \rho' (1600) \) is identified as a radially or orbitally excited state of \( \rho (770) \). There are, however, no conclusive arguments to these assignments. The most striking feature of \( \rho' (1600) \) is that the decay to \( 2\pi \) is much suppressed in spite of the large \( Q \)-value. We assign \( \rho' (1600) \) to an exotic meson \( (\rho \bar{\rho} - n\bar{n}) (\rho \bar{\rho} + n\bar{n}) \). Then \( \rho' (1600) \rightarrow [I=1] + [I=0] \) because of its configuration [Fig. 7]. [We assume that the state with quarks twisted is not contained in this state. See “Decays”.] The smallest number of the \( \pi \)-meson of the \( I=0 \) system is two. Thus the smallest number of the \( \pi \)-meson in the decay of \( \rho' \) is four, because the state of three \( \pi \)-mesons is forbidden by \( G \)-parity conservation. In this way we can explain the smallness of the branching ratio of the decay \( \rho' \rightarrow 2\pi \).

As suggested by Ida, \( N(1470) \) may be also an exotic state, since if we assign \( N(1470) \) to a radially excited state, we have some troubles to explain experimental results, e.g., the \( t \)-dependence of the \( N(1470) \) production in \( \pi N \) scattering.

Decays

We have already discussed the decay \( \psi' \rightarrow \psi 2\pi \). Other decay modes and their widths depend crucially on the mass of the pseudo-scalar meson \( \chi \) which is mainly \( c\bar{c} \) and also the masses of the \( D \) mesons \( (c\bar{\rho} \) and \( c\bar{n} \)). Since we do not know them now, we have to assume them to discuss decays of the \( \psi' \) particle and other particles. We also have to introduce additional assumptions to the Model E. So the considerations in this part are less reliable than other parts.

The basic assumptions \( A_1 \) and \( A_2 \) are as follows: \( A_1 \); transitions shown in Figs. 3(a) and 3(b) are allowed ones, and \( A_2 \); other transitions such as shown in Fig. 3(c) are suppressed ones. We further assume tentatively that to twist quarks in an exotic meson is included in \( A_2 \). Then the transition between the two states shown in Fig. 8 is suppressed. The \( \psi' \) particle is mainly the state a) shown in Fig. 8. We may have to modify assumptions other than the basic assumptions in future when we get more experimental information. Anyway, here we assume them.

We assume the mass of the \( D \) meson is \( 1.7 \sim 1.8 \text{GeV} \), since this value is
reasonable from the analysis$^{18}$ of other experiments and also is supported by the experiment in cosmic ray by Niu et al.$^{17}$ if we assume that they discovered the $D$ meson. This value is much smaller than 2.15 GeV which is derived using the quadratic mass formula in the SU(4) symmetry. We would like to remark that it is dangerous to rely on the mass formula, since the SU(4) symmetry is very badly broken and the linear mass formula may be good for the charmed meson.

Then the $\psi'$ meson can decay to $D\bar{D}$, but the decay is suppressed by the assumption made above. We expect $K\bar{K}\pi\pi$ decay mode where $(K\pi)$ and $(\bar{K}\pi)$ have sharp peaks at 1.7$\sim$1.8 GeV. The decay modes to $K\pi\pi\pi$ (and $\bar{K}\pi\pi\pi$) and $4\pi$ can be expected with branching ratios $1/\sqrt{20}$ and $1/20$ (derived from Cabibbo angle), respectively, relative to $KK\pi\pi$. The decay, $\psi'\to\chi+3\pi$, is also allowed. For a similar reason as the decay $\psi'(1600)\to2\pi$ is suppressed, the decay $\psi'\to3\pi$ is also suppressed compared with the $5\pi$ decay, except for the e.m. interaction.

The $\psi$ particle can decay strongly to $\pi\pi\psi$ and $\chi2\pi$, while the $\psi'$ particle can decay strongly to $\eta\psi$. The $\psi$ and $\psi'$ particles may decay even to a pair of charmed baryon-antibaryon, if the masses are larger than the threshold. $[\psi\to(p\bar{p}c) + (\bar{p}\bar{p}\bar{c})$ and $\psi'\to(p\bar{c}c) + (\bar{p}\bar{c}\bar{c})]$. In an extreme case, the mass of the baryon $(p\bar{p}c)$ may be $\sim$1.9 GeV and the mass of the baryon $(p\bar{c}c)$ may be $\sim$2.0 GeV. These masses are a little lower than the sum of the quark masses assumed above. In this case the rise in $R$ depends partially on the threshold effect of the production of pairs of charmed baryon-antibaryon, as well as pairs of charmed mesons ($D\bar{D}$ and $F\bar{F}$).

The $\Upsilon$ discovered in cosmic ray by Koshiba and his group$^{19}$ may be a baryon $(p\bar{c}c)$. This assignment is different from that by Koshiba and Matsuda.$^{17}$ In our case we can understand the decay $\Upsilon\to N+\phi$ in the usual framework of the weak interaction. We cannot, however, understand the copious production of the $\Upsilon$ particle above $E_{c.m}=$300 GeV. These considerations are speculations based on an extreme case. Anyway, by introducing assumptions on the masses of charmed hadrons as well as additional assumptions in the Model E, as above, we can make the widths of $\psi$ and $\psi'$ broad. We do not discuss further the decays of the exotic mesons and the existence of other possible exotics, since we think it is premature to discuss them further now.

Concluding remarks

A natural question is whether radially or orbitally excited states exist in the Model E. We do not know the answer now since it depends on the dynamics. Even if they exist, it may be difficult to observe them for some reasons. Anyway,
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All of the predictions of the naive non-relativistic quark model may not be true. With more available experimental information, we should construct more realistic models. We hope our model is more realistic than the naive non-relativistic quark model.

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