for convenience I have defined $\varphi_{P(V)} \equiv \theta_{P(V)} - \arctan 1/\sqrt{2}$. The errors in theory are those generated by the uncertainties in $I_{P_j V_i}$, φ_P, and φ_V and demonstrate that current experimental evidence is consistent with the quark-model predictions to an accuracy one might realistically anticipate. The data also confirm $x \simeq 0.7$ as derived from the baryon magnetic moments and expected in some models with confined pointlike quarks.

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Comment on Hadronic Production of Psions

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We discuss a scheme for understanding the observed features of new-particle production. Qualitative tests of the conjectured mechanism are outlined, and the experimental data are reviewed.

In this note we draw attention to a possible mechanism for hadronic production of $J/\psi(3095)$ and related resonances which appear to integrate many experimental observations. We propose that the $J/\psi(3095)$ is, to an excellent approximation, not produced directly in hadron-hadron collisions, but arises from decays of psions with even charge conjugation. Although this mechanism has been mentioned in passing before,[1] recent experimental developments encourage us to present an explicit exposition.

We regard the psions as "hidden new quantum number" states of a massive quark-antiquark pair. For present purposes it is unnecessary to specify the new quantum number carried by the heavy quark which is responsible for the metastability of the psions. Nevertheless it will be convenient to yield to prejudice and designate the new quark as the charmed quark c. The inhibition of the decay of a $c\bar{c}$ bound state into uncharmed hadrons is interpreted as a consequence of the phenomenological Okubo-Zweig-Iizuka (OZI) rule.[2] From the perspective of quantum chromodynamics, circumvention of the OZI rule proceeds by the annihilation of the $c\bar{c}$ pair into gluons which in turn communicate with ordinary hadrons. The notion of asymptotic freedom suggests that the effective coupling constant for the annihilation process is small. On the basis of these ideas and of the analogy with the decays of orthopositronium ($^3S_1$) into three photons and of parapositronium ($^1S_0$) into two photons, Appelquist and Politzer[3] anticipated that even-charge-conjugation ($C=+1$) psions should couple to hadrons much more strongly than do odd-charge-conjugation psions. For example, they predicted a width into hadrons for the 1^1S_0 paracharmonium state approximately 75 times the hadronic width of the 1^3S_1 (3095) orthocharmonium state. The 1^1S_0 state has not yet been established (it may be indicated[4] at 2800 MeV/c^2) so a specific test of these gluon-counting arguments is lacking. However, the discovery of γ transitions to states χ_c of even charge conjugation[5] between the 2^3S_1 (3684) and the 1^3S_1 (3095) lends support to the nonrelativistic charmonium picture from which the hadronic-width predictions arise.[6]

Models for the hadronic production of psions are quite conjectural, but if the hadronic widths of $C=+1$ states do greatly exceed those of $C=-1$ states it is natural to expect that states such as χ_c are produced far more copiously than J/ψ. Then if the states χ_c have appreciable probabilities to decay by cascade into J/ψ, we may imagine that the hadronic production of J/ψ occurs primarily through the chain

$$a+b\to\chi_c+\text{anything},\quad \chi_c\to J/\psi+\gamma \text{ or } J/\psi+\text{hadrons}. \tag{1}$$

Especially for the χ_c states around 3500 MeV/c^2, the photon mode may be significant.

An obvious but dramatic consequence of this hypothesis is that the observed J/ψ is frequently accompanied by a photon. In the $(J/\psi)\gamma$ rest frame, the photon energies assume discrete values corresponding to the radiative transitions $\chi_c\to\gamma J/\psi$. Detection of the accompanying γ would verify the cascade production hypothesis (1) and provide access to the spectroscopy of the $C=+1$ psions.

The cascade hypothesis has consequences for ψ' production as well, since it requires the production and cascade decay of χ_c states with masses exceeding 3684 MeV/c^2. We expect for several reasons that the consequential cross section for ψ' production will be small compared with that for J/ψ production. (Likewise, the lightest bound state of any heavier quarks should be produced far more copiously than the excited states.) First, there is likely to be at least a mild kinematic suppression[7] of heavier χ_c's compared with those at 3400–3550 MeV/c^2. Second, a competition will ensue between the transitions $\chi_c\to\psi'X$ and $\chi_c\to(J/\psi)X$ in which the Q value favors the latter. Third, it appears that the heavy χ_c's must lie in a narrow mass range between ψ' and charm threshold, since any states above charm threshold will presumably contribute negligibly to J/ψ or ψ' production.[8] These tendencies to favor J/ψ over ψ' production are consistent with a recent experimental report[9] that $\sigma(\psi')/\sigma(J/\psi)=(10\pm3)\%$ in 400-GeV/c p-Be collisions. At lower energies, threshold suppressions of both J/ψ and ψ' production are reinforced by the cascade hypothesis. The limit $\sigma(\psi')/\sigma(J/\psi)\lesssim1\%$ in 28.5-GeV/c p-Be collisions[10] seems explicable in these terms. A further corollary of this interpretation is the implication that the directly produced χ_c states should be observable through their hadronic decays. At this time we know too little to be able to suggest dominant channels.

A year ago, Einhorn and Ellis[11] considered the possibility that the hadronic production of psions proceeds not by an exchange process respecting the OZI rule (which would imply[12] the associated production of a pair of charmed hadrons) but by the inverse of the OZI-rule–violating decay mechanism, i.e., by amalgamation of gluons from the colliding hadrons. This analog (see Fig. 1) of the familiar Drell-Yan mechanism[13] for the production of massive photons implements the charmonium description of psion decays.[14] In Ref. 11 it was found that, in a primitive model for the momentum distribution of the gluons, the cross section for production of a $^1S_0$ state of mass 3 GeV/c^2 and width 5 MeV is $\sigma(pp\to{}^1S_0+\text{anything})\simeq300$ to 500 nb for beam momenta of 300–400 GeV/c. Similar cross sections are to be expected also for χ_c production if $\Gamma(\chi_c\to\text{hadrons})$ is a few MeV. Cross sections for J/ψ production will be reduced by the branching ratio for $\chi_c\to(J/\psi)X$. [The current state of psion spectroscopy does not allow us to make quantitative predictions for $\sigma(J/\psi)$.] In addition, the production of psions by this mechanism is central in that $d\sigma/dx_L$ peaks near $x_L=0$. The shape of the differential cross section for J/ψ production will differ somewhat from that for the parent χ_c because of the Q value released in the cascade decay. Our ignorance of gluon distributions precludes our making firm predictions for $d\sigma/dx_L$ in the model. However, the general structure of $d\sigma/dx_L$ will resemble that found for $\eta_c(3000)$ in Ref. 11.

Other specific tests of the gluon-amalgamation

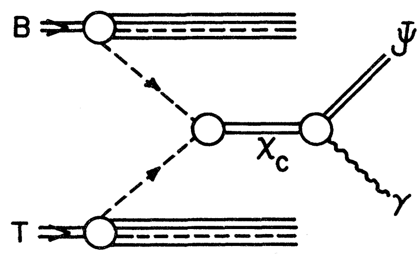

FIG. 1. Gluon-amalgamation model for the reaction $B+T\to\chi_c(\to J/\psi)+\text{anything}$. χ_c denotes any $C=+1$ state more massive than J/ψ. Dashed lines represent gluons; solid lines represent quarks.

mechanism for production of χ_c follow from the flavor-singlet nature of gluons. The gluon distributions within $\pi^\pm$ must be identical by charge-conjugation invariance. Consequently, the equality

$$d\sigma(\pi^+ T \to \chi_c + X) = d\sigma(\pi^- T \to \chi_c + X)$$

holds for a target T of arbitrary isospin. A process sensitive to valence quarks would lead to very different expectations. For example, if χ_c were produced by the annihilation of valence quarks we should anticipate

$$d\sigma(\pi^+ p \to \chi_c + X) \lesssim \tfrac{1}{2} d\sigma(\pi^- p \to \chi_c + X) .$$

Similarly, according to the ideas explored here

$$d\sigma(K^+ T \to \chi_c + X) = d\sigma(K^- T \to \chi_c + X)$$

by charge conjugation, whereas in a valence-quark-annihilation picture

$$d\sigma(K^+ p \to \chi_c + X) \ll d\sigma(K^- p \to \chi_c + X) .$$

To the extent that gluon distributions respect SU(3) symmetry, we also expect

$$d\sigma(KT \to \chi_c + X) = d\sigma(\pi T \to \chi_c + X) .$$

Can we compare the production of psions by pion and proton beams? To do so requires making specific assumptions about the character of the gluon distributions $F_g^B(x)$ of the beam particles. As was pointed out in Ref. 11, dimensional counting[15] leads us to expect that, as $x \to 1$, $F_g^N(x) \sim (1-x)^5$ for a nucleon and $F_g^\pi(x) \sim (1-x)^3$ for a pion. We therefore expect pion beams to be relatively more efficient than proton beams in producing psions at large values of x_L. The absolute normalization depends on the momentum fractions carried by gluons in the beam particles. If it is the same for pions as for protons (~50%), then for energies and longitudinal momentum fractions x_L which are insensitive to the "wee" region, there is no reason to expect the psion production cross sections to be in the ratio of the total cross sections. A specific calculation with $F_g^N(x) = 3(1-x)^5/x$ and $F_g^\pi = 2(1-x)^3/x$ gives for $\chi_c(3500)$ production

$$d\sigma(\pi N)/dx_L \simeq d\sigma(NN)/dx_L \text{ at } x_L = 0 ,$$

and

$$d\sigma(\pi N)/dx_L \simeq 6 d\sigma(NN)/dx_L \text{ at } x_L = 0.6 ,$$

for $s = 300$ GeV^2. These expectations are in accord with the observed data[16] which indicate that for ψ production

$$d\sigma(\pi^+ \mathrm{Be})/dx_L \simeq (1-x_L)^{-2} d\sigma(p\ \mathrm{Be})/dx_L$$

for incident momenta of 150 GeV/c.

In this Comment we have emphasized two ideas. First, we have elaborated the suggestion that the production of J/ψ and ψ' in hadron collisions occurs through the production and cascade decay of $C = +1$ psions. Second, we have reviewed a specific dynamical mechanism which embodies the cascade-production hypothesis and enumerated straightforward tests of it.

Note added.—While preparing this Comment for publication, we received manuscripts from Carlson and Suaya[17] which also call attention to the cascade hypothesis. They have attempted a quantitative estimate of the J/ψ production cross sections.

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[6]See Ref. 3 and E. Eichten *et al.*, Phys. Rev. Lett. 36, 500 (1976).

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Is a State $cc\bar{c}\bar{c}$ Found at 6.0 GeV?

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It is pointed out that the newly discovered particle at 6 GeV may correspond to the $cc\bar{c}\bar{c}$ state which was previously predicted to exist around 6 GeV by the present author. It will decay dominantly to $J/\psi\,(3.1) + \eta_c\,(2.8)$.

One year ago, the present author[1] predicted a $cc\bar{c}\bar{c}$ resonance state at about 6.2 GeV based on a model of charm and exotics. Recently a new resonance[2] at about 6.0 GeV was reported. It is quite natural to consider that the newly discovered resonance corresponds to what was predicted in Ref. 1.[3] In this Letter this possibility will be examined in detail and possible tests of the model will be given.

In the present model the $J/\psi(3.1)$ meson is assigned to a vector meson $c\bar{c}$, as is usual in the charm scheme, while the $\psi(3.7)$ meson is assigned to an exotic meson $c\bar{c}(u\bar{u}+d\bar{d})$. Two resonances, $c\bar{c}(u\bar{u}-d\bar{d})$ $(I=1)$ and $c\bar{c}s\bar{s}$ $(I=0)$, were predicted in Ref. 1 between ~3.7 and ~4.1 GeV, as well as another resonance $cc\bar{c}\bar{c}$ at 6.2 GeV. As a rough estimate for the masses of these resonances, I used the sum of the quark masses, assuming $m_u = m_d = 300\text{–}400$ MeV, $m_s \sim 500$ MeV, and $m_c \sim 1550$ MeV.

The states $q\bar{q}q\bar{q}$ belong to $\underline{84} \oplus \underline{15} \oplus \underline{1}$ in the SU(4) symmetry if two quarks and two antiquarks are symmetric (symmetric states), respectively, in the SU(4) indices, while they belong to $\underline{20} \oplus \underline{15} \oplus \underline{1}$ if two quarks and two antiquarks are antisymmetric (antisymmetric states). The other states belong to $\underline{45} \oplus \underline{45}^* \oplus \underline{15} \oplus \underline{15}$ where two quarks are symmetric and two antiquarks are antisymmetric or vice versa (mixed-symmetry states). The model in Ref. 1 corresponds to the symmetric case (Model I).

An alternative model (Model II) is the one where both the symmetric and antisymmetric states exist. In this model there are six exotic vector mesons $c\bar{c}q'\bar{q}'$ (two $I=1$ and four $I=0$ states), where q' stands for u, d, or s. Note that there are three states in Model I. These states correspond to resonances between 3.7 and 4.4 GeV. I assume that the mixed-symmetry states exist at the higher mass region or do not exist as resonances at all.

I do not discuss here the complications due to spin and orbital angular momenta and just assume that there is a vector meson corresponding to each unitary spin state. I shall discuss the details of the models which depend on dynamics, as well as the justification of the assumptions made here and above, in a separate paper.

The choice between the two models is reserved for future investigation when more experimental data are available. (There are also other variations than Model I and Model II.) I refer to $c\bar{c}(u\bar{u}+d\bar{d})$, $c\bar{c}(u\bar{u}-d\bar{d})$, $c\bar{c}s\bar{s}$, and $cc\bar{c}\bar{c}$ as ψ_ω, ψ_ρ, ψ_φ, and ψ_ψ, respectively. (Note that there are two ψ_ω,