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Comment on Hadronic Production of Psions

S.D. ELLIS
University of Washington,* Seattle, WA 98195

MARTIN B. EINHORN and C. QUIGG†
Fermi National Accelerator Laboratory,§ Batavia, IL 60510

Abstract

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.

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†Alfred P. Sloan Foundation Fellow; also at Enrico Fermi Institute, University of Chicago, Chicago, IL 60637.

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In this note we draw attention to a possible mechanism for hadronic production of Ψ (3095) and related resonances which appears to integrate many experimental observations. We propose that the Ψ (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 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 ψ. Then if the states χ_c have appreciable probabilities to decay by cascade into ψ , we may imagine that the hadronic production of ψ occurs primarily through the chain

$$\begin{aligned} a + b \rightarrow \chi_c &+ \text{anything} \\ &\hookrightarrow \psi + \gamma \\ \text{or} \quad &\psi + \text{hadrons}. \end{aligned} \tag{1}$$

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 $\mathcal{J}$ is frequently accompanied by a photon. In the $(\mathcal{J}\gamma)$ rest frame, the photon energies assume discrete values corresponding to the radiative transitions $\chi_c \rightarrow \gamma\mathcal{J}$. 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 $\mathcal{J}$ 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_cs compared with those at 3400 - 3550 MeV/c^2. Second, a competition will ensue between the transitions $\chi_c \rightarrow \psi' X$ and $\chi_c \rightarrow \mathcal{J}X$ in which the Q-value favors the latter. Third, it appears that the heavy χ_cs must lie in a narrow mass range between ψ' and charm threshold, since any states above charm threshold will presumably contribute negligibly to $\mathcal{J}$ or ψ' production.[9] These tendencies to favor $\mathcal{J}$ over ψ' production are consistent with a recent experimental report[10] that $\sigma(\psi')/\sigma(\mathcal{J}) = (10\pm3)\%$ in 400 GeV/c p Be collisions. At lower energies, threshold suppressions of both $\mathcal{J}$ and ψ' production are reinforced by the cascade hypothesis. The limit $\sigma(\psi')/\sigma(J\!\!\!/\psi) \lesssim 1\%$ in 28.5 GeV/c p Be collisions[11] 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[8] 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. 8 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 $\sigma(pp \to {}^1S_0 + \text{anything}) \simeq 300$ 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 $J\!\!\!/\psi$ 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 $J\!\!\!/\psi$ 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. 8.

Other specific tests of the gluon amalgamation 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

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

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

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

Similarly, according to the ideas explored here

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

by charge conjugation, whereas in a valence quark annihilation picture

$$d\sigma(K^+ p \rightarrow \chi_c + X) << d\sigma(K^- p \rightarrow \chi_c + X).$$

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

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

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. 8, 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

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

and

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

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

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

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 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.

<u>Note Added</u>: 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 ψ production cross section.

FOOTNOTES AND REFERENCES

[1]This possibility occurred long ago to a number of people in addition to the present authors. The first reference to it in the literature is in the Addendum to M.K. Gaillard, B.W. Lee, and J.L. Rosner, Rev. Mod. Phys. 47, 277 (1975). F. Gilman has brought it up repeatedly in private discussions. See also F. Halzen, Wisconsin preprint COO-501(1976).

[2]S. Okubo, Phys. Lett. 5, 165 (1963); G. Zweig, oral tradition (1964); J. Iizuka, Prog. Theoret. Phys. Suppl. 37-38, 21 (1966).

[3]T. Appelquist and H.D. Politzer, Phys. Rev. Lett. 34, 43 (1975).

[4]B. Wiik, in Proc. 1975 Int. Symposium on Lepton and Photon Interactions at High Energies, ed. W.T. Kirk (SLAC, Stanford, 1975), p. 69. J. Heintze, ibid. p. 97.

[5]K. Berkelman, et al., Phys. Lett. 57B, 407 (1975); G.J. Feldman, et al., Phys. Rev. Lett. 35, 821 (1975).

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

[7]Using the specific model of Ref. 8 with $n = 5$, we find that a 3900 MeV/c^2 state will be produced about half as copiously as a 3500 MeV/c^2 state with the same hadronic width, at $s=600$ GeV^2.

[8]M.B. Einhorn and S.D. Ellis, Phys. Rev. Lett. 34, 1190 (1975); Phys. Rev. D12, 2007 (1975).

[9] This is substantiated by the paucity of ψs in the final states of $e^+e^- \to$ hadrons for $E_{CM} > 4$ GeV reported by the SLAC-LBL Collaboration at the 1975 Int. Symposium on Lepton and Photon Interactions at High Energies and G. Goldhaber, private communication.

[10] H.D. Snyder, et al., FERMILAB-Pub-76/32-EXP.

[11] J. Leong, quoted by Gaillard, et al., Ref. 1.

[12] D. Sivers, Phys. Rev. D11, 3253 (1975).

[13] S.D. Drell and T.-M. Yan, Phys. Rev. Lett. 25, 316 (1970).

[14] Another specific mechanism considered in Ref. 8 (see Figs. 1 and 2 thereof) was the production of χ_c or ψ by quark-antiquark annihilation. This mechanism should, in principle, be added to the gluon mechanism, as can be seen by replacing the produced particle by a pointlike coupling to a fictitious neutral current. (A bound on the cross section for χ_c production by this mechanism can be derived in analogy to eq. (1) of Ref. 8.) However, to the extent that charmonium ideas are correct so that $c\bar{c}$ annihilation occurs at very short distances, the absence of a direct local coupling of $c\bar{c}$ to ordinary quarks implies that quark annihilation is negligible compared with the gluon mechanism. This is inherent in the supposition that $\Gamma(\chi_c) >> \Gamma(\psi)$.

[15] S. Brodsky and G. Farrar, Phys. Rev. Lett. 31, 1153 (1973); V. Matveev, R. Muradyan, and A. Tavkhelidze, Lett. Nuovo Cimento 7, 719 (1973).

[16]K.J. Anderson, *et al.*, Phys. Rev. Lett. 36, 237 (1976); See also G.J. Blanar, *et al.*, Phys. Rev. Lett. 35, 346 (1975).

[17]C.E. Carlson and R. Suaya, William and Mary preprints WM-PP-10 (1976), WM-PP-12 (1976).

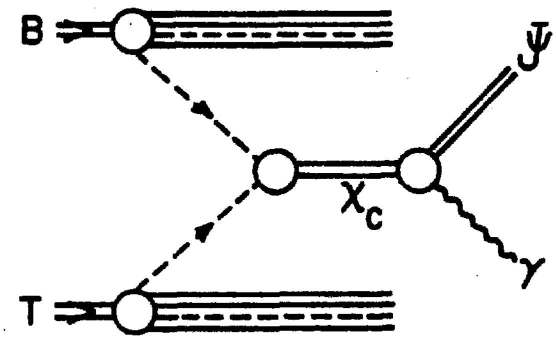

FIGURE CAPTION

Fig. 1: Gluon amalgamation model for the reaction $B + T \to \chi_c(\to \psi\gamma)$ + anything. χ_c denotes any $C = +1$ state more massive than ψ. Dashed lines represent gluons; solid lines represent quarks.