Mechanism of Charmonium Production in Hadronic Collisions

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Two models of J/ψ and ψ' production in hadronic collisions are considered: (I) Drell-Yan quark annihilation and (II) cascade production $AB \to \chi_c X$, $\chi_c \to \gamma\psi$. The present experimental data are shown to rule out (I) as the dominant mechanism. The angular distribution of photons from χ_c decay and lepton pairs from J/ψ decays in the cascade J/ψ production in quantum chromodynamics are predicted and may be used as a test for the models.

One of the most popular descriptions of J/ψ and ψ' production in hadronic collisions is the quark-parton model (I), which supposes that the mechanism of the J/ψ and ψ' production is analogous to the Drell-Yan mechanism of leptonic pair production with large mass and corresponds to the quark-antiquark annihilation from the target and projectile (or vice versa) into J/ψ and ψ' [Fig. 1(a)].[1] Another model (II) of J/ψ and ψ' production discussed in the literature is the cascade process of creation of the C-even charmonium states χ_c through $AB \to \chi_c X$ with their subsequent decays $\chi_c \to \gamma\psi$.[2] The process of χ_c production can proceed in two ways, via annihilation of quarks [Fig. 1(a)] or gluons [Fig. 1(b)]. In Model I the J/ψ production cross sections are determined by the quark and antiquark momentum distributions in the projectile A and the target B. Assuming one or another form of these distributions the authors of Ref. 1 were able to find a consistency between the theoretical expectations for these cross sections and the experimental data. Since, however, the quark and antiquark distributions (in particular, the distributions of charmed quarks) in the quark sea are practically unknown, this fact cannot be an argument for the correctness of the model. In this paper I will discuss tests of both Models I and II independent of quark or gluon distributions in hadrons and show that their experimental examination can distinguish between different models.

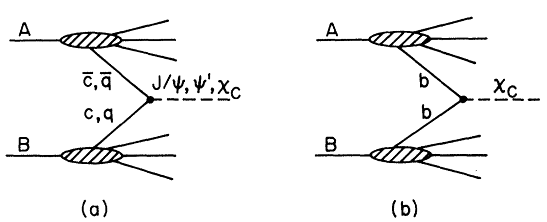

FIG. 1. (a) J/ψ, ψ', and χ_c production in the quark annihilation. (b) χ_c production in the gluon annihilation.

Let us discuss first Model I. It is reasonable here to consider two limiting cases:

(a) The J/ψ and ψ' production proceeds basically via $\bar{c}c$ quark annihilation. Then the vertex $\bar{c}c\psi$ (or $\bar{c}c\psi'$) in J/ψ (or ψ') production by hadrons must be the same as in e^+e^- annihilation (Fig. 2), and consequently[3]

$$\frac{\sigma(AB \to \psi' X)}{\sigma(AB \to \psi X)} = \frac{\Gamma_{ee}(\psi')/m_{\psi'}^3}{\Gamma_{ee}(\psi)/m_{\psi}^3} = 0.27 \pm 0.04. \qquad (1)$$

The experimental data on the ratios of ψ' and J/ψ production cross sections in hadronic collisions give considerably smaller values than is required by Eq. (1) [$\sigma(\psi')/\sigma(\psi) = 0.05$–$0.12$ for different projectiles and energies[4]]; i.e., the model with preferable annihilation $\bar{c}c \to J/\psi$ (ψ') contradicts experiment. Note that the application of analogous consideration to J/ψ and ψ' photoproduction leads to consistency with experiment. Experimentally, in photoproduction[5]

$$\left[\frac{d\sigma(\psi')/dt}{d\sigma(\psi)/dt}\right]_{t=t_{\min}} = 0.294^{+0.15}_{-0.08},$$

compared to the theoretical value

$$[\Gamma_{ee}(\psi')/m_{\psi'}][\Gamma_{ee}(\psi)/m_{\psi}]^{-1} = 0.38 \pm 0.06.$$

(b) The J/ψ and ψ' production proceeds basically via the light u, d, and s quark annihilation. A critical test for this hypothesis is the study of muonic and electronic pair angular distribution from J/ψ decays. (This problem was previously

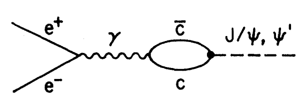

FIG. 2. J/ψ and ψ' production in e^+e^- annihilation.

discussed by Vasavada.[6]) In quantum chromodynamics (QCD) the form of annihilation interaction $\bar{q}q \to \psi$ is determined unambiguously since, as a result of the light-quark chiral invariance, of two possible forms $\bar{q}\gamma_\mu q\psi_\mu$ and $\bar{q}\sigma_{\mu\nu}q(\partial\psi_\mu/\partial x_\nu)$, only one, $\bar{q}\gamma_\mu q\psi_\mu$, survives. Thus, by neglect of the transverse momenta (for $p_{\perp q}$ see the account below) and the light-quark masses in QCD, the μ- or e-pair angular distribution from J/ψ decay is also determined unambiguously and is of the form $W(\theta) = 1 + \cos^2\theta$, where θ is the emission angle of μ (or e) relative to the incident beam direction in the J/ψ rest system. Experimentally, the leptonic pair angular distribution from J/ψ decay was approximated by $d\sigma/d\cos\theta \sim 1 + \alpha\cos^2\theta$ and it was found that $\alpha = -0.28 \pm 0.22$ for incident protons or pions.[7] These results contradict the model of J/ψ production by light-quark annihilation. It can easily be seen that a combined model with both light- and heavy-quark annihilation in J/ψ is also unlikely to be consistent with the experiment. Therefore the Drell-Yan mechanism of quark annihilation cannot be the main source of J/ψ and ψ' mesons in hadronic collisions.

Let us turn to the discussion of the cascade model. Since for the known χ_c states the decay probabilities $\chi_c \to \gamma\psi$ are rather large (from 10% to 50%),[3] J/ψ production by the cascade mechanism may comprise a noticeable and even main part of the production total cross section in hadronic collisions.

In QCD the χ_c production in hadronic collisions may proceed, in principle, via two mechanisms: (1) quark and antiquark annihilation [Fig. 1(a)], and (2) χ_c production in the two-gluon collision [Fig. 1(b)]. I will show that in QCD each of these mechanisms leads to definite and unambiguous predictions for the angular distributions of photons from the decay $\chi_c \to \gamma\psi$ and of leptonic pairs from successive decays $\chi_c \to \gamma\psi$, $\psi \to e^+e^-$ or $\psi \to \mu^+\mu^-$. Therefore, the experimental investigation of these angular distributions will give us a possibility to investigate the mechanism of χ_c production in hadronic collisions. The cascade process of J/ψ production with χ_c creation due to $\bar{c}c$ quark annihilation seems to be less important than the process of a direct J/ψ production in $\bar{c}c$ annihilation, and the latter, as was mentioned above, cannot be the main source of J/ψ mesons in hadronic collisions. Therefore, in the following I will discuss only the light-quark annihilation in χ_c.

I will limit myself to consideration of χ_c production with $J^P = 0^+, 1^+, 2^+$. For scalar χ_c the γ and l^+l^- angular distribution can be found trivially. As is known, the spin-1 meson cannot decay into two massless vector mesons. Thus, the axial meson A_c can be produced only in the gluon annihilation off the mass shell. The amplitude of this process is strongly model dependent. In all the other cases the predictions are unambiguous and weakly model dependent.

As usual, in the Drell-Yan mechanism the quarks and gluons are on the mass shell, i.e., are massless. The form of the interaction vertex $\bar{q}q\chi_c$ and $\bar{b}b\chi_c$ (b denotes gluon) can be determined from the following considerations. In case the A_c is produced in the light-quark annihilation, there are two possible Lorentz- and C-invariant form factors, $\bar{q}\gamma_\mu\gamma_5 q$ and $\bar{q}\gamma_5 qP_\mu$ (P_μ is the A_c momentum). From the chiral invariance of light quarks it follows that in QCD only the first one survives. Analogously, the chiral invariance leads to an unambiguous choice of the vertex $\bar{q}qg_c$ (g_c is the tensor meson) of the form of interaction of g_c with the energy-momentum tensor of the massless quark field. (From the chiral invariance it also follows that scalar χ_c production in the light-quark annihilation must be suppressed.)

In case the tensor meson is produced in the two-gluon annihilation, it is natural to assume that the tensor meson interacts with the energy-momentum tensor of the free gluonic field, $\theta_{\mu\nu}$. Apart from general premises as to the minimal dimension of the operator $\theta_{\mu\nu}$, an argument for such a choice of the interaction vertex $\bar{b}bg_c$ is that the amplitude of the two-gluon annihilation in a system of nonrelativistic $\bar{c}c$ quarks in the $^3P_2$ state (which, as expected, describes the tensor g_c meson) is proportional to $\theta_{\mu\nu}f_{\mu\nu}$ where $f_{\mu\nu}$ is the wave function of the $\bar{c}c$ system in the $^3P_2$ state.

The amplitudes of $\chi_c \to \gamma\psi$ decay were taken as follows: in the case of the axial meson $\epsilon_{\mu\nu\lambda\sigma} \times A_\mu^c F_{\nu\lambda}\psi_\sigma$, where A_μ^c and ψ_σ are the A^c and J/ψ fields, respectively, and $F_{\mu\nu}$ is the tensor of the electromagnetic field; in the case of the tensor meson $g_{\mu\nu}F_{\mu\rho}\psi_\nu q_\rho$, where $g_{\mu\nu}$ is the tensor meson field, and q is the J/ψ momentum. In both cases these are unique lowest-degree amplitudes of $\chi_c \to \gamma\psi$ decay in the photon momentum k. In the calculation the transverse momenta of quarks and gluons were neglected and thus the direction of their momentum coincides with that of the incident beam. The results of the calculations of the photon angular distributions from χ_c decays in reactions $AB \to \chi_c X$, with $\chi_c \to \gamma\psi$, and of lep-

TABLE I. Angular distributions (a) of photons from χ_c decays in reaction $AB \to \chi_c X$ with $\chi_c \to \gamma\psi$; (b) of leptonic pairs l^+l^- in the reaction $AB \to \chi_c X$, with $\chi_c \to \gamma\psi$, $\psi \to l^+l^-$; (c) of leptonic pairs in the same reactions after averaging over the photon emission direction ($l = \mu, e$; A and B are any hadrons). J^P is the spin and parity of χ_c; θ and ϑ are the γ and l^+ emission angles relative to the incident beam direction; and β is an angle between γ and l^+ momenta (all angles in the χ_c rest system).

J^P	Quark mechanism	Gluonic mechanism
	(a)	
0^+	Isotropic	Isotropic
1^+	$1-(1/3)\cos^2\theta$	$\cdots$
2^+	$1-(1/3)\cos^2\theta$	$1+\cos^2\theta$
	(b)	
0^+	$1+\cos^2\beta$	$1+\cos^2\beta$
1^+	$1-\cos\theta\cos\vartheta\cos\beta$	$\cdots$
2^+	$1-2\cos^2\theta\cos^2\vartheta+\cos\theta\cos\vartheta\cos\beta$	$(1+\cos^2\theta)(1+\cos^2\vartheta)$
	(c)	
0^+	Isotropic	Isotropic
1^+	$1-(1/3)\cos^2\vartheta$	$\cdots$
2^+	$1-(1/3)\cos^2\vartheta$	$1+\cos^2\vartheta$

tonic pairs from the cascade process $AB \to \chi_c X$, $\chi_c \to \psi\gamma$, $\psi \to l^+l^-$, are given in Table I.

In the formulas of Table I the terms $\sim k/m_\chi \sim 0.1$ were disregarded. (In this approximation the rest system of χ_c coincides with that of J/ψ.) The consideration of terms $\sim k/m_\chi$ in the assumed form of the $\chi_c \to \gamma\psi$ amplitudes changes the photon emission asymmetry coefficient $-\frac{1}{3}$ in the 1^+ meson decay to $-\frac{1}{3}(1-\frac{8}{3}k/m_\chi) \approx -0.22$ (for $m_\chi = 3.51$ GeV) and does not change it in the 2^+ meson decay. Another form of the $\chi_c \to \gamma\psi$ amplitudes can give corrections to the asymmetry coefficients of order 0.1 due to the terms $\sim k/m_\chi$.

As is seen from Table I, in the case of the tensor meson production g_c ($J^P = 2^+$) the quark and gluon mechanisms lead to very different angular distributions of photons and leptonic pairs that makes it possible to distinguish these two mechanisms.

The above consideration was made neglecting the transverse momenta $p_\perp$ of colliding quarks or gluons compared to $p_\parallel$. Since $p_\parallel \gg p_\perp$, accounting for $p_\perp$ will not strongly change the form of the angular distributions. At $p_\perp \neq 0$ the angular distributions of Table I should be referred to the momentum direction of colliding quarks or gluons at the rest system χ_c which does not now coincide with that of the colliding hadrons. It can easily be shown that in case of χ_c production with small $p_{\perp\chi}$, after averaging over $\vec{p}_\perp$ the angular distributions of photons from χ_c decays (or of leptonic pairs from J/ψ decays averaged over the photon emission angle) which were of the form $1+\alpha\cos^2\theta$ (or $1+\alpha\cos^2\vartheta$) will be of the same form with the replacement $\alpha \to \tilde{\alpha} = \alpha(1-\frac{3}{2}\theta_0^2)/(1+\alpha\theta_0^2/2)$ where $\theta_0^2 = 4\langle p_\perp^2\rangle/m_\chi^2$. To estimate θ_0^2 let us take $\langle p_\perp^2\rangle = \langle p_{\perp\chi}^2\rangle/2 = 0.3$–$0.4$ GeV^2. Then $\tilde{\alpha}/\alpha \approx 0.8$. Such an estimate of corrections accounting for transverse momenta can be used in practice up to $p_{\perp\chi} \lesssim 1$ GeV, i.e., in the main region of χ_c production.

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[1]J. Gunion, Phys. Rev. D 11, 1796 (1975), and 12, 1345 (1975); D. Sivers, Nucl. Phys. B106, 95 (1976); A. Donachie and P. Landshoff, Nucl. Phys. B112, 233 (1976); V. G. Kartvelishvili, A. K. Likhoded, and G. P. Pronko, Institute of High Energy Physics Report No. OTF-76-38, 1976 (to be published).

[2]S. D. Ellis, M. B. Einhorn, and C. Quigg, Phys. Rev. Lett. 36, 1263 (1976); M. Gaillard, B. Lee, and J. Rosner, Rev. Mod. Phys. 47, 277 (1975); C. E. Carlson and R. Suaya, Phys. Rev. D 14, 3120 (1976).

[3]B. H. Wiik, in *Proceedings of the Eighteenth International Conference on High Energy Physics, Tbilisi, U.S.S.R., 1976*, edited by N. N. Bogolubov *et al.* (The Joint Institute for Nuclear Physics, Moscow, U.S.S.R., 1977), Vol. II, p. N79.

[4]H. D. Snyder *et al.*, Phys. Rev. Lett. 36, 1415 (1976); M. Binkley *et al.*, Phys. Rev. Lett. 37, 574 (1976); J. G. Branson *et al.*, Phys. Rev. Lett. 38, 1331 (1977).

[5]U. Camerini *et al.*, Phys. Rev. Lett. 35, 483 (1975).

[6]K. V. Vasavada, SLAC Report No. SLAC-PUB-1883, 1977 (to be published).

[7]Branson *et al.*, Ref. 4.