

ЦЕНТРАЛЬНЫЙ НАУЧНО-ИССЛЕДОВАТЕЛЬСКИЙ ИНСТИТУТ
ИНФОРМАЦИИ И ТЕХНИКО-ЭКОНОМИЧЕСКИХ ИССЛЕДОВАНИЙ
ПО АТОМНОЙ НАУКЕ И ТЕХНИКЕ

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PECULIARITIES OF THE QUARK-GLUON MECHANISM
OF THE FORMATION OF C-EVEN HEAVY QUARKONIA IN HADRON COLLISIONS

ЕРЕВАН-1985

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и технике (ЦНИИатоминформ) 1985г.**

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ОСОБЕННОСТИ КВАРК-ГЛЮОННОГО МЕХАНИЗМА
ОБРАЗОВАНИЯ С-ЧЕТНЫХ ТЯЖЕЛЫХ КВАРКОНИЕВ
В АДРОННЫХ СОУДАРЕНИЯХ

Изучается кварк-глюонный канал $g + q(\bar{q}) \rightarrow \chi^{(J)} + q(\bar{q})$ образования С-четных состояний тяжелых кваркониев $Q\bar{Q}$ ($\chi^{(0)}$, $\chi^{(2)}$ и $\chi^{(1)}$ мезонов) в адронных соударениях. Показано, что нерелятивистский характер $Q\bar{Q}$ -системы и правила Ландау-Янга приводят к качественно различным спектрам для $\chi^{(0)}$, $\chi^{(2)}$ мезонов и $\chi^{(1)}$ мезона. В резком отличии от случая $\chi^{(0,2)}$, спектры которых в первом порядке ТВ имеют полжскую особенность $\sim 1/q_{\perp}^2$ при $q_{\perp} \rightarrow 0$, спектр $\chi^{(1)}$ имеет логарифмический полюс $\sim \ln q_{\perp}^2$

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PECULIARITIES OF THE QUARK-GLUON MECHANISM
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The quark-gluon channel $g + q(\bar{q}) \rightarrow \chi^{(j)} + q(\bar{q})$ of the formation of C-even states of heavy quarkonia $Q\bar{Q}$ (of $\chi^{(0)}$, $\chi^{(2)}$ and $\chi^{(1)}$ mesons) in hadron collisions is studied. The nonrelativistic character of the $Q\bar{Q}$ -system and the Landau-Yang rules are shown to result in qualitatively different spectra for $\chi^{(0)}$, $\chi^{(2)}$ mesons and $\chi^{(1)}$ meson. Strongly differing from the case of $\chi^{(0,2)}$ whose spectra in the lowest order of perturbation theory have a polar peculiarity $\propto 1/q_{\perp}^2$ at $q_{\perp} \rightarrow 0$, the spectrum of $\chi^{(1)}$ has a logarithmic pole $\propto \ln q_{\perp}^{-2}$.

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1. Introduction

In our previous paper [1] we have mentioned about the role of the physics of "quarkonia" - mesons composed of heavy quarks $Q\bar{Q}$, in quantum chromodynamics (QCD) and the significance of the study of peculiarities of the formation of C-even P-wave states of these quarkonia produced in hadron collisions. We have discussed there also the specific features of χ -particle production cross sections in quark and gluon channels due to the Landau-Yang rule and non-relativistic nature of quarkonia. It has been established that in the quark channel $q + \bar{q} \rightarrow \chi^{(J)} + q$ distributions in q_{\perp} of three $\chi^{(J)}$ ($J = 0, 1, 2$) are alike: $d\sigma/dq_{\perp}^2 \propto q_{\perp}^{-2}$ (in the region $q_{\perp} < M_{\chi}$ the form of spectra is defined by the parameter ϵ/M_{χ} (where ϵ is the binding energy) whose smallness agrees with nonrelativistic character of motion of quarks $Q\bar{Q}$ in a meson), and in the gluon channel $gg \rightarrow \chi^{(J)} + g$ distributions qualitatively differ. For $\chi^{(0)}$ and $\chi^{(2)}$ the spectrum $d\sigma/dq_{\perp}^2 \propto q_{\perp}^{-2}$ is characteristic (whose peculiarity at $q_{\perp} \rightarrow 0$ is smoothed due to the effect of the gluon form factor T_G^2 arising on consideration of multiple radiation of bremsstrahlung gluons), for $\chi^{(1)}$ the spectrum in

q_{\perp} is much more sloping (the bremsstrahlung radiation of gluon from relatively large distances $\rho_{\perp} \sim q_{\perp}^{-1} \gg M_{\chi}^{-1}$ by initial partons is suppressed due to the Landau-Yang ban, and the infrared peculiarity of radiation is lacking in the final state).

The present paper is devoted to the study of distributions in transverse momenta q_{\perp} of $\chi^{(0)}$, $\chi^{(2)}$ and $\chi^{(1)}$ mesons in their quark-gluon formation channel $g + q(\bar{q}) \rightarrow \chi^{(J)} + q(\bar{q})$ at hadron collisions.

2. Amplitudes of two-gluon decays of $\chi^{(0)}$, $\chi^{(2)}$, $\chi^{(1)}$ mesons

The production of $\chi^{(J)}$ mesons in a quark-gluon channel $g + q(\bar{q}) \rightarrow \chi^{(J)} + q(\bar{q})$ is determined in the lowest order by the α_s diagram of fig.1. Therefore, in order to obtain the behavior of the $\chi^{(J)}$ production differential cross section in q_{\perp} we should have explicit expressions for the amplitudes of two-gluon decays $\chi^{(J)} \rightarrow 2g$ (the decay to virtual gluons is implied). Our calculations have shown that the spectra $d\sigma/dq_{\perp}^2$ of $\chi^{(0)}$ and $\chi^{(2)}$ mesons are alike, therefore, we will analyze only $\chi^{(0)}$ and $\chi^{(1)}$ mesons, and at the very end we will present the form of the spectrum $d\sigma/dq_{\perp}^2$ for $\chi^{(2)}$ meson as well.

Thus, for a further analysis we should know amplitudes $M_{0^+ \rightarrow 2g}^{\mu\nu; ab}(K_1, K_2)$ and $M_{1^+ \rightarrow 2g}^{\lambda, \mu\nu; ab}(q, K_1, K_2)$ of two-gluon decays of $\chi^{(0)}$ and $\chi^{(1)}$ mesons (see fig.2). Using the method of obtaining the form of the amplitude $\chi^{(0)} \rightarrow 2g$ in [2], after some simple transformations we obtain

$$M_{0^+ \rightarrow 2g}^{\mu\nu; ab}(K_1, K_2) = \frac{4g_s^2 \psi_1 q^2}{\sqrt{3} (2K_1 K_2)^2} \delta_{ab} \left\{ g^{\mu\nu} [3(2K_1 K_2)^2 - 4K_1^2 K_2^2 + (4K_1 K_2)(K_1^2 + K_2^2)] - \right. \\ \left. - (4K_1 K_2) [3K_2^{\mu} K_1^{\nu} + K_1^{\mu} K_2^{\nu}] - 4K_1^2 [K_2^{\mu} (K_1 - K_2)^{\nu}] - \right. \\ \left. - 4K_2^2 [K_1^{\nu} (K_2 - K_1)^{\mu}] \right\}, \quad (1)$$

where μ, ν and a, b are, respectively, the vector and color indices of gluons with momenta K_1 and K_2 , and

$$q^2 = (K_1 + K_2)^2 \quad (\text{see fig.2a}).$$

In ref.[1] a compact expression was obtained for the amplitude $\chi^{(1)} \rightarrow 2g$:

$$M_{1^+ \rightarrow 2g}^{\xi, \mu\nu; ab}(q, K_1, K_2) = \frac{4i g_s^2 \psi_1}{\sqrt{2} (K_1 K_2)^2} \delta_{ab} (q^2 g_{\mu\nu} - q_\mu q_\nu) \times \quad (2)$$

$$\times \left\{ \left[\varepsilon^{\alpha\beta\gamma} K_{2\alpha} (K_1^2 g_{\beta\mu} - K_{1\mu} K_{2\beta}) \right] + \left[\varepsilon^{\mu\alpha\beta\gamma} K_{1\alpha} (K_2^2 g_{\beta\nu} - K_{2\beta} K_{2\nu}) \right] \right\}$$

where ξ is the vector index of the $\chi^{(1)}$ state (see fig.2b).

Since for two-particle decays of $\chi^{(0)}$ and $\chi^{(1)}$ mesons we have expressions for the amplitudes (1) and (2), respectively, we may pass on to the calculation of differential spectra in q_\perp .

3. Spectra $d\sigma/dq_\perp^2$ of χ -mesons in a quark-gluon channel of $g + q(\bar{q}) \rightarrow \chi + q(\bar{q})$ production

The diagram of the χ -meson production cross section in a quark-gluon channel in the highest order in α_s is depicted in fig.3. The differential cross section of the production of χ with the velocity y and the transverse with respect to the collision axis momentum q_\perp has the form

$$\frac{d\sigma^{Jc}}{dq_\perp^2 dy} = \frac{\alpha_s C_F}{2S(N^2-1)} \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} D_1^g(x_1) D_2^{q(\bar{q})}(x_2) \delta(\ell^2) \phi_{Jc}^{gq(\bar{q})} \quad (3)$$

where

$$\phi_{0^+}^{gq(\bar{q})} = \frac{1}{K^4} \cdot \left\{ -\frac{1}{4} \text{Sp}(\hat{K}_2 \gamma_5 \hat{\ell} \gamma_5) \right\} g_{\sigma\tau}^+ M_{0^+ \rightarrow 2g}^{\sigma+\nu}(K_1, K) M_{0^+ \rightarrow 2g}^{\tau+\nu'}(K_1, K) \quad (4)$$

$$\Phi_{1+}^{gq(\bar{q})} = \frac{1}{K^4} \left\{ -\frac{1}{4} S_p(\hat{K}_2 \gamma' \hat{e} \gamma') \right\} g_{6\tau}^\perp M_{1+ \rightarrow 2g}^{S, \sigma^4} (q, K_1, K) M_{1+ \rightarrow 2g}^{S, \tau^4} (q, K_1, K) \quad (5)$$

$$\times (q_{\parallel} q_{\parallel}' / q^2 - g_{\tau\tau}')^{\perp}$$

In (3-5) X_1 and X_2 are the portions of hadron momenta taken away by a gluon and a quark, respectively (i.e. $K_1 = P_1 X_1$, $K_2 = P_2 X_2$, $P_1^2 \approx P_2^2 \approx 0$), $g_{6\tau}^\perp$ is the tensor perpendicular to the collision plane (see e.g. [3]). After some simple transformations in (4) and (5), and taking into account the relations $K_1^2 \approx 0$, $K_1 g_{6\tau}^\perp = 0$, $(K_\perp)^2 = -K_\perp^2$ for $\Phi_{0+}^{gq(\bar{q})}$ and $\Phi_{1+}^{gq(q)}$ we obtain the following expressions

$$\Phi_{0+}^{gq(\bar{q})} = \left(\frac{4}{\sqrt{3}} g_s^2 \psi_1 \right)^2 \frac{q^2}{(K_1 K)^4} \left\{ \left(\frac{3K_1 K + K^2}{K^2} \right) (2(K_1 K_2)^2 K_1^2 - K^2 (K_1 K_2)^2) \right\} \quad (6)$$

$$\Phi_{1+}^{gq(\bar{q})} = (2\sqrt{2} g_s^2 \psi_1)^2 \frac{q^2}{(K_1 K)^4} \left\{ q^2 ((2K_1 K_2) - (K_1 K))^2 + ((2K_1 K_2)^2 K_1^2 - K^2 (K_1 K)^2) \right\} \quad (7)$$

Substituting (6) and (7) in (3) and using Sudakov's parametrization for q : $q = y_1 P_1 + y_2 P_2 + q_\perp$ ($q_\perp = -K_\perp$) we obtain the following expressions for differential cross sections

$$\frac{d\sigma^{(0+)}}{dy dQ_1^2} = \frac{521}{N^2 - 1} \alpha_s^3 \pi^2 \psi_1^2 \frac{1}{5} \cdot \frac{1}{3} \int \frac{(2Q_1^2 + 3(1-z))^2}{Q_1^2 (Q_1^2 + (1-z))^3} \cdot \frac{(1-z)(1+(1-z)^2)}{z^2} dz \quad (8)$$

$$\frac{d\sigma^{(1+)}}{dy dQ_1^2} = \frac{521}{N^2 - 1} \alpha_s^3 \pi^2 \psi_1^2 \frac{1}{5} \cdot \frac{1}{2} \int \frac{((2-z)^2(1-z) + (1+(1-z)^2) Q_1^2)(1-z)}{(Q_1^2 + (1-z))^3 \cdot z^2} dz \quad (9)$$

where $Q_1^2 \equiv q_\perp^2 / q^2$ and $z \equiv y_2 / x_2$. Hence, we obtain for distributions without specification of forms of distribution functions of quarks and gluons in a hadron

$$\frac{1}{6} \frac{d\sigma^{(0+)}}{dydQ_1^2} = \frac{1}{3} \int_0^1 \frac{(2Q_1^2 + 3(1-z)^2)(1-z)(1+(1-z)^2)}{Q_1^2 (Q_1^2 + (1-z))^3 z^2} dz \quad (10)$$

$$\frac{1}{6} \frac{d\sigma^{(1+)}}{dydQ_1^2} = \frac{1}{2} \int_0^1 \frac{((2-z)^2(1-z) + (1+(1-z)^2)Q_1^2)(1-z)}{(Q_1^2 + (1-z))^3 z^2} dz \quad (11)$$

$$\frac{1}{6} \frac{d\sigma^{(2+)}}{dydQ_1^2} = \frac{8}{3} \int_0^1 \frac{(1-z)(1+(1-z)^2)}{Q_1^2 (Q_1^2 + (1-z))^3 z^2} dz \quad (12)$$

In the case of $J = 2$ calculations are carried out by the projector $\Pi(2) = (1/2)(\delta_{\alpha\alpha'}\delta_{\beta\beta'} + \delta_{\alpha\beta'}\delta_{\alpha'\beta} - (2/3)\delta_{\alpha\beta}\delta_{\alpha'\beta'})$

since it is technically diffi-

cult to find and use explicit formulae for the amplitudes

$\chi^{(2)} \rightarrow 2g$ (see [1] and [2]). The form of these distributions in Q_1 is shown in fig.4.

It is easy to notice from (10) and (11) that for $\chi^{(1)}$ at $Q_1 \rightarrow 0$ ($q_1 \ll M_\chi$) the contribution in the cross section is made by the region $z \sim 1$ (i.e. the produced ℓ -quark is soft) and in that region $d\sigma/dQ_1^2 \sim \ln Q_1^{-2}$, the spectrum of $\chi^{(1)}$ meson in the region $Q_1 \rightarrow 0$ is more smooth than that of $\chi^{(0)}$ and $\chi^{(2)}$ mesons having the behavior $d\sigma/dQ_1^2 \sim 1/Q_1^2$ (see fig.4).

Conclusion

We considered the spectrum $d\sigma/dQ_1^2$ of heavy C-even quarkonia $\chi^{(J)}$ produced in hadron collisions in a quark-gluon channel $g + q(q) \rightarrow \chi^{(J)} + q(\bar{q})$. In this channel the distributions in q_1 for $\chi^{(0)}$ and $\chi^{(2)}$ rapidly increase at $q_1 \rightarrow 0$ and formally in the main order in α_s have a polar peculiarity $\sim 1/q_1^2$ ($d\sigma/dq_1^2 \sim 1/q_1^2$), which is smoothed

by the gluon form factor T_G^2 during the consideration of the highest gluon corrections (see e.g. [1]). For $x^{(1)}$ at $q_1 \rightarrow 0$ ($q_1 \ll M_x$) the spectrum is more smooth $d\sigma/dq_1^2 \sim \ln(\frac{q_1^2}{q^2})^{-1}$ and this contribution is gathered mainly from the region $z \sim 1$ (i.e. the produced quark (antiquark) is soft). This is the result of the nonrelativistic character of $Q\bar{Q}$ system and the Landau-Yang rule forbidding the radiation of bremsstrahlung gluons from relatively large distances $\beta_1 \sim 1/q_1 \gg 1/M_x$ (see [1])

The author is indebted to Yu.L.Dokshitzer for constant stimulating and fruitful discussions, E.Sh.Bgorian and S.G.Martinyan for critical remarks as well as to G.Z.Zazian for his help in numerical calculations.

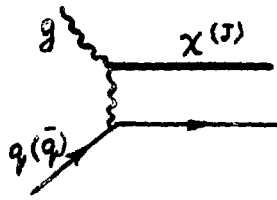
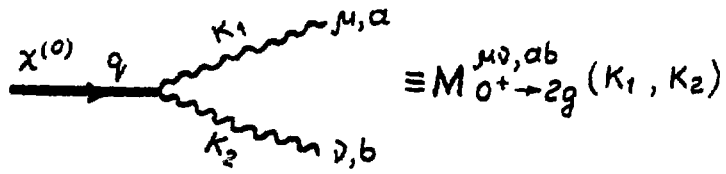
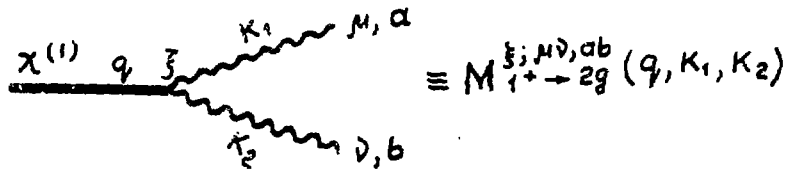


Fig. 1



a)



b)

Fig. 2

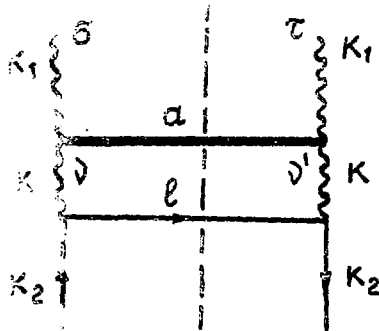


Fig. 3

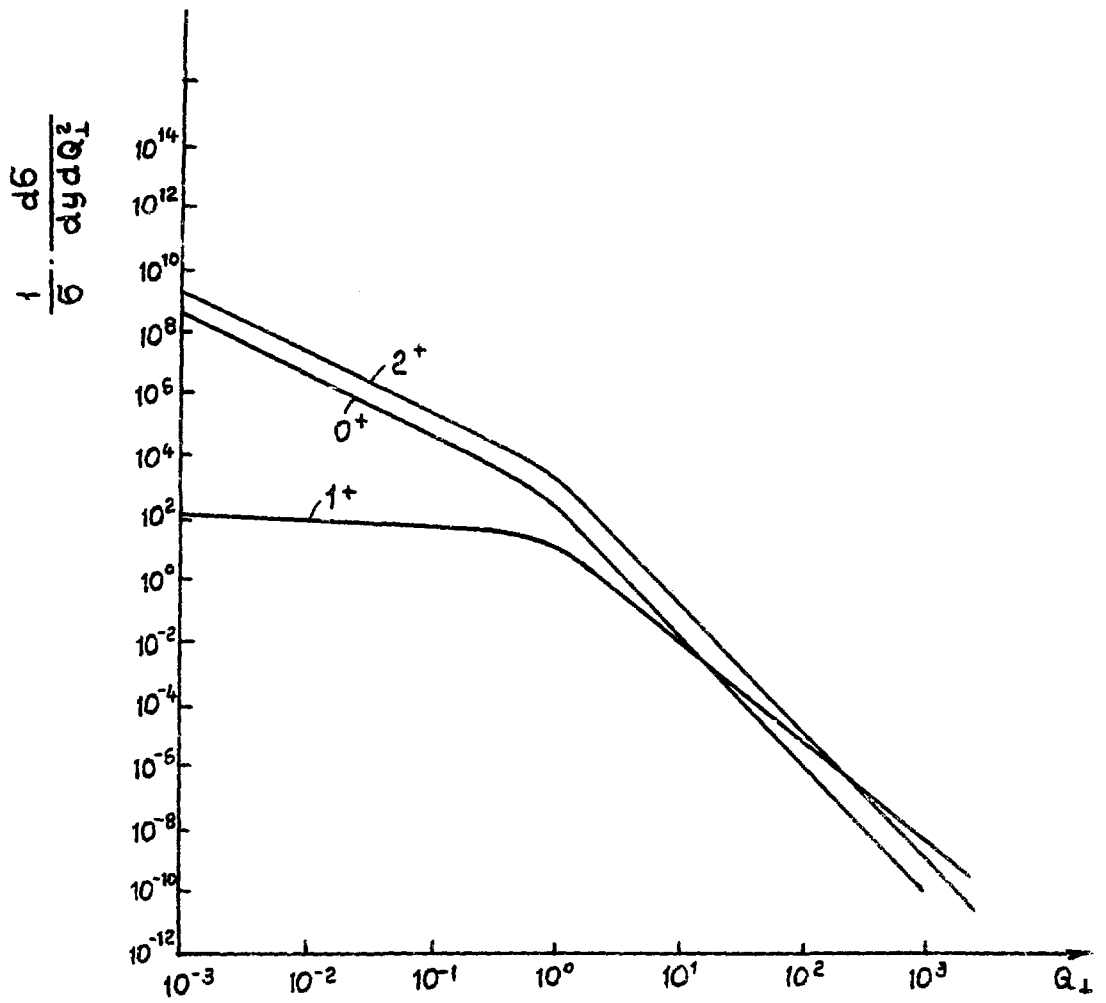


Fig.4

Figure Captions

1. Diagram of the lowest order for the transformation of the χ - meson in the $q\bar{q}$ - channel.
2. Amplitudes of two-gluon decays of $\chi^{(0)}$ and $\chi^{(1)}$ mesons
 - a) amplitudes $\chi^{(0)} \rightarrow 2g$
 - b) amplitudes $\chi^{(1)} \rightarrow 2g$
3. Diagram for the χ meson production cross section in the $q\bar{q}$ - channel in the highest order in α_s .
4. Comparison of forms of the spectra $\frac{1}{6} \frac{d\sigma}{dydQ_1^2}$ of $\chi^{(J)}$ ($J = 0, 1, 2$) mesons in the quark-gluon channel

$$q + q(\bar{q}) \rightarrow \chi^{(J)} + q(\bar{q}) .$$

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The manuscript was received 22 April 1985

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ТЯЖЕЛЫХ КВАРКОНИЕВ В АДРОННЫХ СОУДАРЕНИЯХ

(на английском языке, перевод Л.Н.Багдасаряна)

Редактор Л.П. Мукаян

Технический редактор А.С. Абрамян

Подписано в печать 8/VI-85г. ВБ-08903 Формат 60x84/16
Офсетная печать. Уч. изд. л. 0,8 Тираж 299 экз. ц. 9 к.
Зак. тип. № 311 Индекс 3624

Отпечатано в Ереванском физическом институте
Ереван 36, Маркарянна 2

индекс 3624



ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ