LEPTOPRODUCTION OF HEAVY QUARKS WITH THE ANOMALOUS CHROMOMAGNETIC MOMENT

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The differential and total cross sections of the heavy quark pair production (taking into account the quark anomalous chromomagnetic moment) are presented for electron--nucleon and neutrino-nucleon (at the expense of neutral weak currents) collisions. The contribution of two pole diagrams, describing the interaction of the electron and the neutrino with the gluon from the initial nucleon, is taken into account. The dependence on the quark azimuthal angle and on the virtual boson polarization parameter is studied. Those contributions to the deep-inelastic structure functions which are stimulated by the heavy quark pair creation are calculated in this pole approximation. The influence of the initial photon polarization on the heavy quark pair photoproduction is outlined. It is shown that the available experimental data for the J/ψ leptoproduction allows us to obtain the following estimation $|\varkappa| \leqslant 1.5\div 2$ (in quark magnetons) for the charm quark anomalous chromomagnetic moment.

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1. Introduction

The investigation of the photo- ($\gamma+\mathrm{N} \to \mathrm{Q\bar{Q}}+\mathrm{X}$, [1], X is a nondetected set of hadrons, Q is the heavy quark), electro- ($\mathrm{e}+\mathrm{N} \to \mathrm{e}+\mathrm{Q\bar{Q}}+\mathrm{X}$, [2]) or neutrino- ($\nu+\mathrm{N} \to \nu+\mathrm{Q\bar{Q}}+\mathrm{X}$, [3]) production of the heavy quark pairs is the most convenient way to study the gluon distribution function in hadrons (of the longitudinal momenta). In these cases the lepton-gluon fusion mechanism for the heavy quark pair production is the most probable. These reactions are an effective source of new particles and they allow us to study different properties of heavy quarks. Thus, the reaction $\nu+\mathrm{N} \to \nu+\mathrm{Q\bar{Q}}+\mathrm{X}$ may be exceptionally useful for the determination of the Q quark neutral weak current structure [4]. This is important for checking the correctness of various unified theories of weak and electromagnetic interactions. At present the neutral weak current structure is deter-

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mined only for the nonstrange u and d quarks, i.e. only for one quark doublet in the Weinberg-Salam model [5].

Since the Q quark masses are rather large, calculations of the above mentioned processes are carried out by the quantum chromodynamic methods. For all that it was assumed that the quark-gluon interaction is the same as the electron-photon interaction in quantum electrodynamics, i.e. the Dirac type interaction which is characterized in the coloured SU(3) symmetry by one constant.

In this paper we investigate the influence of one more possible quark-gluon interaction (the Pauli interaction) constant characterized by the anomalous chromomagnetic moment (ACM) on the behaviour of various heavy quark leptoproduction variables. The quark ACM naturally arises when we take into account the higher order corrections to the usual standard quark-gluon interaction constant [6]. In the general case the quark ACM must not be a constant and it must depend on the squared momentum transfer (the gluon virtuality degree). But in the small momentum transfer region (as in the case of the considered processes) the quark ACM may be considered as some phenomenological constant. It is necessary to stress that the quark ACM can exert a significant influence on charmonium spectroscopy [7] and that of quarkonium in general [8]. It was shown previously that taking into account the quark ACM was essential in describing the spin-spin part of the Hamiltonian and it allowed us to improve the charmonium spectroscopy.

2. *The differential cross section*

The matrix element for any of the processes

$$e+g \to e+Q\bar{Q}, \qquad \nu+g \to \nu+Q\bar{Q},$$

in the lowest order in the quark-gluon coupling constant (for the two diagrams in Fig. 1) can be written in the form

$$M = \frac{e^2}{q^2} G_{ef} l_\mu J_\mu, \qquad l_\mu = \bar{u}(k_2)\gamma_\mu(v_e+a_e\gamma_5)u(k_1),$$

$$J_\mu = g_s\bar{u}(p_2)\left[\gamma_\mu(v_Q+a_Q\gamma_5)\frac{\hat{p}_2-\hat{q}+m}{t-m^2}\left(\gamma_\nu-\frac{\kappa}{2m}\sigma_{\nu\lambda}k_\lambda\right)\right.$$

$$\left.+\left(\gamma_\nu-\frac{\kappa}{2m}\sigma_{\nu\lambda}k_\lambda\right)\frac{\hat{q}-\hat{p}_1+m}{u-m^2}\gamma_\mu(v_Q+a_Q\gamma_5)\right]u(-p_1)U_\nu(k) \tag{1}$$

where g_s is the quark-gluon coupling constant, e_Q is the electric charge of the Q quark (in units of the proton charge e), κ is the hypothetic anomalous chromomagnetic moment of the Q quark (in quark magnetons), m is the quark mass, $U_\nu(k)$ is the four-vector of the gluon polarization (the four-momenta designations are shown in Fig. 1). For the heavy quark pair electroproduction, it is necessary to take $G_{ef} = 1$, $v_e = 1$, $v_Q = e_Q$, $a_e = a_Q = 0$. The matrix element of the heavy quark pair production in the neutrino-gluon collisions due to neutral weak currents can be obtained if in Eq. (1) we set $G_{ef} = Gq^2/e^2\sqrt{2}$, $v_e = a_e = 1$, $a_Q = e_Q/2|e_Q|$, $v_Q = (1/2-2e_Q\sin^2\theta_W)e_Q/|e_Q|$, θ_W is the Weinberg angle (later on we shall consider the simplest version of the SU(2)×U(1) unified model of weak and electromagnetic interactions [5]).

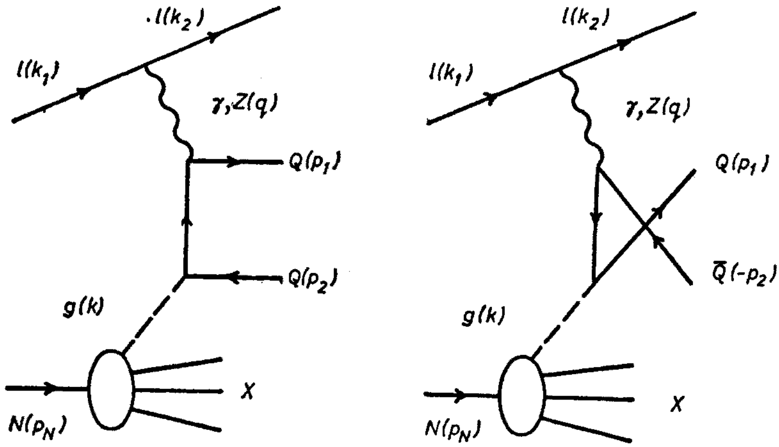

Fig. 1. The pole approximation for leptoproduction of heavy quarks

After summing over the final quark and antiquark polarizations and averaging over the initial gluon polarizations the squared modulus of the matrix element can be written in the following form

$$\overline{|M|^2} = \frac{e^4}{q^4} G_{ef}^2 l_{\mu\nu} T_{\mu\nu}, \qquad T_{\mu\nu} = \overline{J_\mu J_\nu^*},$$

$$l_{\mu\nu} = 2\delta_l[(v_e^2+a_e^2)(2k_{1\mu}k_{2\nu}+2k_{1\nu}k_{2\mu}+q^2 g_{\mu\nu}) \pm 4iv_e a_e \varepsilon_{\mu\nu\alpha\beta}k_{2\alpha}k_{1\beta}], \tag{2}$$

where $\delta_e = 1/2$ for the electroproduction, $\delta_e = 1$ for the neutrinoproduction. Signs $\pm$ correspond to the neutrino or the antineutrino scattering.

In the coordinate system where the z axis is directed along the momentum q and the xz plane is coincident with the lepton scattering plane, the product of the tensors $l_{\mu\nu}$ and $T_{\mu\nu}$ has the form (in the c.m.s. of the quark-antiquark pair)

$$l_{\mu\nu}T_{\mu\nu} = 2\delta_e \frac{-q^2}{1-\varepsilon}\Bigg\{(v_e^2+a_e^2)\Bigg[T_{xx}+T_{yy}+\varepsilon\cos 2\varphi(T_{xx}-T_{yy})$$

$$+2\frac{q_0^2}{-q^2}\left(T_{zz}+\frac{q^2}{q_0^2}T_{00}-\frac{|\boldsymbol{q}|}{q_0}(T_{0z}+T_{z0})\right)+\varepsilon\sin 2\varphi(T_{xy}+T_{yx})$$

$$+\cos\varphi\sqrt{2\varepsilon(1+\varepsilon)\frac{q_0^2}{-q^2}}\left(T_{xz}+T_{zx}-\frac{|\boldsymbol{q}|}{q_0}(T_{0x}+T_{x0})\right)$$

$$+\sin\varphi\sqrt{2\varepsilon(1+\varepsilon)\frac{q_0^2}{-q^2}}\left(T_{yz}+T_{zy}-\frac{|\boldsymbol{q}|}{q_0}(T_{0y}+T_{y0})\right)\Bigg]$$

$$\pm 2iv_e a_e\left[\cos\varphi\sqrt{2\varepsilon(1-\varepsilon)\frac{q_0^2}{-q^2}}\left(T_{yz}-T_{zy}-\frac{|\boldsymbol{q}|}{q_0}(T_{y0}-T_{0y})\right)\right.$$

$$\left.-\sin\varphi\sqrt{2\varepsilon(1-\varepsilon)\frac{q_0^2}{-q^2}}\left(T_{xz}-T_{zx}-\frac{|\boldsymbol{q}|}{q_0}(T_{x0}-T_{0x})\right)-\sqrt{1-\varepsilon^2}(T_{xy}-T_{yx})\right]\Bigg\}, \quad (3)$$

where $q=(q_0,\boldsymbol{q})$, φ is the quark azimuthal angle, $\varepsilon=\left(1-2\frac{\vec{q}^2}{q^2}\,\mathrm{tg}^2\frac{\theta_e}{2}\right)^{-1}$, θ_e is the lepton scattering angle in the laboratory frame. In Eq. (3) the terms proportional to $v_e a_e$ are due to the P-invariance violation in the lepton current.

The differential cross section for any of the processes $e(\nu)+g\to e(\nu)+Q\bar{Q}$, corresponding to the detection of the final lepton and quark, can be written as

$$d\sigma=\frac{\mathscr{E}_2}{\mathscr{E}_1}\frac{\overline{|M|^2}}{2^9\pi^5}\beta d\mathscr{E}_2 d\Omega_e d\Omega_Q, \quad (4)$$

where $\mathscr{E}_1(\mathscr{E}_2)$ is the energy of the initial (final) lepton in the laboratory frame, $d\Omega_l$ is the final lepton solid angle in the same frame, $d\Omega_Q$ is the Q quark solid angle in the c.m.s. of the $Q\bar{Q}$ pair, $\beta=\sqrt{1-4m^2/s}$, $s=(p_1+p_2)^2$ is the $Q\bar{Q}$ invariant mass.

The tensor $T_{\mu\nu}$ is the squared function of the variable κ and, therefore, it can be presented in the form

$$T_{\mu\nu}=T^{(0)}_{\mu\nu}+\kappa T^{(1)}_{\mu\nu}+\kappa^2 T^{(2)}_{\mu\nu},$$

$$T^{(0)}_{\mu\nu}=-\pi\alpha_s\left\{\frac{4}{\alpha_t^2}\left[(v_Q^2+a_Q^2)\left(g_{\mu\nu}(\alpha_t\alpha_u-2m^2q^2)-2(\alpha_t+2m^2)(k,p_1)_{\mu\nu}\right.\right.\right.$$

$$\left.\left.+4m^2(p_1,p_2)_{\mu\nu}\right)+a_Q^2 4m^2(2m^2-\alpha_t)g_{\mu\nu}-4iv_Qa_Q\varepsilon_{\mu\nu\alpha\beta}(\alpha_t k_\alpha p_{1\beta}-2m^2q_\alpha p_{1\beta})\right]$$

$$+[p_1\leftrightarrow p_2,\mu\leftrightarrow\nu]+\frac{4}{\alpha_t\alpha_u}\left[(v_Q^2+a_Q^2)\left(2q^2(s-2m^2)g_{\mu\nu}+8m^2k_\mu k_\nu-4\alpha_t p_{1\mu}p_{1\nu}\right.\right.$$

$$-4\alpha_u p_{2\mu}p_{2\nu}+2(s-2m^2)(k,p_1)_{\mu\nu}+2(s-2m^2)(k,p_2)_{\mu\nu}$$

$$\left.+2(4m^2-s-q^2)(p_1,p_2)_{\mu\nu}\right)+a_Q^2(4m^2(4m^2-s-q^2)g_{\mu\nu}-16m^2k_\mu k_\nu)$$

$$\left.\left.+4iv_Qa_Q\varepsilon_{\mu\nu\alpha\beta}((s-2m^2)(p_1-p_2)_\alpha k_\beta+(4m^2-s-q^2)p_{1\alpha}p_{2\beta})\right]\right\},$$

$$T^{(1)}_{\mu\nu}=-\pi\alpha_s\left\{\frac{6}{\alpha_t}\left[(v_Q^2+a_Q^2)((s-q^2)g_{\mu\nu}-2(k,p_1)_{\mu\nu})-2a_Q^2\alpha_t g_{\mu\nu}\right.\right.$$

$$\left.+4iv_Qa_Q\varepsilon_{\mu\nu\alpha\beta}k_\alpha p_{1\beta}\right]+[p_1\leftrightarrow p_2,\mu\leftrightarrow\nu]+\frac{4}{\alpha_t\alpha_u}\left[(v_Q^2-a_Q^2)\left(-\tfrac{1}{2}(s-q^2)^2g_{\mu\nu}\right.\right.$$

$$+4q^2k_\mu k_\nu+3\alpha_t(k,\, p_2)_{\mu\nu}+3\alpha_u(k,\, p_1)_{\mu\nu})+a_Q^2((s-q^2)\,(m^2-q^2)g_{\mu\nu}-4m^2k_\mu k_\nu)$$

$$+iv_Q a_Q\varepsilon_{\mu\nu\alpha\beta}(2(\alpha_u-\alpha_t)k_\alpha q_\beta+(5s+2q^2)k_\alpha(p_1-p_2)_\beta)]\Big\},$$

$$T^{(2)}_{\mu\nu} = -\pi\alpha_s\Big\{8\Big[(v_Q^2+a_Q^2)\Big(\frac{s}{4m^2}\,g_{\mu\nu}-\frac{1}{m^2}\,(p_1,\, p_2)_{\mu\nu}\Big)-a_Q^2 g_{\mu\nu}$$

$$+\frac{i}{m^2}\,v_Q a_Q\varepsilon_{\mu\nu\alpha\beta}p_{2\alpha}p_{1\beta}\Big]+\frac{4}{\alpha_t\alpha_u}\Big[(v_Q^2-a_Q^2)\Big(\Big(\frac{s\alpha_t\alpha_u}{2m^2}-\tfrac{1}{2}\,(s-q^2)^2\Big)\,g_{\mu\nu}$$

$$+\frac{\alpha_t^2}{m^2}\,p_{2\mu}p_{2\nu}+\frac{\alpha_u^2}{m^2}\,p_{1\mu}p_{1\nu}+\frac{q^2}{m^2}\,\alpha_t(k,\, p_2)_{\mu\nu}+\frac{q^2}{m^2}\,\alpha_u(k,\, p_1)_{\mu\nu}$$

$$+q^2\Big(2-\frac{q^2}{m^2}\Big)\,k_\mu k_\nu\Big)+a_Q^2(4m^2-s-q^2)k_\mu k_\nu+iv_Q a_Q\varepsilon_{\mu\nu\alpha\beta}((s-q^2)\,(p_2-p_1)_\alpha k_\beta$$

$$+\Big(1+\frac{q^2}{m^2}\Big)(\alpha_t-\alpha_u)q_\alpha k_\beta\Big]\Big\}, \tag{5}$$

where $\alpha_t = m^2-t$, $\alpha_u = m^2-u$, $(k,\, q)_{\mu\nu} = k_\mu q_\nu+k_\nu q_\mu$. Here the terms proportional to q_μ are omitted since they do not contribute to the differential cross section.

The important property of the tensor $T_{\mu\nu}$ is that its symmetric part is simultaneously P-even and its antisymmetric part is P-odd. This is a consequence of the pole mechanism considered here. In the general case, both P-even and P-odd parts of the tensor $T_{\mu\nu}$ must contain a symmetric part. The tensor $T^{(0)}_{\mu\nu}$ was obtained earlier [9] for the processes e(ν) + g → e(ν) + $Q\overline{Q}$. The components of the tensor $T_{\mu\nu}$ used in Eq. (4) are given in the Appendix.

By analysing Eq. (5) one can notice that the tensors $T^{(1,2)}_{\mu\nu}$ for the process e + g → e + $Q\overline{Q}$ are orthogonal not only to the four-momentum q_μ (as should be by virtue of the quark electromagnetic current conservation in the approximation considered) but it is also orthogonal to the four-momentum k_μ, viz., $T^{(1,2)}_{\mu\nu}k_\mu = T^{(1,2)}_{\mu\nu}k_\nu = 0$. It means that the tensor structure of $T^{(1,2)}_{\mu\nu}$ can be written in the following way

$$T^{(1,2)}_{\mu\nu} = A^{(1,2)}G_{\mu\nu}+B^{(1,2)}P_{1\mu}P_{1\nu},$$

$$G_{\mu\nu} = g_{\mu\nu}+q^2\,\frac{k_\mu k_\nu}{(kq)^2}-\frac{(k,\, q)_{\mu\nu}}{(kq)}, \qquad P_{1\mu} = G_{\mu\nu}p_{1\nu}, \tag{6}$$

where the invariant structures are determined by the formulae

$$A^{(1)} = -4\pi\alpha_s e_Q^2\,\frac{(s-q^2)^2}{\alpha_t\alpha_u}, \qquad B^{(1)} = 0,$$

$$A^{(2)} = 4\pi\alpha_s e_Q^2\Big[\frac{(s-q^2)^2}{2\alpha_t\alpha_u}-\frac{s}{m^2}\Big], \qquad B^{(2)} = 4\pi\alpha_s e_Q^2\,\frac{(s-q^2)^2}{m^2\alpha_t\alpha_u} \tag{7}$$

The tensor $G_{\mu\nu}$ is transverse in the chosen coordinate system (only G_{xx} and G_{yy} components differ from zero) and the vector $P_{1\mu}$ has only one nonzero component ($P_{1x} = -\sqrt{s}\,\beta \sin\theta/2$, θ is the angle between the momentum $\boldsymbol{q}$ and the quark momentum $\boldsymbol{p}_1$ in the $Q\bar{Q}$ c.m.s.). Therefore, the quark ACM leads to a quite definite dependence of the cross section on the azimuthal angle φ for heavy quark pair electroproduction on the gluon

$$l_{\mu\nu}T_{\mu\nu}^{(1,2)} = \frac{q^2}{1-\varepsilon}\left[2A^{(1,2)} + \frac{s}{4}\beta^2 \sin^2\theta B^{(1,2)}(1+\varepsilon\cos 2\varphi)\right]. \tag{8}$$

It follows from Eqs. (7) and (8) that the quark ACM makes contribution only to the transverse components of the differential cross section, namely, to T_{xx} and T_{yy}. Note that $T_{xx}-T_{yy}$ contains only the squared contributions of κ. Therefore, the quark ACM manifestation should be sought only in these combinations.

3. *The structure functions*

The result of integration over the final $Q\bar{Q}$ pair in $\gamma^*(Z^*)+g \to Q+\bar{Q}$ is determined by the following tensor

$$W_{\mu\nu} = (2\pi)^3 \int \frac{d^3p_1}{(2\pi)^3 2p_{10}} \frac{d^3p_2}{(2\pi)^3 2p_{20}} \delta(k+q-p_1-p_2)T_{\mu\nu}. \tag{9}$$

For $\gamma^*+g \to Q+\bar{Q}$ the tensor $W_{\mu\nu}$ is characterized by two standard structure functions

$$W_{\mu\nu} = F_1(z, q^2)\left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) + \frac{1}{(kq)}F_2(z, q^2)\left(k_\mu - q_\mu\frac{kq}{q^2}\right)\left(k_\nu - q_\nu\frac{kq}{q^2}\right). \tag{10}$$

The tensor $W_{\mu\nu}$ for $Z^*+g \to Q+\bar{Q}$ is determined by a greater number of structure function in the general case. Some of them are multiplied by the tensor structures proportional to q_μ, q_ν and do not make any contribution to the massless neutrino scattering cross section. The structure function multiplied by $\varepsilon_{\mu\nu\alpha\beta}k_\alpha q_\beta$ is equal to zero for the considered mechanism by virtue of the CP-invariance of the weak interaction with neutral currents.

Using Eq. (5), we can obtain the structure functions

F_2 (z, q^2) and F_L $(z. q^2)$ F_2 (z, q^2) $-2zF_1$ (z, q^2)

$$\frac{\pi}{\alpha_s}F_2(z, q^2) = (v_Q^2+a_Q^2)\left\{\beta\left[4z^2(1-z) - \frac{z^2}{2} - 2\gamma z(1-z)\right]\right.$$

$$\left. + \Lambda\left(\frac{z}{2} - z^2(1-z) + 2\gamma^2(1-3z) - 4\gamma^2 z^3\right) + \kappa\frac{z}{2}\Lambda + \kappa^2(1-z)\frac{1}{8\gamma}\beta\right\}$$

$$+a_Q^2\left\{2\gamma z\Lambda + \kappa[\beta(\tfrac{3}{2}z - \tfrac{3}{4} - \tfrac{9}{4}z^2) + \tfrac{1}{2}\Lambda z(1+\gamma)] + \kappa^2\left[\beta\left(\tfrac{3}{4} - \frac{z^2}{4} + \frac{1}{4\gamma}(\tfrac{7}{2} + z(2-z))\right.\right.\right.$$

$$+\frac{1}{16\gamma z^2}(1-\tfrac{13}{3}z+4z^2)\left(1+\frac{2\gamma z}{1-z}\right)\right)-\tfrac{1}{4}\Lambda(\tfrac{1}{4}-\tfrac{5}{4}z-\gamma z+\tfrac{3}{2}z^2+3\gamma z^2)\Bigg]\Bigg\},$$

$$\frac{\pi}{\alpha_s}F_L(z,q^2) = (v_Q^2+a_Q^2)\,[2z^2(1-z)\beta-4\gamma z^3\Lambda]+a_Q^2\Big\{-4\gamma z^2(1-z)\beta$$

$$+2\gamma\Lambda(z-2z^2(1-z(1+2\gamma)))+\kappa[\tfrac{3}{2}z(1-z)\beta+\tfrac{1}{2}\Lambda(\gamma z(1-z)-z^2)]$$

$$+\kappa^2\left[\tfrac{1}{4}\beta\left(2+\frac{3}{\gamma}+\frac{1-z+2\gamma z}{6\gamma z^2(1-z)}(1-2z)^2\right)+\tfrac{1}{4}\Lambda\left(\frac{z}{2}-z^2(1+2\gamma)\right)\right]\Bigg\},$$

$$\gamma = \frac{m^2}{-q^2},\qquad \Lambda = \ln\frac{1+\beta}{1-\beta} \tag{11}$$

If $\kappa = 0$ one can obtain from Eq. (11) the well-known expressions for the heavy quark leptoproduction structure functions [9]. It is seen that the quark ACM does not make any contribution to the $Q\bar{Q}$ pair production by the longitudinal virtual photons.

In terms of the gluon structure functions the total cross section of the $Q\bar{Q}$ pair leptoproduction on the nucleon is determined by the following formula

$$F_{2,L}^{tot}(x,q^2) = \int_{ax}^{1} dy G(y,q^2)F_{2,L}\left(\frac{x}{y},q^2\right), \tag{12}$$

where $G(y,q^2)$ is the gluon distribution function in the nucleon, $a = 1-4m^2/q^2$. If one takes an interest in only the $Q\bar{Q}$ bound state production, one can use the following equation [10]

$$F_{2,L}^{bound}(x,q^2) = \frac{1}{N}\int_{ax}^{bx} dy G(y,q^2)F_{2,L}\left(\frac{x}{y},q^2\right), \tag{13}$$

where $b = 1-4m_1^2/q^2$, m_1 is the mass of the lightest meson with the open flavour, N is the number of the $Q\bar{Q}$ bound states in the interval $4m^2 < s < 4m_1^2$. We shall use for the charm production $N = 8$, $m = 1.25$ GeV, $m_1 = 1.86$ GeV and for the b quark production $N = 14$, $m = 4.7$ GeV, $m_1 = 5.35$ GeV [11].

It is seen from Fig. 2 that the quark ACM changes only the absolute values of the electroproduction structure functions (and of the neutrinoproduction, Fig. 3), but does not considerably change the character of the x and q^2 dependence. The gluon distribution function for the nucleon was taken from Ref. [12]. The fact that we take into account the quark ACM only in the small interval of negative values κ results in decreasing the absolute values of the electroproduction structure function $F_2^{tot}(x,q^2)$ (as compared with the quantum chromodynamic predictions). In all other cases the structure function $F_2^{tot}(x,q^2)$ is increased. For example, at $q^2 = -20\ \text{GeV}^2$ and $x = 0.01$ the total charm

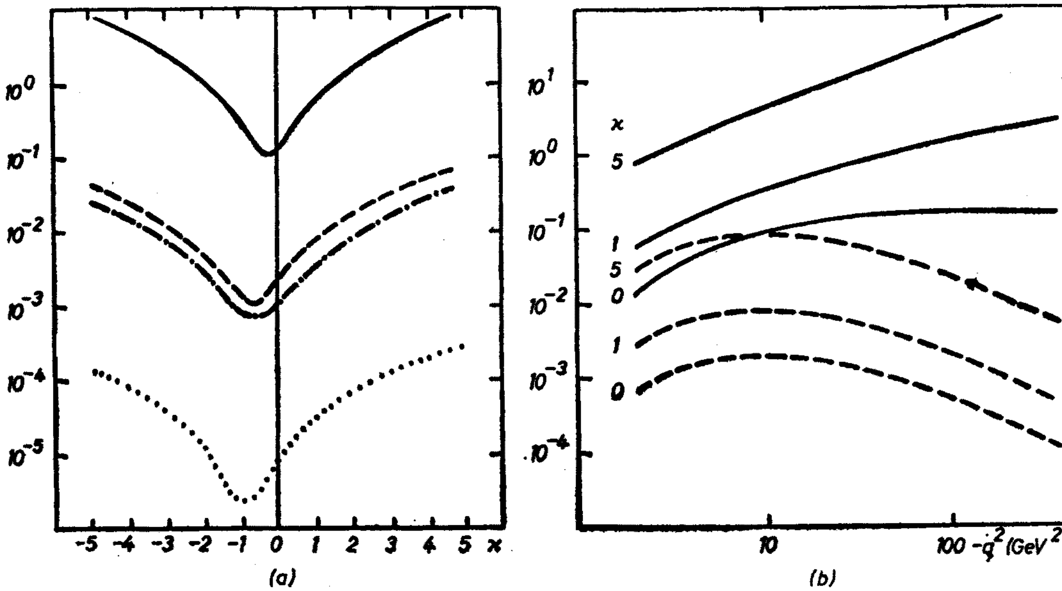

Fig. 2. Electroproduction structure functions, plotted versus (a) the quark ACM $\varkappa$ at $x = 0.01$ and $q^2 = -20\ \mathrm{GeV}^2$ and (b) the squared momentum transfer q^2 at $x = 0.01$. Solid and dashed (dashed-dotted and dotted) curvers correspond to charm (bottom) structure functions $F_2^{\mathrm{tot}}(x, q^2)$ and $F_2^{\mathrm{bound}}(x, q^2)$

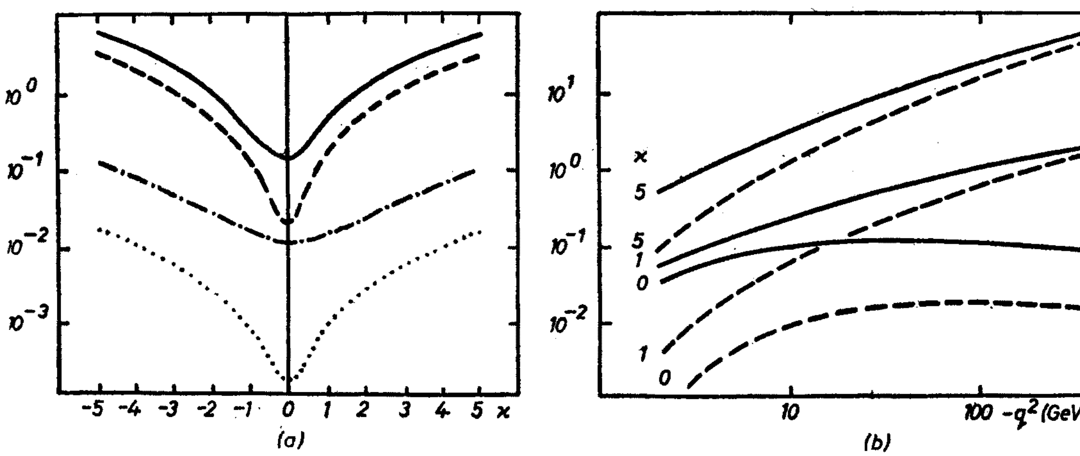

Fig. 3. Neutrinoproduction structure functions, plotted versus (a) the quark ACM $\varkappa$ at $x = 0.01$ and $q^2 = -20\ \mathrm{GeV}^2$ and (b) the squared momentum transfer q^2 at $x = 0.01$. Solid and dashed (dashed-dotted and dotted) curves correspond to charm (bottom) structure functions $F_2^{\mathrm{tot}}(x, q^2)$ and $F_L^{\mathrm{tot}}(x, q^2)$

production in $F_2^{\mathrm{tot}}(x, q^2)$ is increased from 0.12 to 9.1 if the charm quark ACM is changed from 0 to 5. The fact that we take into account the quark ACM for the neutrinoproduction of the heavy quarks always results in increasing the absolute values of the structure functions $F_2(x, q^2)$ and $F_L(x, q^2)$. The influence of the quark ACM is increased with increasing $|q^2|$ and decreasing x. Not to contradict the available experimental data on $F_2(x, q^2)$ [13], it is necessary to limit the charm quark ACM by the value $|\varkappa| \lesssim 1.5 \div 2$.

4. *The heavy quarks photoproduction*

The total cross section for the $Q\bar{Q}$ bound state photoproduction in the considered model is determined by the formula

$$\sigma(\gamma N \to Q\bar{Q}X) = \frac{1}{NS}\int\limits_{4m^2}^{4m_1^2} dsG\left(\frac{s}{S}, s\right)\sigma_{\gamma g}(s), \tag{14}$$

where $S = (q+p_N)^2$, $\sigma_{\gamma g}(s)$ is the total cross section of the pair production in the photon-gluon fusion

$$\sigma_{\gamma g}(s) = \frac{8\pi^2\alpha}{s} R_{\mu\nu}W_{\mu\nu}, \tag{15}$$

where $R_{\mu\nu}$ is the initial photon density matrix.

It is seen from Eq. (10) that the total cross section of the linear polarized photon absorbtion is equal to the total cross section of the nonpolarized photon absorption. Therefore, setting $R_{\mu\nu} = -g_{\mu\nu}/2$ we obtain in the considered approximation

$$\sigma_{\gamma g}(s) = \frac{2\pi\alpha\alpha_s e_Q^2}{s}\left[\ln\frac{1+\beta}{1-\beta}\left(1+\lambda-\frac{\lambda^2}{2}+\kappa\right)+\beta\left(\frac{\kappa}{\lambda}-1-\lambda\right)\right], \tag{16}$$

where $\lambda = 4m^2/s$.

The available J/ψ photoproduction experimental data has a better agreement with predictions for the mechanism under consideration at $\kappa \neq 0$, viz., $\kappa \approx -1$ (Fig. 4). At $\sqrt{S} \lesssim 50$ GeV the Υ photoproduction cross section is about two orders of magnitude less than the J/ψ photoproduction cross section.

It would be interesting to investigate the dependence of the heavy quark photoproduction differential cross section on the initial photon Stokes parameters. In the general case the tensor $R_{\mu\nu}$ has the form

$$R_{\mu\nu} = -\tfrac{1}{2}\, g_{\mu\nu}+ \frac{\xi_1}{2}(e_\mu^{(1)}e_\nu^{(2)}+e_\mu^{(2)}e_\nu^{(1)})- \frac{i\xi_2}{2}(e_\mu^{(1)}e_\nu^{(2)}-e_\mu^{(2)}e_\nu^{(1)})$$

$$+\frac{\xi_3}{2}(e_\mu^{(1)}e_\nu^{(1)}-e_\mu^{(2)}e_\nu^{(2)}), \tag{17}$$

where

$$e_\mu^{(1)} = N_\mu/\sqrt{-N^2}, \quad e_\mu^{(2)} = P_\mu/\sqrt{-P^2}, \quad N_\mu = \varepsilon_{\mu\alpha\beta\gamma}p_{1\alpha}p_{2\beta}q_\gamma,$$

$$P_\mu = \varepsilon_{\mu\alpha\beta\gamma}N_\alpha k_\beta q_\gamma,$$

ξ_i are the photon Stokes parameters. Then, for the differential cross section of the process $\gamma+g \to Q+\overline{Q}$ we obtain

$$\frac{d\sigma}{dt} = \frac{\pi\alpha\alpha_s e_Q^2}{4s^2}\left\{\frac{\alpha_t}{\alpha_u}+\frac{\alpha_u}{\alpha_t}+\frac{4m^2s(\alpha_u\alpha_t-m^2s)}{\alpha_u^2\alpha_t^2}\right.$$
$$\left.+\xi_3\frac{(\alpha_u\alpha_t-m^2s)s}{2m^2\alpha_u\alpha_t}\left(\frac{8m^4}{\alpha_u\alpha_t}-\kappa^2\right)+\kappa\frac{s^2}{\alpha_u\alpha_t}+\kappa^2\frac{s}{2m^2}\right\}. \quad (18)$$

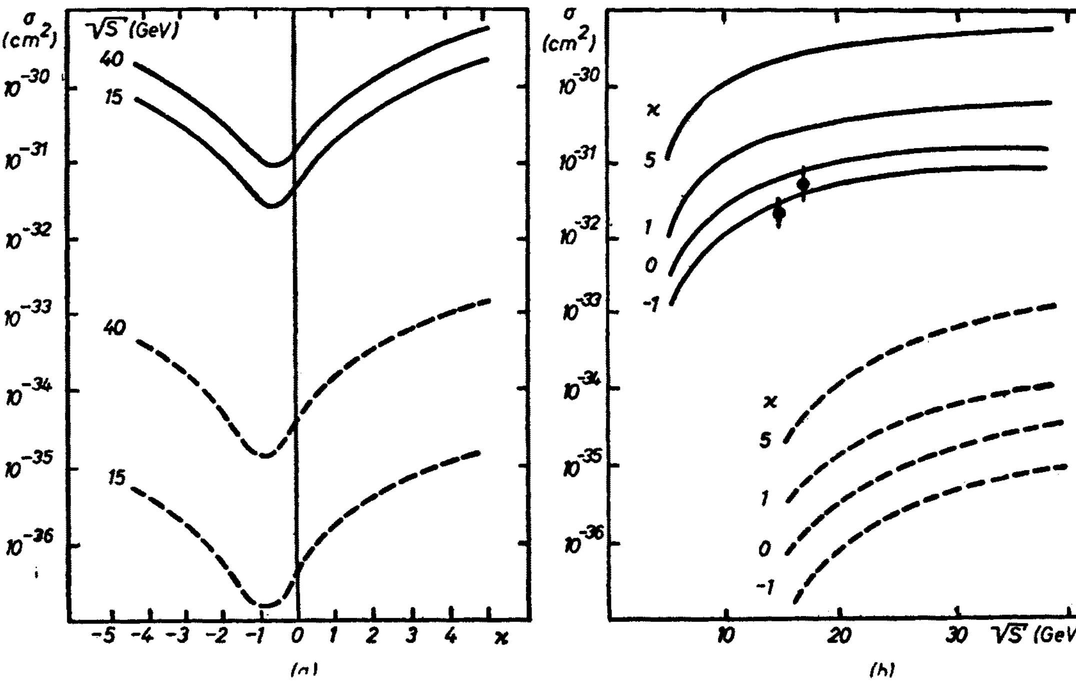

Fig. 4. Total cross section of the $Q\bar{Q}$ bound states photoproduction as a function of the quark ACM ϰ (a) and the energy $\sqrt{S}$ (b). Solid and dashed curves correspond to J/ψ and Υ photoproduction. Experimental data are taken from Ref. [20]

As it should be expected, the differential cross section (18) does not depend on the parameters ξ_1 and ξ_2. It is important to stress that the sign of the contribution proportional to ξ_3 in Eq. (18) depends on the value of κ. It can be seen that this additional contribution is always positive if $|\kappa| > \sqrt{2}$. If $|\kappa| < \sqrt{2}$ the sign can be changed by changing the quark jet angle. Therefore, the investigation of the polarization effects in the jets photoproduction may be useful for the accurate definition of the quark anomalous chromomagnetic moment.

5. Conclusion

The available experimental data on the J/ψ photo- and electroproduction does not contradict the charm quark ACM value $|\kappa| \sim 1.5\div 2$ (in natural quark units). The larger values of κ are unacceptable. It is interesting to compare the limitations we have found with the estimations for the quark ACM available in literature. The values of the charm quark ACM required in the charmonium spectroscopy are dependent on the specific form of the potential used: $\kappa = 1.1$ [7, 14], $\kappa = 4.4$ [15], $\kappa = 5.1$ [16]. From the above analysis it follows that the large values of κ ($\kappa \sim 4\div 5$) contradict the J/ψ leptoproduction experiments. As a result of the last experimental charmonium level structure investigations [17], the situation with η_c and η_c' has changed essentially. Thus, the existence of η_c' has not been confirmed and the η_c mass turned out to be large, $m_\eta \sim 3$ GeV. Therefore, the difficulty with the spin-spin interaction in charmonium is essentially resolved and, hence, the introduction of the charm quark ACM becomes unnecessary. As a result, the values $\kappa \sim 4\div 5$ must contradict the new charmonium spectroscopy. But nevertheless, the problem of the D-D* and F-F* mesons mass splitting remains unsolved [18].

The quark ACM form factor calculations carried out in the framework of quantum chromodynamics lead to the formula [19] $\kappa(q^2) = (-m^2/q^2)^d - 1$, where $d = 3\alpha_s(-q^2)/4\pi$. Hence, it follows that at short distances $|q^2| \sim m^2$, $\kappa \sim 0$ and at long distances $\kappa \gtrsim 1$.

In conclusion we can claim that the investigations of the deep-inelastic charm particle leptoproduction will allow us to define precisely the value of the quark chromomagnetic moment.

APPENDIX

The components of the tensor $T_{\mu\nu}$ are determined by the following formulae

$$T_{yy}^{(0)} = \pi\alpha_s \left\{ (v_Q^2 + a_Q^2) \left[8\,\frac{1+\beta^2\cos^2\theta}{1-\beta^2\cos^2\theta} - 32\beta^2\sin^2\theta\,\frac{z(1-z)}{(1-\beta^2\cos^2\theta)^2} \right] + a_Q^2\,\frac{128\gamma z}{1-\beta^2\cos^2\theta}\,[4\gamma z - (1-z)(1-\beta^2\cos^2\theta)] \right\},$$

$$T_{xx}^{(0)} = \pi\alpha_s \left\{ (v_Q^2 + a_Q^2) 16\beta^2\sin^2\theta\,\frac{z(1-z)(1+4\gamma-\beta^2\cos^2\theta)}{(1-\beta^2\cos^2\theta)^2} + a_Q^2\,\frac{128\gamma z}{1-\beta^2\cos^2\theta}\,[4\gamma z - (1-z)(1-\beta^2\cos^2\theta)] \right\} + T_{yy}^{(0)},$$

$$T_{zz}^{(0)} = \pi\alpha_s \left\{ (v_Q^2 + a_Q^2) \left[16\beta^2\cos^2\theta\,\frac{z(1-z)(1+4\gamma-\beta^2\cos^2\theta)+\beta^2\cos^2\theta-1-8\gamma z}{(1-\beta^2\cos^2\theta)^2} - 8\,\frac{1-\beta^2}{1-\beta^2\cos^2\theta} \right] + a_Q^2 16\,\frac{1-\beta^2}{1-\beta^2\cos^2\theta} \right\} + T_{yy}^{(0)},$$

$$T_{xz}^{(0)} = T_{zx}^{(0)}$$

$$= -\pi\alpha_s \left\{ (v_Q^2 + a_Q^2) 8\beta^2\sin\theta\cos\theta\,\frac{1-\beta^2\cos^2\theta+8\gamma z-4z(1-z)(1-\beta^2\cos^2\theta(1-4\gamma))}{(1-\beta^2\cos^2\theta)^2} \right\},$$

$$T^{(1)}_{yy} = T^{(1)}_{xx} = \pi\alpha_s \left\{ (v_Q^2 + a_Q^2) \frac{16}{1-\beta^2\cos^2\theta} - 8a_Q^2 \frac{1-2z(1+\gamma)-3\beta^2\cos^2\theta}{1-\beta^2\cos^2\theta} \right\},$$

$$T^{(1)}_{zz} = -\pi\alpha_s a_Q^2 8 \frac{1+\dfrac{2z(2-\gamma)}{1-z} - 2z(1+\gamma) + 3\beta^2\cos^2\theta}{1-\beta^2\cos^2\theta},$$

$$T^{(1)}_{xz} = T^{(1)}_{zx} = \pi\alpha_s a_Q^2 \frac{24\beta^2 \sin\theta\cos\theta}{1-\beta^2\cos^2\theta},$$

$$T^{(2)}_{yy} = \pi\alpha_s \left\{ (v_Q^2 + a_Q^2) \left[\frac{16}{1-\beta^2} - \frac{8}{1-\beta^2\cos^2\theta} \right] + a_Q^2 \left[\frac{8}{1-\beta^2\cos^2\theta} + 8\frac{4-\beta^2}{1-\beta^2} \right] \right\},$$

$$T^{(2)}_{xx} = \pi\alpha_s \left\{ (v_Q^2 + a_Q^2) \frac{8}{1-\beta^2\cos^2\theta} + a_Q^2 \left[\frac{8\beta^2\cos^2\theta}{1-\beta^2} - \frac{16}{1-\beta^2\cos^2\theta} \right] \right\},$$

$$T^{(2)}_{xz} = T^{(2)}_{zx} = -\pi\alpha_s \frac{8\beta^2 \sin\theta\cos\theta}{1-\beta^2} a_Q^2,$$

$$T^{(0)}_{xy} = -T^{(0)}_{yx} = \pi\alpha_s \frac{32 i v_Q a_Q \beta\cos\theta}{(1-\beta^2\cos^2\theta)^2} [(1-\beta^2\cos^2\theta)(1-2z+2z^2) + 8\gamma z^2],$$

$$T^{(0)}_{0y} = -T^{(0)}_{y0} = \pi\alpha_s \frac{16 i v_Q a_Q \beta\sin\theta}{(1-\beta^2\cos^2\theta)^2} [(1-\beta^2\cos^2\theta)(1-2z) - 8\gamma z],$$

$$T^{(0)}_{yz} = -T^{(0)}_{zy} = \pi\alpha_s \frac{16 i v_Q a_Q (1-2z)\beta\sin\theta}{(1-\beta^2\cos^2\theta)^2} [(1-\beta^2\cos^2\theta)(1-2z) - 8\gamma z],$$

$$T^{(1)}_{xy} = -T^{(1)}_{yx} = \pi\alpha_s \frac{8 i v_Q a_Q \beta\cos\theta}{1-\beta^2\cos^2\theta}(13-7z),$$

$$T^{(1)}_{0y} = -T^{(1)}_{y0} = -T^{(1)}_{yz} = T^{(1)}_{zy} = -\pi\alpha_s \frac{4 i v_Q a_Q \beta\sin\theta}{1-\beta^2\cos^2\theta}(3-7z),$$

$$T^{(2)}_{xy} = -T^{(2)}_{yx} = \pi\alpha_s 4 i v_Q a_Q \beta\cos\theta \left(\frac{4}{1-\beta^2} + \frac{\dfrac{1}{\gamma} - 4}{1-\beta^2\cos^2\theta} \right),$$

$$T^{(2)}_{0y} = -T^{(2)}_{y0} = \pi\alpha_s \frac{8 i v_Q a_Q \beta\sin\theta}{1-\beta^2\cos^2\theta},$$

$$T^{(2)}_{yz} = -T^{(2)}_{zy} = \pi\alpha_s 8 i v_Q a_Q \beta\sin\theta \left(\frac{2}{1-\beta^2} - \frac{1}{1-\beta^2\cos^2\theta} \right).$$

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