Moscow University
Physics Bulletin
Vol. 60, No. 6, pp. 22-30, 2005

Vestnik Moskovskogo
Universiteta. Fizika
UDC 539.137.12/6

ATOMIC AND NUCLEAR PHYSICS

ANALYSIS OF THE ANOMALOUS BEHAVIOR OF D*-MESON PRODUCTION CROSS SECTIONS IN DEEP INELASTIC e^-p AND e^+p SCATTERING IN THE HERA COLLIDER

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An explanation is offered of the anomalous difference in the D^*-meson production cross sections discovered in the ZEUS experiment in deep inelastic e^-p and e^+p scattering in the HERA Collider.

INTRODUCTION

In one of the most recent works of the ZEUS Collaboration [1] which studies the interaction of electrons (e^-) and positrons (e^+) with protons (p) in the HERA Collider at 300 GeV (center-of-mass energy), it was found that there is a discrepancy in the behavior of the D^*-meson production cross sections in e^-p and e^+p scattering. This discrepancy, namely, the excess of the D^*-meson production cross sections in e^-p scattering over that in e^+p scattering was observed with an exchange-photon virtuality $Q^2 > 40$ GeV^2.

If we assume that the observed anomaly is not related to the measurement conditions or the quality of interaction reconstruction, we should look for an explanation in a mechanism specific to heavy quark production that is sensitive to the charge asymmetry of e^-p and e^+p collisions. In this paper we propose one such explanation related to the specific behavior of production cross sections of heavy quarks in the impact parameter space.

KINEMATICS OF D^* PRODUCTION

The production of charm, or hadrons containing a single c quark, is described by the mechanism of photon–gluon fusion,

$$\gamma + g \to c\bar{c}, \tag{1}$$

where, in the scattering of a lepton (electron or positron) with momentum k by a proton with momentum P, the virtual photon γ with momentum $q = k - k'$ interacts with the gluon g which transfers momentum xP (Fig. 1). The variable x, which specifies the fraction of the proton momentum transferred by the gluon, is related to the Bjorken variable $x_{Bj} = Q^2 2Pq$ as

$$x = x_{\rm Bj} + S_{cc}/yS,$$

where $y = Pq/Pk$ is the fraction of the lepton energy transferred to the photon in the beam-proton rest frame; $S = (k+P)^2$ is the square of the invariant lepton–proton energy; and $S_{cc} = (q + xP)^2$ is the square of the invariant energy of the produced quark–antiquark pair. The amount of this energy determines the production threshold for charmed quarks of mass M_c,

$$(q + xP)^2 > (2M_c)^2.$$

This relation limits the exchange-photon virtuality,

$$Q^2 < xyS - 4M_c^2 = Q^2_{\max}. \tag{2}$$

When only light quarks are involved, the upper kinematic limit on photon virtuality is a constant, $Q^2_{\max} = S$.

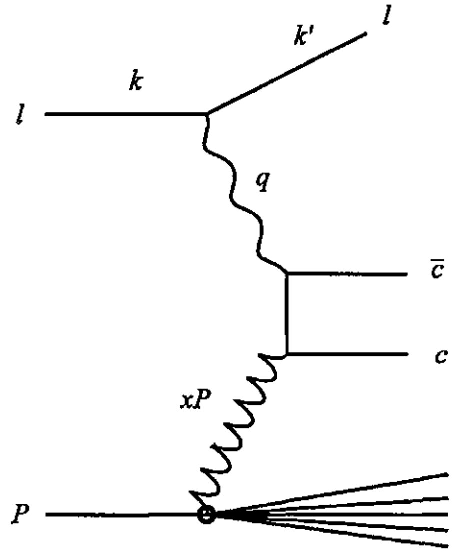

Fig. 1

Diagram of $c\bar{c}$ pair production in deep inelastic lepton–proton scattering.

LEPTON–PROTON SCATTERING IN THE IMPACT PARAMETER REPRESENTATION

In the space of the impact parameter b, which is the canonical conjugate of the t-channel photon momentum, imposing condition (2) is equivalent to placing a limit on the impact parameter. Indeed, as $Q^2_{\max}$ grows, the overlap function

$$G(b, Q^2_{\max}) = \int dx_{\rm Bj}\, h^2(b, x_{\rm Bj}, Q^2_{\max}),$$

with

$$h(b, x_{\rm Bj}, Q^2_{\max}) = \int\limits_0^{Q^2_{\max}} \sqrt{\frac{d\sigma}{dQ^2\, dx_{\rm Bj}}}\, J_0\big(b\sqrt{Q^2}\,\big)\, dQ^2,$$

which determines the process cross section in the b-representation, becomes more central, which corresponds to an increase in the contribution of states with smaller values of the impact parameter, The result of the correlation

$$\langle Q^2 \rangle \sim \frac{1}{\langle b^2 \rangle}$$

may be the elimination of a fraction of the events from the set of lepton–proton collisions potentially capable of producing a $c\bar{c}$ pair. This may happen if the initial lepton–proton state with kinematic characteristics meeting condition (2) undergoes a change in which the impact parameter increases. The latter is possible since the impact parameter operator does not commute with the Hamiltonian and the initial $e^{\pm}p$ states with an impact parameter b_0 prepared outside the interaction region, equation (1), may evolve into states with impact parameters $b_{\pm}$ (larger or smaller than b_0) before the interaction (1) takes place.

The asymmetry in the cross section of D^* production in e^-p and e^+p interactions in this case can be explained if one examines the evolution of the initial impact-parameter state related to the photon emission in the initial state or, in other words, to the Coulomb lepton–proton interaction prior to photon–gluon fusion.

Note that allowing for the effect of Coulomb forces in $e^{\pm}p$ scattering is meaningful only for photons with finite virtuality, Indeed, when the exchange photon with the four-momentum $q^{\mu} = (q^0, 0, 0, |q|)^*$ is quasireal, the second term in the integrand of the electromagnetic amplitude of the scattering of a lepton with the current j^l by a proton with the current j^p,

$$A = -i \int \left[\frac{j_1^l j_1^p + j_2^l j_2^p}{q^2} + \frac{j_3^l j_3^p - j_0^l j_0^p}{q^2} \right] d^4x, \tag{3}$$

vanishes, since from the continuity conditions for both currents,

$$q^{\mu} j_{\mu} = q^0 j_0 - |q| j_3 = 0, \tag{4}$$

it follows that for the quasireal photon $q^0 \cong |q|$ we have $j_3 \cong j_0$, with the result that the longitudinal and scalar contributions cancel out, leaving in the amplitude the two transverse contributions, which describe

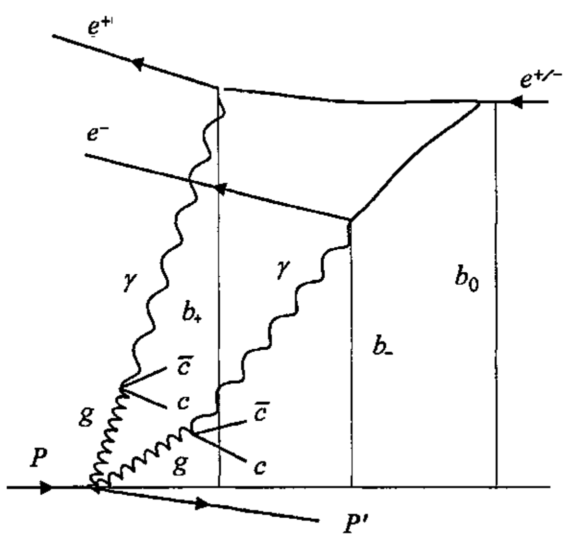

Fig. 2

Interaction of electron e^- and positron e^+ with proton p: b_0 is the impact parameter prior to the evolution of the $e^{\pm}$ paths, b_+ and b_- are the impact parameters after the evolution of the $e^{\pm}$ paths at the moment of interaction of virtual photon γ with gluon g from the proton.

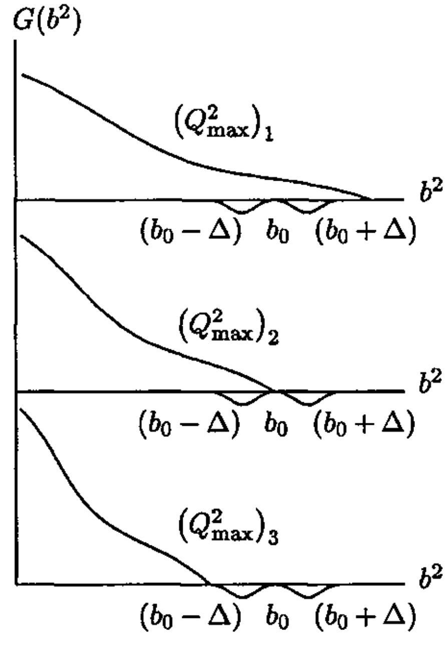

Fig. 3

Overlap function shape as a function of $Q^2_{\max}$: $(Q^2_{\max})_1 < (Q^2_{\max})_2 < (Q^2_{\max})_3$. Changes in the initial impact parameter, $b_0 \to (b_0 + \Delta)$ and $b_0 \to (b_0 - \Delta)$, lead to cross-section asymmetry of $e^{\pm}p$ collisions, with the size of this asymmetry determined by the shape of the overlap function. An increase in asymmetry corresponds to an increase in the admissible, by condition (2), values of the exchange-photon virtuality.

* Here and in what follows the coordinate system is chosen in accordance with that of the ZEUS experiment [2, 3]. The Z-axis is directed along the beams of the colliding protons and leptons in the direction of the proton beam, the Y-axis is directed upward, and the X-axis to the center of the accelerator.

the propagation of the quasireal photon. As for a virtual photon, plugging j_3^l and j_3^p from equation (4) into (3), we arrive at the following expression for the lepton–proton scattering amplitude:

$$A = -i \int \left[\frac{j_1^l j_1^p + j_2^l j_2^p}{q^2} + \frac{j_0^l j_0^p}{|q|^2} \right] d^4x,$$

where the second term in the integrand describes the instantaneous Coulomb interaction between j_0^l and j_0^p. Here the radius of the lepton–proton Coulomb interaction is limited by various screen effects determined by the density and configuration of the colliding particle beams.

Allowing for the Coulomb interaction makes possible the following scenario of symmetry breaking between the cross sections $\sigma(D^*)$ in the e^-p and e^+p collisions. Let us examine the initial e^-p and e^+p states with identical kinematic characteristics and equal impact parameters, When the beams of the colliding particles "bump" into each other, a lepton that emits virtual photons in the proton's field is deflected from its initial path (Fig. 2), with the result that the initial impact parameter b_0 decreases in e^-p scattering and increases in e^+p scattering.

The kinematic condition needed for the production of heavy quarks, equation (2), controls the structure of the overlap function $G(b^2)$, decreasing the value of the mean impact parameter as Q^2_{max} grows, as schematically shown in Fig. 3.

Figure 4 presents the results of calculations of the first two moments of the distribution of the square of the impact parameter within the ranges of the kinematic variables Q^2, x_{Bj}, and y corresponding to the results of measurements done in [1]. Clearly, as Q^2_{max} increases, the overlap functions become more central. As a result, starting from a certain value of Q^2, changes in the initial lepton path may break the symmetry of the contributions of states with impact parameters b_- and b_+, i.e., an increase in the initial impact parameter in e^+p interactions may lead to a decrease in the contribution of these processes into the cross section compared to that in e^-p interactions.

To check the meaningfulness of the above ideas, we must estimate the size of the variation of the impact parameter, $\Delta b = |b_0 - b_\pm|$.

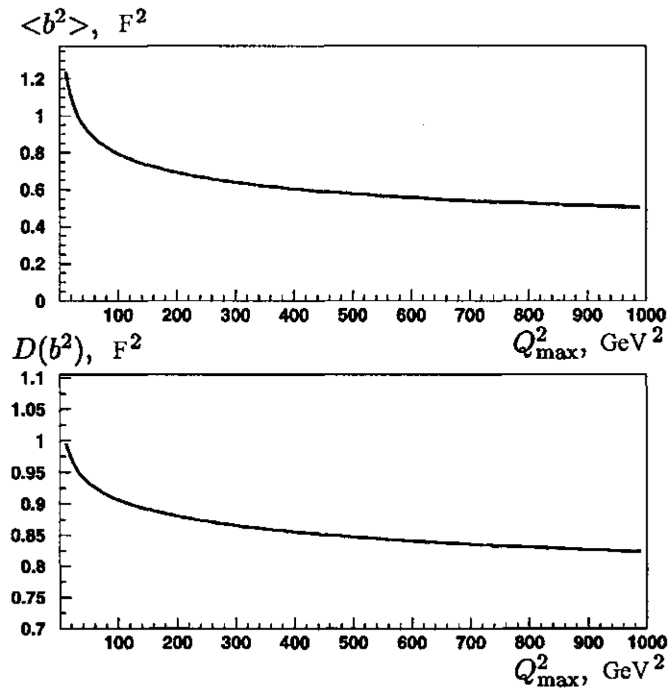

Fig. 4

Mean value and variance of the overlap function $G(b^2)$ as functions of Q^2_{max}.

EVOLUTION OF THE LEPTON PATH IN THE COULOMB FIELD

We will assume from the start that the initial impact parameter undergoes a change when particle bunches collide. Let us examine the motion of a lepton in the field of the proton charge, to which end we go over to the proton's rest frame and determine the rate of deflection of the incident lepton in the plane perpendicular to the beam direction.

The equation of motion for a lepton of mass m_e and charge q_l in the field of a proton at rest q_p is

$$m_e \frac{d\mathbf{V_R}}{(1-V_R^2)^{3/2}} = \frac{q_l q_p}{r^3}\mathbf{r}\, dt,$$

where $\mathbf{V_R}$ is the lepton velocity in the direction of the force (we call this the radial lepton velocity). Excluding the time variable from the above equation and bearing in mind that vector $\mathbf{r}$, directed from the proton at rest to the lepton, is collinear to $\mathbf{V_R}$ in e^+p interactions,

$$dr = \frac{V_R}{\sqrt{1-V_R^2}}\, dt,$$

and anticollinear to $\mathbf{V}$ in e^-p interactions,

$$dr = -\frac{V_R}{\sqrt{1-V_R^2}}\, dt,$$

we find that

$$\frac{m_e}{1-V_R^2} = 2\frac{\alpha_{\rm em}}{r} + C.$$

Here we have used the following normalization of the unit charge in the system with $\hbar, c = 1$:

$$|q_l q_p| = \frac{1}{137} = \alpha_{\rm em}.$$

Allowing for the obvious boundary condition

$$\lim_{r\to\infty} V_R = 0,$$

we arrive at an expression for the absolute value of the radial lepton velocity

$$V_R = \sqrt{\frac{2\alpha_{\rm em}}{2\alpha_{\rm em} + r m_e}}.$$

Let α be the angle between $\mathbf{r}$ and the positive direction of the z-axis. For the longitudinal and transverse components of the radial lepton velocity we have

$$V_{R\parallel} = V_R \cos\alpha, \quad V_{R\perp} = V_R \sin\alpha.$$

The component $V_{R\parallel}$ has the same sign as the longitudinal component of the beam-lepton velocity $\mathbf{v}$, which in the proton rest frame is

$$\mathbf{v} = \frac{\mathbf{P}_l E_p - \mathbf{P}_p E_l}{E_l E_p - P_l P_p},$$

where $\mathbf{P}_l$ and E_l are the beam-lepton momentum and energy, and $\mathbf{P}_p$ and E_p are the beam-proton momentum and energy in the lab reference frame.

Now it is easy to derive an expression for the absolute values of the longitudinal ($V_\parallel$) and transverse ($V_\perp$) components of the total lepton velocity in the proton rest frame:

$$V_\parallel = \frac{V_{R\parallel} + |\mathbf{v}|}{1 + V_{R\parallel}|\mathbf{v}|}, \quad V_\perp = \frac{V_{R\perp}}{1 + V_{R\parallel}|\mathbf{v}|}\sqrt{1-\mathbf{v}}. \qquad (5)$$

Assuming that there is azimuthal symmetry, we can estimate the size of the variation of the impact parameter by numerically calculating the lepton path,

$$dr_{\|} = V_{\|}\frac{r\sqrt{1-V^2}}{V_{\|}\sin\alpha - V_{\perp}\cos\alpha}d\alpha, \quad dr_{\perp} = V_{\perp}\frac{r\sqrt{1-V^2}}{V_{\|}\sin\alpha - V_{\perp}\cos\alpha}d\alpha,$$

which is parabolic in the case of $e^{-}p$ scattering and hyperbolic in the case of $e^{+}p$ scattering. For the maximal distance between the point where the evolution of the lepton path begins and the point where the lepton, having emitted a hard photon, initiates photon–gluon fusion (1), we take the radius L of a sphere inside which there is only one particle from the proton bunch. In this way we have effectively allowed for the Coulomb screening of protons inside the bunch

$$L = \sqrt[3]{3/(4\pi\rho)}.$$

Here $\rho = N + p/\Delta V_p$ is the particle number density in the proton bunch, with ΔV_p the bunch volume, and N_p the number of protons in the bunch,

$$N_p = I_p/(q_p f N_B).$$

Here I_p is the proton bunch current, f is the bunch reversal frequency, and N_B is the number of bunches. The parameters of the HERA Collider needed for calculating L are listed in Table 1. Figure 5 shows the dependence of the variation of the impact parameter, Δb, on the initial impact parameter b_0. This dependence reflects the relationship between the components of the total lepton velocity (5) as the radius of the Coulomb interaction changes from $r = L = 10^6$ fm to $r = 50$ fm.

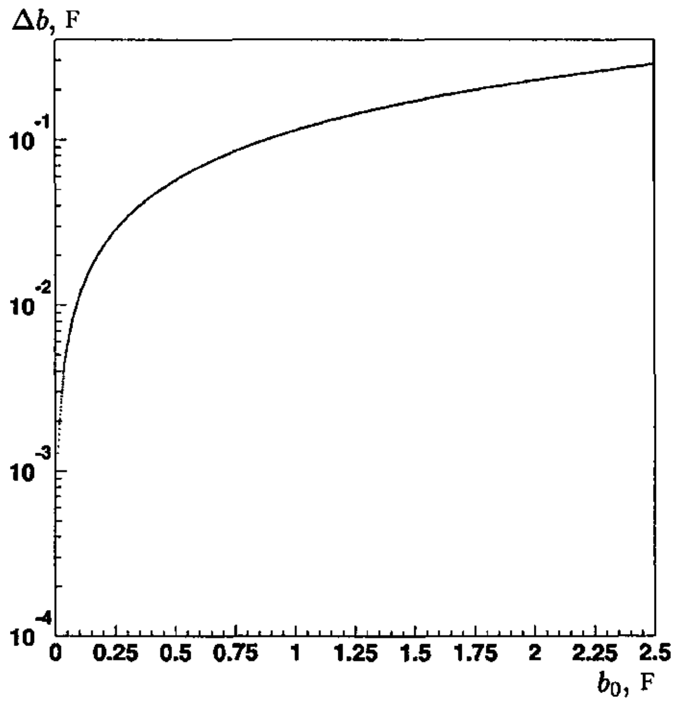

Fig. 5

Variation of impact parameter Δb as a function of the initial impact parameter b_0.

Table 1

Parameters of Beams in HERA Collider [4]

Beam parameters	$e^{\pm}$	P
Momentum, GeV	27.6	920.
Maximal current, mA	37	99.
Number of bunches	174 + 15*	174 + 6*
Horizontal beam size, mm	0.2	0.2
Vertical beam size, mm	0.054	0.054
Longitudinal beam size, mm	8	170
Length of HERA circle, m	6336	
Instantaneous luminosity, $cm^{-2}\ s^{-1}$	1.2×10^{31}	

* Number of uncolliding bunches (pilot bunches).

COMPARISON OF THE DIFFERENTIAL CROSS SECTIONS OF e^-p AND e^+p INTERACTIONS

To estimate the possibility of asymmetry of the e^-p and e^+p cross sections emerging within the scheme that we have just described, let us examine the differential distributions in the variables S_{cc}, x_{Bj}, and Q^2. The spectra in these variables were calculated by the Monte Carlo method of simulating the lepton–proton interactions with allowance for the kinematics of c-quark production and the lepton path evolution. Simulation was carried out within the kinematic limits corresponding to the results of measurements done

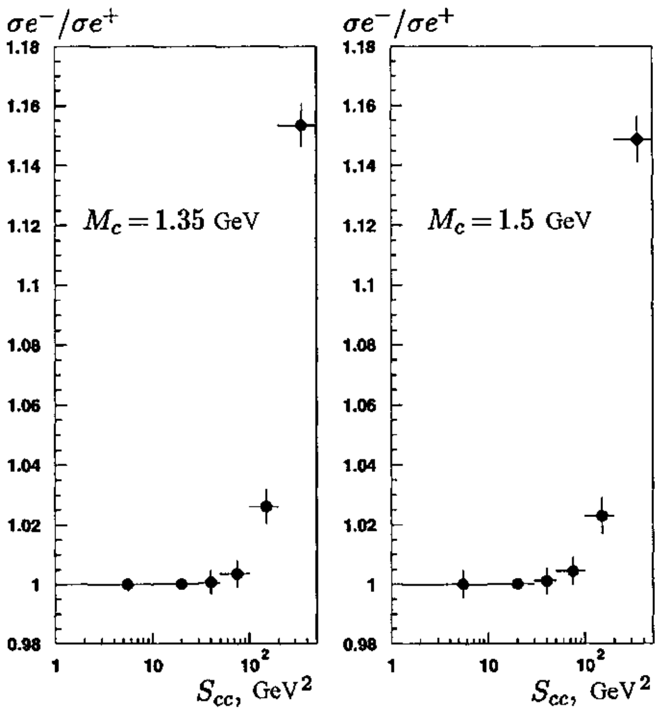

Fig. 6

Ratio of the D^*-meson production cross sections as a function of the variable S_{cc}. The differential cross sections for e^+p and e^+p collisions ($\sigma e^{\pm}$) were obtained by the Monte Carlo method for two values of the c-quark mass M_c.

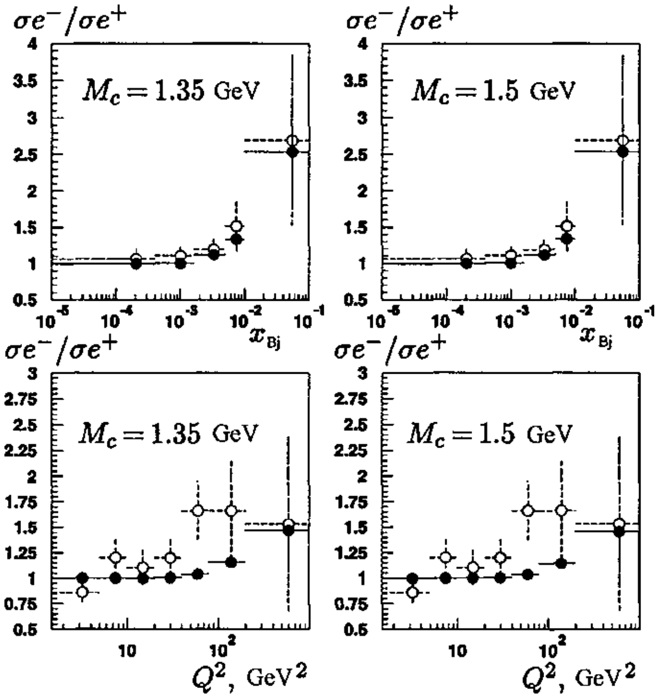

Fig. 7

Ratio of the D^*-meson production cross sections as a function of the variables $x_{\rm Bj}$ and Q^2. The open circles represent the experimental data taken from [1], and the black circles represent the results of Monte Carlo calculations for two values of the c-quark mass M_c.

in [1]. Two values were calculated in an event with a certain $Q^2_{\rm max}$: $\langle b(Q^2_{\rm max})\rangle$ and $D(b)$. For the overlap function with these parameters the initial parameter b_0 was drawn and the change in the impact parameter, Δb, was determined, and then the weight of the event was calculated: $G(b_0 - \Delta b)$ for the e^-p interaction, and $G(b_0 + \Delta b)$ for the e^+p interaction.

Thus, two events identical in the kinematic parameters and belonging to e^-p and e^+p interactions were compared.

Figure 6 shows the ratio of the differential cross sections of e^-p and e^+p interactions as a function of the photon–gluon interaction energy S_{cc} for two values of the c-quark mass: $M_c = 1.35$ GeV and $M_c = 1.5$ GeV. The value of S_{cc} depends on the values of the longitudinal and transverse momenta of c quarks and determines the behavior of the pseudorapidities and transverse momenta of D^* mesons. The distribution in this variable demonstrates a monotonic rise in the asymmetry of e^-p and e^+p cross sections as S_{cc} increases. The results of calculations for these two values of M_c are, for all practical purposes, identical.

Figure 7 shows the results of calculations of the asymmetry of e^-p and e^+p cross sections for the variables x_{Bj} and Q^2. This figure shows, for the sake comparison, the results of measurements done in [1]. The asymmetry effect is satisfactorily reproduced both qualitatively and quantitatively. As in the experimental data, the excess of e^-p cross sections for the Bjorken variable becomes noticeable at $x_{\rm Bj} \cong 10^{-3}$, while for the photon virtuality Q^2 it begins at 40 GeV^2. As in the previous case, the results of calculations for $M_c = 1.35$ GeV and $M_c = 1.5$ GeV are, for all practical purposes, identical.

CONCLUSION

We have examined one explanation of the difference in the D^*-meson production cross sections for deep inelastic e^+p and e^-p scattering. The key issues of the present approach are the kinematic condition needed for the production of heavy quarks, related to the shape of the overlap function, and the possibility of evolution of the lepton path in the Coulomb field of the proton as a result of photon emission in the initial state.

The calculations done within this approach reproduce the data on the anomalous behavior of the e^-p and e^+p cross sections obtained in the ZEUS experiment.

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