Diffractive charm photoproduction at HERA $ep$-collider

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The cross section of the $D^*$-meson diffractive photoproduction at the HERA collider has been calculated in the framework of perturbatively motivated model for the different kinematic regions. The comparison between the different Pomeron models has been performed.

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From the experimental data, collected at HERA ep-collider, one can conclude that the charm production model proposed in article (below denoted as BKL), allows to describe inclusive photoproduction and deep inelastic production of \( D^{*+}(2010) \)-mesons (below denoted as \( D^* \)-mesons), as well as inclusive photoproduction \( D_s \)-mesons, with a good accuracy.

Recently new data on \( D^* \)-meson diffractive photoproduction have been presented by the ZEUS collaboration. In this connection we try to describe these new data in the framework of the BKL model.

Let us remind the general features of this model. In the BKL approach one needs to produce perturbatively \( c \) - and \( \bar{d} \)-quarks which softly form \( D^* \)-meson. These perturbatively produced \( c \) - and \( \bar{d} \)-quark are valence ones for the meson. The soft hadronization process of the \( cd \)-pair color singlet state is described by the average value of the operator:

\[
\langle O_{(1)} \rangle = \frac{1}{12 M_{D^*}} \left( -g^{\mu \nu} + \frac{p_{D^*} \nu p_{D^*}^\nu}{M_{D^*}^2} \right) \langle D^*(p_{D^*})|(\bar{c}\gamma_\mu d)(\bar{d}\gamma_\nu c)|D^*(p_{D^*}) \rangle,
\]

where \( p_{D^*} \) is \( D^* \)-meson momentum, and \( M_{D^*} \) is the meson mass. In the framework of the nonrelativistic potential model the average value of the operator correspond with the squared wave function in the origin:

\[
\langle O_{(1)} \rangle_{NR} = |\Psi(0)|^2. \]

The hadronization of the color octet state is described by the average value of the analogous operator:

\[
\langle O_{(8)} \rangle = \frac{1}{8 M_{D^*}} \left( -g^{\mu \nu} + \frac{p_{D^*} \nu p_{D^*}^\nu}{M_{D^*}^2} \right) \langle D^*(p_{D^*})|(\bar{c}\gamma_\mu \lambda^a d)(\bar{d}\gamma_\nu \lambda^b c)|D^*(p_{D^*}) \rangle \delta^{ab}.
\]

It is worth to mention that the BKL model is based on the partonic concept of the hadronic structure. Indeed, in the framework of the partonic model for the system of the infinite momentum the valence quark structure functions are determined as follows:

\[
\begin{align*}
\langle x^v \rangle_c &= \int d^2 p_T dx x \cdot f^v_c(x, p_T) \approx \frac{m_c}{M_{D^*}}, \\
\langle x^v \rangle_d &= \int d^2 p_T dx x \cdot f^v_d(x, p_T) \approx \frac{\bar{\Lambda}}{M_{D^*}},
\end{align*}
\]

where \( \langle x^v \rangle_c + \langle x^v \rangle_d \approx 1 \), and \( \bar{\Lambda} \) is the energy of the quark coupling into the meson. In the framework of the BKL model we neglect the quark velocity difference and assume quark velocities to be equal to each other: \( \nu_c = \nu_d \). The effective mass of the light quark \( m_d \) in such approach plays the role of the infrared cut. We take this mass equal to \( \bar{\Lambda} \). Thus we obtain the following equations:

\[
\begin{align*}
\langle x^v \rangle_c &= x^v_c = \frac{m_c}{M_{D^*}}, \\
\langle x^v \rangle_d &= x^v_d = \frac{m_d}{M_{D^*}}.
\end{align*}
\]

Now it is clear that the BKL model is an extention of the parton model for the case of final hadrons in the framework of the valence quark approximation.

This fact distinguishes the BKL approach from perturbative calculations based on the fragmentation model of the hadronisation. In the framework of the fragmentation model of the hadronization it is supposed that the perturbatively produced single \( c \)-quark becomes a meson at large distances. This meson gets a fraction \( z \) of the \( c \)-quark transverse momentum \( k_T \) with the probability determined by the fragmentation function \( D_{c \rightarrow D^*}(z, \mu) \):

\[
\frac{d^2 \sigma_{D^*}}{dz dp_T^2} = \frac{d \tilde{\sigma}_{\bar{c}c}(k_T, \mu)}{dk_T} \bigg|_{k_T = z} \frac{D_{c \rightarrow D^*}(z, \mu)}{z}.
\]
where $D_{c\to D^*}(z,\mu)$ is normalized to the probability of $c$-quark to become a $D^*$-meson $w(c \to D^*)$, measured in the $e^+e^-$-annihilation [8] ($w(c \to D^*) = 0.22 \pm 0.014 \pm 0.014$). $\mu$ is the scale at which the perturbative partonic cross section of the $c\bar{c}$-pair production $d\sigma_{c\bar{c}}/dk_T$ is calculated.

It is clear that in the fragmentation approach one can not take into account the possibility for the $c$-quark to hadronize via the interaction with the quark sea of the initial hadron (recombination mechanism). That is why one needs to account this opportunity for $c$-quark to become a $D^*$-meson in the framework of some additional model.

In the framework of the BKL approach both fragmentation and recombination mechanisms are accounted naturally in the calculations. It is worth to mention that both the fragmentation mechanism and the recombination one are described by the same set of the diagrams.

The fragmentation mechanism dominates at the large transverse momentum of the $D^*$-meson in accordance with the factorization theorem. The main contribution at small transverse momenta is due to the recombination mechanism, i.e. due to the fusion of $c$-quark and a light quark from the sea of the initial hadron. It is worth to mention that the recombination contribution mechanism corresponds with higher twist contribution to the transverse momentum distribution.

As it was shown in many articles, devoted to the fragmentation model, the particular form of the fragmentation function affects calculation results insignificantly. In the majority of the articles the Peterson [11] fragmentation function is used:

$$ D(z) = N \frac{1}{z(1 - \frac{1}{z} - \epsilon z^2)^2}, \quad (7) $$

where $N$ is normalization factor, and $\epsilon$ is a free phenomenological parameter dependent on the scale $\mu$. The results would not change crucially if the parameterization of Kartvelishvili-Likhoded-Petrov [10] is used:

$$ D(z) = N z^{-\alpha_c} (1 - z)^{\gamma - \alpha_d}, \quad (8) $$

where $\alpha_c = -3$, $\alpha_d = 1/2$ and $\gamma = 3/2$.

In the BKL model at large transverse momenta ($p_T^{D^*} > 20$) the $D^*$-meson cross-section can be expressed by formula [3], if the following pertubatively motivated form for fragmentation function is used [11]:

$$ D_{c\to D^*}(z) = \frac{8\alpha_s^2\langle O^{eff}\rangle}{27m_d^2} \frac{r z(1-z)^2}{(1 - (1-r)z)^6} [2 - 2(3 - 2r)z + 3(3 - 2r + 4r^2)z^2 - 2(1 - r)(4 - r + 2r^2)z^3 + (1 - r)^2(3 - 2r + 2r^2)z^4], \quad (9) $$

where $r = m_d/(m_d + m_c)$ and

$$ \langle O^{eff}\rangle = \langle O_{(1)}\rangle + \frac{1}{8}\langle O_{(8)}\rangle. \quad (10) $$

Meson production in $e^+e^-$-annihilation is caused by fragmentation mechanism only. This fact allows to define $\langle O^{eff}\rangle$ using $w(c \to D^*)$ and quark masses:

$$ w(c \to D^*) = \int_0^1 D_{c\to D^*}(z)dz = \frac{\alpha_s^2\langle O_{(1)}\rangle(\mu)}{m_d^3} \cdot I(r), \quad (11) $$

where $I(r)$ is determined in [3]. The value of $w(c \to D^*)$ is known from the experiment.

So one can determine the value of $\langle O^{eff}\rangle$ for fixed values of $m_d$, $m_c$ and $\mu$. Assuming

$$ \mu = m_{D^*}, $$

$$ m_d = 0.3 \text{ GeV}, $$

$$ m_c = 1.5 \text{ GeV} \text{ and } w(c \to D^*) = 0.22. $$

one obtains

$$ \langle O^{eff}(m_{D^*})\rangle = 0.25 \text{ GeV}^3. $$
The best description of the experimental data on the charm photoproduction and the deep inelastic charm production at HERA can be achieved if $(O_{(8)})/(O_{(1)}) = 1.3$.

The mentioned values of the parameters were taken both for the presented calculations and for the calculations of the $D^*$-meson nondiffractive production cross section [8].

BKL model can be used for all values of $D^*$-meson transverse momentum in the contrast to the fragmentation model which is valid only for large transverse momentum (our estimation shows that fragmentation model can be used for $p_T^{D^*} > 20$ GeV).

We use the parameter values [12] to calculate the cross-section of the $D^*$-meson diffractive production in the framework of the BKL model.

We choose one of the known form of the Pomeron flux parametrization [12]:

$$f_{p^*/p}(x_{p^*}, t) = \frac{1}{2} \frac{1}{2.3 x_{p^*}^2} \left[ 6.38 e^{-8|t|} + 0.424 e^{-3|t|} \right],$$

where $t$ is the squared transfer momentum in the proton vertex, and $x_{p^*}$ is the momentum fraction of the proton carried away by the Pomeron. We neglect the amplitude dependence on $t$ in the calculations.

We suppose that the Pomeron consists of the gluons only and used two types of the gluonic distribution inside the Pomeron $G(\beta)$:

$$\beta G(\beta) = \begin{cases} 6\beta(1 - \beta) & \text{“hard” Pomeron;} \\ 6(1 - \beta)^5 & \text{“soft” Pomeron,} \end{cases}$$

where $\beta$ is the fraction of the Pomeron momentum carried off by a gluon.

In Fig.1 the calculation of the differential distributions of the $D^*$-meson production has been performed for the kinematic region investigated by ZEUS Collaboration [10]: $130 < W < 280$ GeV, $Q^2 < 1$ GeV$^2$, $p_T^{D^*} > 2$ GeV, $|\eta^{D^*}| < 1.5$, 0.001 < $x_{p^*}$ < 0.018, where $W$ is the invariant mass of the photon-proton system, $Q^2$ is the photon virtuality and $\eta^{D^*}$ is the pseudorapidity of the $D^*$-meson. The value of $\eta^{D^*}$ is determined by the angle $\theta$ between the initial proton direction and the $D^*$-meson in the laboratory system as follows: $\eta^{D^*} = -\ln(tg^2 \frac{\theta}{2})$.

The cross sections calculated for this kinematic region in the frame work of BKL model have the following numerical values:

$$\sigma_{BKL} = \begin{cases} 0.77 \pm 0.02 & \text{“hard” Pomeron;} \\ 0.56 \pm 0.03 & \text{“soft” Pomeron.} \end{cases}$$

From the transverse momentum distributions one can conclude, that the calculation with the soft Pomeron predicts more rapid decreasing of the cross section with increasing transverse momentum than the calculation with the hard Pomeron.

From the distribution in $D^*$ pseudorapidity one can see that the model of the hard Pomeron predicts the cross section values of the $D^*$ meson production in the forward direction essentially larger than the ones predicted by the soft Pomeron model. The predictions of these models for the $D^*$-meson backward production in the considered kinematic region are practically the same.

The hard Pomeron model predicts the distribution maximum at small $M_x$ values. The soft Pomeron model calculation yields the distribution maximum at $M_x$ over 20 GeV.

In the considered range of $x_{p^*}$ the differential cross sections calculated with different models of Pomeron, show quite different behaviour: hard Pomeron decreases with $x_{p^*}$ while soft Pomeron increases instead.

The ZEUS Collaboration plans to continue the analysis of the diffractive photoproduction of the $D^*$ meson. That is why we have calculated the total and the differential cross sections for 0.001 < $x_{p^*}$ < 0.2 (Fig. 2):

$$\sigma_{BKL} = \begin{cases} 1.64 \pm 0.02 & \text{“hard” Pomeron;} \\ 5.45 \pm 0.02 & \text{“soft” Pomeron.} \end{cases}$$

and for the 0.001 < $x_{p^*}$ < 0.1 (Fig. 3):

$$\sigma_{BKL} = \begin{cases} 1.51 \pm 0.03 & \text{“hard” Pomeron;} \\ 3.56 \pm 0.03 & \text{“soft” Pomeron.} \end{cases}$$
It is evident that for these ranges of $x_P$ the difference between the soft Pomeron model and the hard Pomeron model is more essential than for the $0.001 < x_P < 0.018$. The soft Pomeron model leads to the larger value of the cross section than the hard Pomeron model.

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Fig. 1. The BKL model predictions for the differential cross sections of the $D^*$ diffractive photoproduction at HERA: a) $p_{T}^{D^*}$; b) $\eta^{D^*}$; c) $M_X$; d) $x_{IP}$ are calculated in the kinematic region: $130 < W < 280$ GeV, $Q^2 < 1$ GeV$^2$, $p_{T}^{D^*} > 2$ GeV, $|\eta^{D^*}| < 1.5$, \( 0.001 < x_{IP} < 0.018 \). The solid histograms stand for the calculations with the hard Pomeron model, and the dashed ones stand for the calculations with the soft Pomeron one.
Fig. 2. The BKL model predictions for the differential cross section of the $D^*$ diffractive photoproduction at HERA: a) $p_T^{D^*}$; b) $\eta^{D^*}$; c) $M_X$; d) $x_{IP}$ are calculated in the kinematic region: $130 < W < 280$ GeV, $Q^2 < 1$ GeV$^2$, $p_T^{D^*} > 2$ GeV, $|\eta^{D^*}| < 1.5$, $0.001 < x_{IP} < 0.2$. The solid curves stand for the calculations with the hard Pomeron model, and the dashed ones stand for the calculations with the soft Pomeron model.
Fig. 3. The BKL model predictions for the differential cross section of the $D^*$ diffractive photoproduction at HERA: a) $p_T^{D^*}$; b) $\eta^{D^*}$; c) $M_X$ are calculated in the kinematic region: $130 < W < 280$ GeV, $Q^2 < 1$ GeV$^2$, $p_T^{D^*} > 2$ GeV, $|\eta^{D^*}| < 1.5$, $0.001 < x_{P^*} < 0.1$. The solid curves stand for the calculations with the hard Pomeron model, and the dashed ones stand for the calculations with the soft Pomeron model.