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PRODUCTION OF D-MESONS IN pp-COLLISIONS AND QUARK-GLUON STRING MODEL

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Образование D-мезонов в pp-взаимодействиях
и модель кварк-глюонных струн

Модель кварк-глюонных струн с введенной ранее зависимостью кварковых функций и функций фрагментации кварков в адроны от поперечного импульса применена для количественной оценки дифференциальных сечений рождения D-мезонов в pp-взаимодействиях при различных начальных энергиях. Сравнение расчетов с экспериментальными данными при энергии $\sqrt{s} = 27.4$ ГэВ показывает, что хорошее описание спектров как по фейнмановской переменной x, так и по поперечному импульсу p_T достигается при значении пересечения реджевской траектории чармония, близком к нулю. Отмечается, что такие значения пересечения $(\alpha_{Q\bar{Q}}(0) \cong 0)$ свидетельствуют о сильной нелинейности траекторий тяжелых кваркониев при малых переданных четырехимпульсах; это означает, что вклад периферического механизма может быть значительным в процессах с рождением тяжелых ароматов.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Lykasov G.I., Sergeenko M.N. E2-92-51
Production of D-Mesons in pp-Collisions
and Quark-Gluon String Model

The calculation results of the inclusive spectra of D-mesons produced in pp-collisions as the functions of the Feynman variable x and transverse momentum p_T are presented in the frame of the quark-gluon string model, in which the dependence of quark distributions in hadrons and quark fragmentation functions on $p_\perp$ is taken into account. Good agreement with experimental data at $\sqrt{s} = 27.4$ GeV is achived for the value of interception of the Regge-trajectory charmonium near to zero. The satisfactory description of the experimental data in the frame of QGSM indicates domination of the peripheral mechanism of the D-meson production at high energies.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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1. Introduction

The calculations of inclusive spectra of heavy flavour particles produced in hadron collisions at high energies as the functions of longitudinal and transverse momenta allow one to study the QCD–mechanism of heavy quark production. Besides, these calculations are necessary for the planning of new experiments (UNK, LHC, SSC) for the search for new flavour, for example a top–quark. Strategies in the search for new flavours such as top are supposed to have better estimates of cross sections and of momentum distributions in phase space not only of the new flavour, but which is perhaps more important, of lighter flavours which greatly contribute to the background.

Usually the observables of heavy flavour particles produced in hadron collisions are calculated in the frame of perturbative QCD [1-6]. However these calculations result in the values of cross sections of c– and b–quark production which are less than the experimental values especialy in the region of small p_T [7,8]. On the other hand, soft processes are well described in the frame of the peripheral models.

The experimental data show that the main part of charmed particles is produced in soft processes in the fragmentation region of the projectile particle [9-16]. Besides, the D-meson and Λ_c-baryon distributions have the form, which is analogical to the spectra of the K-meson and Λ-hyperon, that is mainly concentrated in the region of small transverse momenta p_T, $p_T \leq 1$ GeV/c. That points out the analogy between the production mechanisms of heavy flavour particles and hadrons, containing light u– , d– and s-quarks. So in ref. 8 the transition of c- and b-quarks into hadrons was described with the help of the recombination model [17], taking into account the interaction of yielded of Q-quarks with the quarks from incident hadrons. Such inclusion of interaction with the valence quarks allows one to describe the production of leading part of charm particles. In this model a recombination function $R(x_q, x, z)$ is expressed through

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interception $\alpha_{Q\bar{Q}}(0)$ of leading Regge $Q\bar{Q}$-trajectory. It is noted, that the observable distribution of the leading particles could be easily explained by the nonperturbative mechanism of charm quark hadronisation.

The increase of total cross sections of D-meson production as the functions of the energy [12,14] points out that this behavior corresponds to the multipomeron asymptotic, i.e. here the theory of the supercritical pomeron and also the quark-gluon string model (QGSM) [19-21] is applicable.

Earlier the description of the energy dependence of cross sections for production of heavy flavour and of the invariant inclusuve spectra of D- and B-mesons and Λ_c-baryons as the function of the Feynman variable x was obtained in the frame of QGSM [22-24]. In the present paper the calculations of the inclusive spectra of D^+- , D^-- , D^0- and $\bar{D}^0$-mesons as the function of x and p_T are performed in the frame of the modified QGSM in which the dependence of quark distributions in hadrons and the quark fragmentation functions on p_T is taken into account [25-27]. As was shown in our ref. [27], the successive division of the transverse momentum p_T between n-Pomeron showers or 2n quark-antiquark chains gives strong dependence of $\langle p_T\rangle$, $\langle p_T\rangle \sim \sqrt{n}$, and other hadron characteristics on n.

2. Calculation of the cross sections

Consider the process of the D-meson production in pp-collision $pp \to DX$ at high energy in the frame of QGSM but including the transverse motion of quarks and diquarks in colliding protons as it was made in refs. [25-27]. As is known, the cylinder-type diagrams cut in the s-channel give the main contribution to this process [19]. The expression for the invariant inclusive hadron spectrum corresponding to these diagrams can be written in the following form [19,26]:

$$E\frac{d\sigma}{d^3\vec{p}} \equiv \frac{2E^*}{\pi\sqrt{s}}\frac{d\sigma}{dx\,dp_T^2} = \sum_{n=0}^{\infty}\sigma_n(s)\phi_n(x,p_T), \qquad (1)$$

where σ_n is the cross section for production of the n-pomeron chain (or 2n quark-antiquark strings), decaying into hadrons, $\Phi_n(x,p_T)$ is the x- and p_T-dstribution of hadrons produced in the decay of the n-pomeron chain. These functions $\Phi_n(x,p_T)$ were represented in the following form:

$$\phi_n(x,p_T) = \int_{x_+}^{1}dx_1\int_{x_-}^{1}dx_2\Psi_n(x,p_T;x_1,x_2), \qquad (2)$$

$$\Psi_n(x,p_T;x_1,x_2) = F_{qq}^{(n)}(x_+,p_T;x_1)F_{q_v}^{(n)}(x_-,p_T;x_2)/\tilde{F}_{q_v}^{(n)}(0,p_T) +$$
$$F_{q_v}^{(n)}(x_+,p_T;x_1)F_{qq}^{(n)}(x_-,p_T;x_2)/\tilde{F}_{qq}^{(n)}(0,p_T) +$$
$$2(n-1)F_{q_s}^{(n)}(x_+,p_T;x_1)F_{\bar{q}_s}^{(n)}(x_-,p_T;x_2)/\tilde{F}_{q_s}^{(n)}(0,p_T),$$

where $x_\pm=0.5[(x_T^2+x^2)^{1/2}\pm x]$, $x_T=2[(m_D^2+p_T^2)/s]^{1/2}$; m_D is the mass of D-meson, $\sqrt{s}$ is the total energy of colliding protons in c.m.s.

$$F_\tau^{(n)}(x_\pm,p_T;x_{1,2}) = \int d^2k_T\tilde{f}_\tau^{(n)}(x_{1,2},k_T)\tilde{G}_{\tau\to h}\left(\frac{x_\pm}{x_{1,2}},k_T;p_T\right), \qquad (3)$$

$$\tilde{F}_\tau^{(n)}(0,p_T) = \int_0^1 dx'\int d^2k_T\,\tilde{f}_\tau^{(n)}(x',k_T)\tilde{G}_{\tau\to h}(0,p_T) = \tilde{G}_{\tau\to h}(0,p_T). \qquad (4)$$

Here τ means the flavour of the valence (or sea) quark or diquark, $\tilde{f}_{\tau}^{(n)}(x,k_T)$ is the quark distribution function, depending on the longitudinal momentum fraction x and the transverse momentum k_T in the n–Pomeron chain ;

$$\tilde{G}_{\tau\to h}(z,k_T;p_T) = z\tilde{D}_{\tau\to h}(z,k_T;p_T),$$

$\tilde{D}_{\tau\to h}(z,k_T;p_T)$ is the fragmentation function of quark or diquark of flavour τ into the hadron h (D-meson in our case).

The quark functions $\tilde{f}_{\tau}(x,k_T)$ are represented in the factorized form: $\tilde{f}_{\tau}(x,k_T)=f_{\tau}(x)g_{\tau}(k_T)$, and the k_T-distributions of quarks are chosen in the Gauss form $g_{\tau}(k_T)=(\gamma/\pi)\exp(-\gamma k_T^2)$. Then the quark functions in the n-Pomeron chain will be factorized too [25-27]:

$$\tilde{f}_{\tau}^{(n)}(x,k_T) = f_{\tau}^{(n)}(x)g_{\tau\to h}^{(n)}(k_T), \tag{5}$$

where

$$g_{\tau\to h}^{(n)}(k_T) = (\gamma_n/\pi)\exp(-\gamma_n k_T^2), \qquad \gamma_n=\gamma/n . \tag{6}$$

The fragmentation functions were represented in the following form:

$$\tilde{G}_{\tau\to h}(z,k_T;p_T) = G_{\tau\to h}(z,p_T)\tilde{g}_{\tau\to h}(\tilde{k}_T); \tag{7}$$

$$\tilde{g}_{\tau\to h}(\tilde{k}_T) = (\tilde{\gamma}/\pi)\exp(-\tilde{\gamma}\tilde{k}_T^2), \tag{8}$$

$$\tilde{k}_T = p_T-zk_T , \qquad z = \frac{x_\pm}{x_{1,2}} .$$

Thus, substituting (5)-(8) in (3), after integration over d^2k_T we have following simple expression for the functions $F_{\tau}^{(n)}$:

$$F_{\tau}^{(n)}(x_\pm,p_T;x_{1,2}) = \tilde{f}_{\tau}^{(n)}(x_{1,2})G_{\tau\to h}\left(\frac{x_\pm}{x_{1,2}},p_T\right)\tilde{I}_n\left(\frac{x_\pm}{x_{1,2}},p_T\right), \tag{9}$$

where functions $\tilde{I}_n(z,p_T)$ are [25,27]:

$$\tilde{I}_n(z,p_T) = (\gamma_z/\pi)\exp(-\gamma_z p_T^2), \tag{10}$$

$$\gamma_z = \tilde{\gamma}/(1+n\rho z^2), \qquad \rho = \tilde{\gamma}/\gamma .$$

As is known, the differential cross section $d\sigma/dp_T^2$ of the hadron production is approximated at high energies by the Gauss distribution at $p_T\le0.5$ Gev/c. However at $p_T\ge0.5$ GeV/c the data about p_T–distribution are more better approximated by the function $\exp(-Bp_T)$. Therefore we used, according to ref. [25], the following expression instead of (10):

$$I_n(z,p_T) = \frac{B_z^2}{2\pi(1+B_z m_D)} \exp[-B_z(m_T-m_D)], \tag{11}$$

where $B_z=B_0/(1+n\rho z^2)$, $B_0=2m\tilde{\gamma}$, $m_T^2=p_T^2+m_D^2$.

The fragmentation functions $D_{\tau\to h}(z)$ of charmed particles were obtained earlier in refs. [23,24]; they have the following form:

$$\begin{aligned} G_{u\to D^+}(z,p_T) &= a_0(1-z)^{-\alpha_\psi(0)+\lambda+2[1-\alpha_\rho(0)]}, \\ G_{ud\to D^0}(z,p_T) &= a_0(1-z)^{-\alpha_\psi(0)+\lambda+2[\alpha_\rho(0)-\alpha_N(0)]+1}, \\ G_{uu\to \bar{D}^0}(z,p_T) &= a_0(1-z)^{-\alpha_\psi(0)+\lambda+2[\alpha_\rho(0)-\alpha_N(0)]}(1+a_1z^2), \end{aligned} \tag{12}$$

where $\lambda=2\alpha'_{D^*}(0)p_T^2, \alpha_\rho(0)=0.5$, $\alpha_N(0)=-0.5$, α'_{D^*} is the slope of the Regge-trajectory at t=0 (t is the square of the 4-momentum transferred).

Now we calculate the D-mesons distribution as a function of the variable x. Integrating (1) over d^2p_T, we have for the invariant cross section:

$$F(x) = \int E \frac{d\sigma}{d^3\vec{p}} d^2p_T = \sum_{n=0}^{\infty} \sigma_n(s) \int \phi_n(x,p_T) d^2p_T . \qquad (13)$$

Differential cross sections $d\sigma/dp_T^2$ of the production of D^+-, $\bar{D}^-$-, D^0-, $\bar{D}^0$-mesons were calculated using the following formula:

$$\frac{d\sigma}{dp_T^2} = \frac{\pi}{2} \sqrt{s} \sum_{n=0}^{\infty} \sigma_n(s) \int \frac{1}{E^*} \phi_n(x,p_T) dx, \qquad (14)$$

which is obtained immediately from (1) after integration over dx.

3. Results and discussions

The calculation results of differential cross sections performed using the formulae (13), (14) are presented in Figs. 1, 2. First we note that there is a very strong dependence of cross sections on the value of the interception $\alpha_\psi(0)$ of the Regge-trajectory. The solid curves correspond to the case when $\alpha_\Psi(0)=0$, and the dashed curves correspond to $\alpha_\Psi(0)=-2.18$; the respective values of parameters a_0, a_1 entering into the fragmentation functions (12): $a_0=0.1 \cdot 10^{-3}$, $a_1 = 5$ and $a_0=0.5 \cdot 10^{-3}$, $a_1 = 15$. The comparison of the calculations using QGSM with the experimental data was performed in ref. [24] and a better description of the invariant spectra $x d\sigma/dx$ was obtained at $\alpha_\Psi(0)=0$. As seen from Figs. 1, 2, the better coincidance of theoretical calculations with the experimental data about the p_T^2-distribution

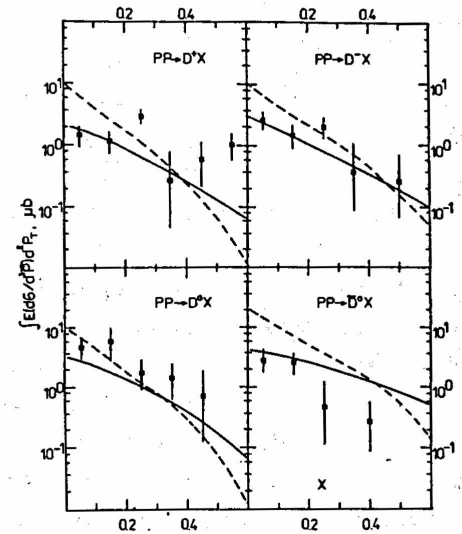

Fig. 1. The inclusive invariant cross sections of the reactions pp→DX at $\sqrt{s}$=27.4 GeV as functions of x; ■ - experimental data /13/, solid curves correspond to the calculations with interception $\alpha_\psi(0)=0$, dashed curves correspond to $\alpha_\psi(0)=-2.18$.

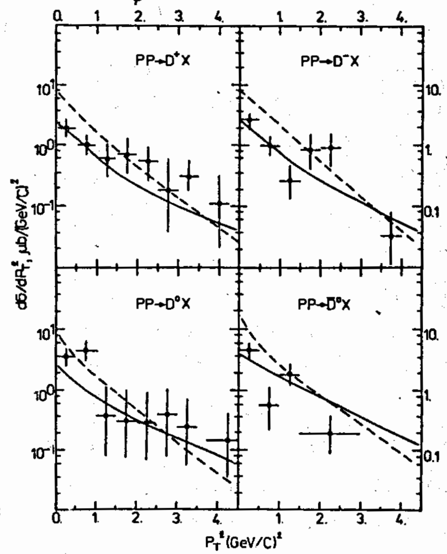

Fig. 2. The cross sections of the reactions pp→DX at $\sqrt{s}$=27.4 GeV as functions of p_T^2; ● - experimental data /12/, solid curves correspond to the calculations with interception $\alpha_\psi(0)=0$, dashed curves correspond to $\alpha_\psi(0)=-2.18$.

is at $\alpha_\Psi(0)=0$, which corresponds to the nonliniear Regge Ψ-trajectory.

The calculations of the inclusive spectra of all D–mesons are performed at $\underset{\sim}{B}_0=5.2\ (\text{Gev/c})^{-1}$, $\rho=3.1$ and corresponds to the parameter $\gamma=1.39\ (\text{Gev/c})^{-2}$. The better coincidence of our calculations with the experimental data is for D^+- and D^0-mesons.

The behaviour of the inclusive spectra presented in Figs. 1, 2 can be understood if we suggest the leading particle effect [11]. If we assume, that the proton consists of the quark and diquark, then, according to the idea of QGSM, a projectile proton is the leader in the soft diquark of the pp-process. And after production of $c\bar{c}$-pair from the vacuum the colour singlet system of charmed hadrons can be produced as a combination of c-quark and diquark of the proton or the combination of $\bar{c}$-quark and the valence quark of the initial proton. If the mass of the system (qq)c is not large the leading charmed hadron D^+, D^0 or Λ_c containing c-quark can be produced.

This qualitative explanation of soft production of charmed particles is confirmed by the quantitative calculations presented in Figs. 1, 2, i.e. the good description of inclusive spectra. Note, as mentioned above, that the value of the interception $\alpha_\Psi(0) = 0$, which indicates the nonlinier behaviour of the Regge-trajectory of mesons containing the heavy c–quark.

In Figs. 3-6 there are the calculation results for the cross sections of reactions $pp\to D^+X$ and $pp\to D^-X$ at the energies of the future colliders - UNK ($\sqrt{s}$=75 GeV), LHC ($\sqrt{s}$=16 TeV), SSC ($\sqrt{s}$=40 TeV). These estimated predictions could be useful both at the stage of planning and prognosis of the experiments and in performing experiments, as well as for comparison with predictions of other models.

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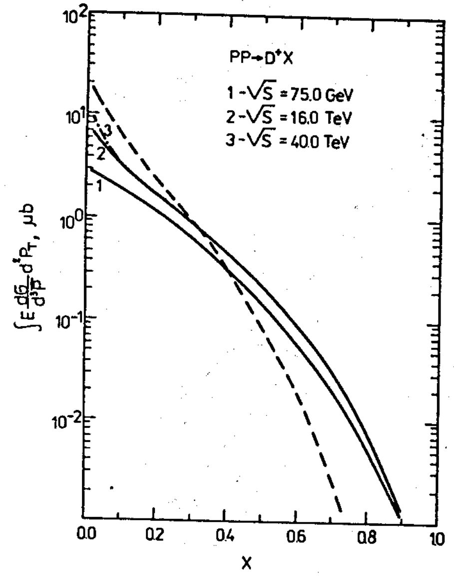

Fig. 3. Estimates of the cross sections for reaction $pp\to D^+X$ at the future collider energies as functions of x. Solid curves correspond to interception $\alpha_\psi(0)=0$, dashed one - $\alpha_\psi(0)=-2.18$ at $\sqrt{s}$=75 GeV.

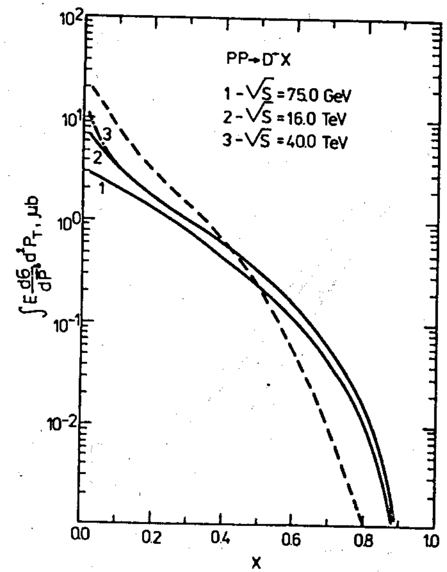

Fig. 4. The same as in Fig. 3, but for reaction $pp\to D^-X$.

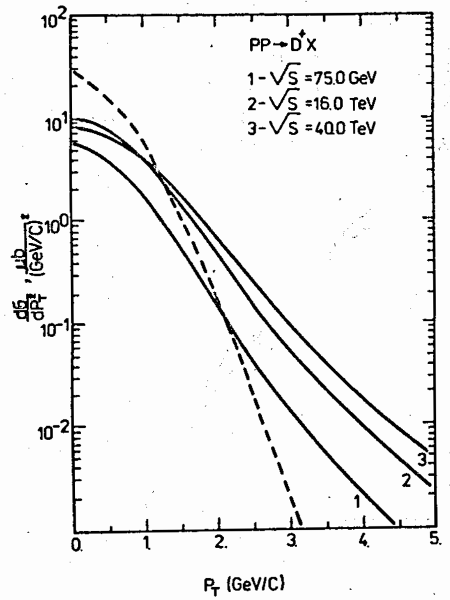

Fig. 5. Estimates of the cross sections for reaction $pp \to D^+X$ at the future collider energies as functions of p_T^2. Solid curves correspond to interception $\alpha_\psi(0)=0$, dashed one - $\alpha_\psi(0)=-2.18$ at $\sqrt{s}=75$ GeV.

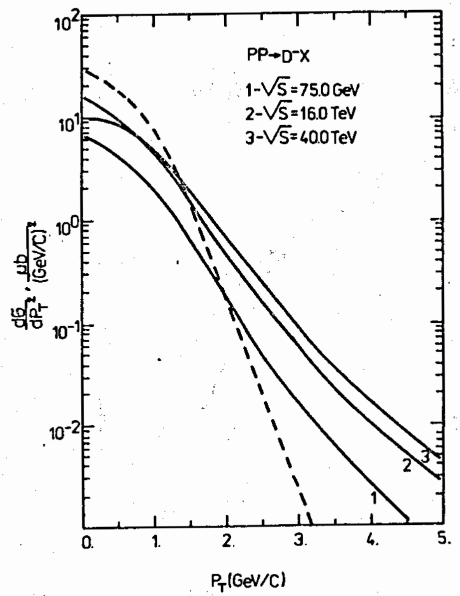

Fig. 6. The same as in Fig. 5, but for reaction $pp \to D^-X$.

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