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c-QUARKS AS PARTONS AND CHARM HADROPRODUCTION

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С-КВАРКИ В РОЛИ ПАРТОНОВ И РОЖДЕНИЕ ОЧАРОВАННЫХ
ЧАСТИЦ В АДРОННЫХ СТОЛКНОВЕНИЯХ

Рассмотрены процессы рождения очарованных адронов в адронных столкновениях, происходящие за счет "возбуждения" моря тяжелых $c\bar{c}$ кварков-партонных внутри начальных адронов. Сформулирована двухкомпонентная модель таких процессов, учитывающая наряду с жестким рассеянием тяжелых кварков-партонных их выживание с малыми переданными импульсами, приводящее к рождению очарованных адронов преимущественно в области фрагментации. Вычислены сечения и инклюзивные спектры для обеих компонент рассеяния: пертурбативной и непертурбативной. Модель хорошо воспроизводит экспериментальные данные по рождению очарованных частиц на ускорителях FNAL, ISR и позволяет однозначно проэкстраполировать сечения и инклюзивные спектры адронного рождения c -кварков в область сверхвысоких энергий.

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c-QUARKS AS PARTONS AND CHARM HADROPRODUCTION

The charmed hadron production in hadronic collisions due to the "excitation" of heavy $C\bar{C}$ -quark-parton sea inside initial hadrons is considered. A two-component model for these processes is formulated taking into account both the heavy quark-parton hard scattering and their nonperturbative excitation with small transferred momenta. This last mechanism leads to charm production mainly in the fragmentation region. The model reproduces experimental situation on charm hadroproduction at FNAL + ISR region and allows to extrapolate C -quark production cross sections and inclusive spectra up to superhigh energy region.

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1. Introduction

As it was recently realized, the experimental situation on charmed hadron production cannot be described in terms of models where a heavy quark pair $C\bar{C}$ is created at small distances as a result of two gluon fusion (see, e.g., reviews [1, 2]).

An alternative (or additional) mechanism is now widely discussed [2-6] in which C or \bar{C} -quark (open charm) production takes place due to the virtual $C\bar{C}$ -pair excitation inside one of the initial hadrons (see Fig.1). The crucial point of this approach is to define the $C\bar{C}$ -parton distribution inside light hadron, e.g., inside proton.

The total inclusive cross section of $C\bar{C}$ -pair production in pp-collision c.m. frame has then the following general form:

$$\sigma(pp \rightarrow C\bar{C} + \dots) = 4 \int dx \int dt C(x,t) \frac{d\sigma}{dt} \quad (1)$$

where $d\sigma/dt$ is the differential cross section of C or \bar{C} -parton scattering on the projectile proton (summed over all constituents of projectile that may contribute into the scattering subprocess). Here

$c(x, t) = \bar{c}(x, t)$ is the C - or \bar{C} -quark distribution inside proton. The dependence of this distribution on transferred momentum t reflects the fact that C -quarks inside proton are virtual and interact with other partons. The factor 4 takes into account that the C -quark excitation may occur inside both initial protons and in two ways: first, by C -quark scattering itself (the so-called "active" C -quark) and, second, by its \bar{C} -partner scattering (the C -quark being in this case "spectator"). Experimentally, Λ_c -baryon and D -meson production is measured. Neglecting $\bar{\Lambda}_c$ and hidden charm states, the cross section (1) consists of two parts:

$$\sigma(pp \rightarrow c\bar{c} + \dots) \simeq \sigma(pp \rightarrow \Lambda_c \bar{D} + \dots) + \sigma(pp \rightarrow D \bar{D} + \dots)$$

In this paper we shall try to calculate the cross section (1) and corresponding inclusive spectra of C -quark production at high energies (beginning from the FNAL region). A definite choice of C -quark distribution that we have made is based on simple and as seems to us natural argument of parton model applicability for heavy quark-antiquark fluctuation inside a fast moving proton.

The main result that will be obtained below is the following. The C -quark excitation mechanism is actually able to describe the experimental situation on charm hadroproduction if we introduce a nontrivial C -quark distribution evolution in the $|t| \ll M_C^2$ region where QCD perturbation theory (PT) is inapplicable. In this region C -quark excitation proceeds due to the "normal" strong interaction at large distances. This nonperturbative (NP) excitation turns out dominating at large longitudinal momenta X_L of produced charmed particles thoroughly solving the problem with

observed effect of "diffractive" Λ_c -production [1-2].*)

In Ref. [4] a radical viewpoint has been adopted that $C\bar{C}$ -quarks always exist inside the proton ("intrinsic" charm), i.e. the scattering with an arbitrarily small (kinematically allowed) momentum transfer is able to produce open charm. According to Ref. [4], the intrinsic charm distribution is fixed and does not change with t .

In contrast with this, we suppose that $C(x, t)$ distribution is gradually "switched on" from certain minimal values of $|t|$ up to large $|t|$'s in the PT region.

It is important to note in advance that C -quark excitation mechanism considered here (and in other versions in Refs. [3-6]) is by no means universal. Indeed, a notion of $C(x)$ parton distribution by itself implies that it contains only those $C\bar{C}$ -pairs which are a part of initial proton wave function and are not created during the pp -interaction. A clear distinction between these two alternatives is possible only if X is large enough. It means that we must consider only those C, \bar{C} -partons that are not wee ($X > M_c/\sqrt{S}$). Hence the inclusive cross sections calculated below in the framework of the C -quark excitation model are incomplete at small $|X_L|$ values ($|X_L| \leq M_c/\sqrt{S}$). Some other mechanism (such as two-gluon fusion) must be added in the central region. At FNAL energies M_c/\sqrt{S} is already ~ 0.1 . It means that at lower energies the excitation mechanism is inessential since there is no room to

*) Note that in Ref. [7] an essentially nonperturbative mechanism of charm hadroproduction at large X_L has been considered in terms of multiperipheral approach dealing with intermediate hadron (and not parton) $C\bar{C}$ -states.

introduce $C(x)$ distribution.

Further we proceed as follows.

In Sec.2 the choice of C -quark distribution inside proton is made. In Sec.3 that part of inclusive cross section is calculated which corresponds to the $C\bar{C}$ -parton scattering at large momentum transfer (PT region). In Sec.4 the estimates of NP region contribution into the $C\bar{C}$ -quark excitation are obtained. In Sec.5 the comparison of both contributions with the experiment is done and the obtained results are discussed.

For definiteness, we shall consider only $p\bar{p}$ -collisions. As it will become evident, the results obtained below don't change for all types of NN and $N\bar{N}$ -collisions. As for the πN -collisions, some inessential quantitative details quoted below are to be taken into account. Again for definiteness we shall speak of C -quark excitation bearing in mind the evident $C \rightarrow \bar{C}$ symmetry.

2. c - Quark Distribution Inside Proton

The $C\bar{C}$ -pairs inside proton enter the parton sea which consists mainly of gluons and light quark pairs.

If an incident distribution $C(x, Q_0^2)$ is defined, where $Q_0^2 \sim 1 \text{ GeV}^2$ is the minimum momentum transfer determining the PT validity region, then $C(x, t)$ is calculable at $|t| \geq Q_0^2$ from PT evolution equations *). At the same time, within the limits of PT, nothing can be

*) We will deliberately distinct the scale Q_0 from the close scale M_c , bearing in mind also heavier quarks for which these scales are different.

where in the $|uudc\bar{c}\rangle$ state C -quark and \bar{C} -quark (the latter together with light partons) carry away respectively x and $1-x$ fraction of initial momentum. We neglect light quark masses and transverse momenta as compared with M_c .

Comparing $\tau_{c\bar{c}}$ with the mean interaction time of the scattering with momentum transfer t , $\tau_{int} \geq (\sqrt{|t|})^{-1}$, we obtain a certain condition

$$|t| \gg M_c^2 \left(\frac{M_c^2}{S} \right) / x^2 (1-x)^2 \equiv t_0(x) \quad (3)$$

which is the parton model constraint for $C\bar{C}$ -quarks with momenta

$$x > M_c/\sqrt{S} \quad (1-x > M_c/\sqrt{S}).$$

Therefore, in Eq.(1) the integration boundaries should be chosen as

$$M_c/\sqrt{S} \leq x \leq 1 - M_c/\sqrt{S}, \quad |t| \geq t_0(x).$$

The t_0 value defined in Eq.(3) serves as a natural lower boundary, up to which the distribution $c(x,t)$ may exist. Thus the quoted in [4] assumption $c(x,0) = c(x,t) \neq 0$ ("intrinsic" charm hypothesis), in fact, contradicts the parton model applicability condition.

At the same time, it immediately follows from Eq.(3) that fast (in X scale) C -partons can participate in a scattering with sufficiently small $|t| \ll Q_0^2$ due to the Lorentz dilatation of their lifetime (2).

The $t_0(x)$ dependence at various energies is shown in Fig.2. Starting already with FNAL energies ($\sqrt{S} = 20 + 25$ GeV) a nonperturbative region $|t| \leq Q_0^2$ exists for C -quark distribution. This region grows with energy involving slower and slower (in X scale) partons. In accordance with that, we choose a $c(x,t)$ distribution in a standard form

$\sim x^{-a}(1-x)^b$, ($a \leq 1$), but with powers a and b varying with t in the region $t_0 \leq |t| \leq Q_0^2$, so that a gradual "inclusion" of $C(x, t)$, first, at higher, then at lower values of X is provided:

$$C(x, t) = \begin{cases} 0, & |t| \leq t_0 \\ \eta(\gamma+1)\langle c \rangle x^{-\eta}(1-x)^{\eta\gamma}, & t_0 \leq |t| \leq Q_0^2, \\ (\gamma+1)\langle c \rangle x^{-1}(1-x)^\gamma, & |t| \geq Q_0^2 \end{cases} \quad (4)$$

where $\eta \equiv (|t| - t_0) / (Q_0^2 - t_0)$, $\langle c \rangle \equiv \int x c(x, Q_0^2) dx$

The choice of $C(x, t)$ at $|t| \geq Q_0^2$ coincides with universal distribution of sea partons $\sim 1/x$ at small X 's. Along with that, following [4, 5], we assume that $C(x)$ at large X is harder than for light quarks sea (for the latter $\gamma \sim 10$). Indeed, being a part of fast proton, C and \bar{C} -quarks, as they are heavier than other partons, carry higher average momenta

$$\langle x_c \rangle = \int x c(x) dx / \int c(x) dx$$

We take $\gamma = 3$ (close to the corresponding value for the valence quarks) and $\langle C \rangle = 0.5\%$ (the value quoted in Refs. [3, 5]). As will become evident further, these parameters are easily fixable from relevant data and our choice is in fact in agreement with the crude experimental information available.

The form of C -quark distribution at $|t| \geq Q_0^2$ may be, in principle, extracted from the experiments on deep inelastic charm lepton production. For example, the EMC data [11] on muon production of charmed particles at $\sqrt{s} = 22$ GeV (where the second muon is registered from the charm

decay) allow one to derive the differential cross section $d\sigma/dx_{Bj}$ over Bjorken variable x_{Bj} . At small x_{Bj} 's the $c\bar{c}$ -pair muoproduction proceeds mainly through the fusion of virtual photon and gluon. Starting with $x_{Bj} \geq M_c/\sqrt{s}$, $c\bar{c}$ -partons inside initial nucleon manifest themselves and at sufficiently large x_{Bj} the cross section will be, in fact, dominated by the c -quark "photoexcitation" mechanism. In this case, $d\sigma/dx_{Bj}$ is expressed directly via $C(x)$:

$$d\sigma_{EMC}^c/dx_{Bj} \approx 5.04 \cdot 10^{-34} \text{ cm}^2 B(c \rightarrow \mu) \frac{C(x_{Bj})}{x_{Bj}} \quad (5)$$

where $B(c \rightarrow \mu) = 8\%$ is a semileptonic branching ratio and the kinematical regions over Q^2 and ν are taken into account for the given experiment [11]. The comparison of the experimental cross section $d\sigma/dx_{Bj}$ with the photon-gluon fusion model prediction presented in Ref. [11] shows some excess of experimental points at large x_{Bj} (see Fig.3). The precise value of this excess is difficult to estimate since experimental errors are large and the fusion model predictions (the dashed line in Fig.3) are essentially model-dependent. Assuming that the cross section in this region is actually determined by the inherent c -quark distribution in nucleon and using (5), it is easy to obtain $d\sigma/dx_{Bj}$ for various choices of (Nos.1-4 solid lines in Fig.3). It is seen that the distribution

$$C(x) = 18x^2 \left[\frac{1}{3}(1-x)(1+10x+x^2) - 2x(1+x) \ln \frac{1}{x} \right]$$

from [4] as well as $C(x) \sim (1-x)$ from [5] yield a rather large cross section as compared with the experiment in the region $x_{Bj} > 0.3$. On the contrary, the c -quark distribution from [3], which, as it has been assumed there, must manifest itself up to $x_{Bj} \sim \frac{M_c^2}{\sqrt{s}}$, yields a

considerable excess in the region $X_{Bj} < 0.1$. A somewhat better agreement at large X_{Bj} is obtained by our choice (4) at $\gamma = 3$, $\langle C \rangle = 0.5\%$. Of course, the agreement can be improved by means of parameters fitting or complicating the very form of the C -quark distribution. However, as the data [11] in the region of large X_{Bj} are too crude, it makes not much sense to deal with this. Nevertheless our claim is that the improvement of data on the $d\sigma/dX_{Bj}$ distribution of charm muoproduction in the region $X_{Bj} > 0.3$ will make it possible to derive directly C -quark distribution at large X . Unfortunately, nobody knows so far how to measure this cross section at higher energies, where the applicability region of parton model for C -quarks begins at lower values of X .

After we have assumed the existence of $C\bar{C}$ -partons in nonperturbative region $|t| \leq Q_0^2$, the cross section (1) of charm hadroproduction should be divided into two parts: contribution of PT region and that of NP region:

$$\sigma(pp \rightarrow C\bar{C} + \dots) = 4 \int dx \left\{ \int_{|t|=Q_0^2}^{1-M_c/\sqrt{s}} \int_{|t|=Q_0^2}^{Q_0^2} C(x,t) \frac{d\sigma}{dt} dt + C(x, Q_0^2) \int_{Q_0^2}^{\infty} \frac{d\sigma}{dt} dt \right\} \quad (6)$$

Since the boundary Q_0^2 is conventional, the following natural interpolation condition must hold:

$$\left. \frac{d\sigma}{dt} \right|_{|t|=Q_0^2}^{NP} = \left. \frac{d\sigma}{dt} \right|_{|t|=Q_0^2}^{PT}$$

Let us calculate both contributions to (6), separately.

3. Contribution of Perturbation Theory Region

At $|t| \geq Q_0^2$ C - and \bar{C} -partons scattering takes place on separate partons: quarks and gluons of projectile proton. The $O(\alpha_s^2)$ diagrams of these subprocesses are shown in Fig.4. Their calculation was performed earlier in Refs. [3, 5], so we shall repeat it in general features. The main contribution to the cross section is given [3, 5] by the scattering of C -quark on gluon (Fig.4b), namely by the diagram with t -channel gluon exchange (the third one in Fig.4b). At sufficiently high energies for this diagram $\frac{d\sigma}{dt} \sim \frac{2\pi\alpha_s^2}{t}$, which corresponds to a constant cross section of elementary process $\sigma(qc \rightarrow qc) \sim 1/Q_0^2$. In subsequent approximate expressions we shall restrict ourselves to this leading contribution. The result of numerical calculations with account of all diagrams of Fig.4b, c are presented in Figs. 5-8.

The total cross section of C -quark production in PT region can be presented [3, 5] in a form resembling Drell-Yan formula:

$$\sigma^{PT}(\sqrt{s}) = 4 \int_{M_c/\sqrt{s}}^{1-M_c/\sqrt{s}} c(x, Q_0^2) dx \int_{y_{min}}^1 G(y) dy \int_{Q_0^2}^{|t_{max}|} \frac{d\sigma}{dt} d|t| \quad (7)$$

where $y_{min} = M_c Q_0 / s x$; $|t_{max}| \sim s x y$; $G(y) = 3(1-y)^5/y$ is the standard gluon distribution inside proton at $|t| \geq Q_0^2$. After integrating over t and y (in (1) and (6) it is assumed that integration over y is included in $\frac{d\sigma}{dt}$) we arrive at

$$\sigma^{PT}(\sqrt{s}) = \frac{12\pi\alpha_s^2}{Q_0^2} \int dx c(x, Q_0^2) \left\{ \ln \frac{s x}{M_c^2} - \text{const} - O\left(\frac{M_c^2}{s}\right) \right\} \quad (8)$$

The integrand in (8), generally speaking, does not coincide with inclusive distribution of produced c -quark $d\delta/dx_L$. The latter should be calculated directly from (7) replacing $t \rightarrow x_L$ (see, e.g. [5]). Nevertheless, the integrand (8) serves as a reliable approximation for $d\delta/dx_L$ at large \sqrt{s} by making replacement $x \rightarrow x_L(1-\xi)$, where $\xi = (Q_0/M_c) \ln M_c/Q_0 \ln \sqrt{s}/M_c$. Finally, the inclusive distribution of produced c -quarks in PT region up to factors $\sim \ln \frac{sx}{M_c^2}$ coincides at sufficiently high energies (actually beginning with ISR region) with initial c -quark distribution in proton.

The results of numerical integration of Eq.(7) yielding inclusive cross section $d\delta/dx_L$ at energies $\sqrt{s} = 25, 60, 540$ GeV are presented in Fig.5, while dimensionless spectra

$$dN/dx_L = 1/6 \left(d\delta/dx_L \right)$$

in a wider energy range (up to cosmic ray region $E \sim 10^3 \div 10^5$ TeV or $\sqrt{s} = 1.4 \cdot 10^3 \div 1.4 \cdot 10^4$ GeV) in Fig.6 at $\gamma = 3$, $\langle C \rangle = 0.5\%$, $Q_0^2 = 1 \text{ GeV}^2$, $\alpha_S(Q_0^2) = 0.4$ ($\Lambda_{QCD} = 150 \text{ MeV}$), $M_c = 1.5 \text{ GeV}$. In calculating a diagram of Fig.4c the following distribution of light quarks is taken:

$$q(x) \sim \frac{(1-x)^3}{\sqrt{x}}$$

The inclusive spectra presented in these figures also take into account a slight difference between active c -quark directly scattered on gluon and spectator c -quark produced as a result of \bar{c} -quark scattering. Formally, from the very beginning, one should consider a double distribution of

$$c\bar{c} \text{ -pairs inside proton } c\bar{c}(x, x', t) \text{ so that} \\ \int_0^{1-x} c\bar{c}(x, x', t) dx' \equiv c(x, t); \int_0^{1-x'} c\bar{c}(x, x', t) dx \equiv \bar{c}(x', t) \quad (9)$$

For the correct account of spectator, it is necessary to replace the integrand in (1):

$$4c(x) \frac{d\delta}{dt}(x,t) \rightarrow 2c(x) \frac{d\delta}{dt}(x,t) + 2 \int c\bar{c}(x,x') \frac{d\delta}{dt}(x',t) dx' \quad (10)$$

Then the first term in (10) corresponds to the active C -quark, and the second one to the spectator. We assume that $c\bar{c}(x,x')$ depends only on the sum of momenta $x+x'$ (in the general case there must be symmetry $c\bar{c}(x,x') = c\bar{c}(x',x)$ so that $c(x) = \bar{c}(x)$). Then $c\bar{c}(x,x')$ is restored unambiguously by a given $c(x)$ from (4). In order to obtain total inclusive spectrum, one should make in the first term (10) a transformation $t \rightarrow X_L$ and integrate it over X , then in the second term immediately replace $X \rightarrow X_L$ and integrate it over t . This modification leads to a slight numerical change in spectra at small X_L . Note that the role of a spectator mechanism in the production of charmed particles with large X_L was absolutely overestimated in Ref.[5]. That happened because, as it was assumed in Ref.[5], C -quark generation in proton with momentum fraction X is always followed by the \bar{C} -quark with momentum fraction $1-X$. We argue that the $C\bar{C}$ -pair has in fact a vanishing probability to carry the whole momentum of proton and C, \bar{C} -quark production with large X_L occurs, as will be seen below, out of the PT-region.

Note once more that our model in $X_L < M_c/\sqrt{s}$ region is incomplete since some additional mechanism besides the excitation must contribute in this region.

The approximate integral (8) yields the following total cross section of C -quark production at a given energy

$$\sigma^{c\bar{c}}(\sqrt{s}) \approx \alpha_s^2 \langle C \rangle \cdot 176 \text{ mb} \left\{ \ln^2 \frac{\sqrt{s}}{M_c} - 5.1 \ln \frac{\sqrt{s}}{M_c} + 6.8 \right\}$$

at $\gamma = 3$, $Q_0^2 = 1 \text{ GeV}^2$, $M_c = 1.5 \text{ GeV}$.

The results of exact integration of cross section (7) over x , y , and t (the separate contributions of Fig.4b, c diagrams) are presented in Fig.8.

The origin of the asymptotic energy behaviour of the obtained cross section is evident: the first logarithm comes from the denominator $1/x$ in gluon distribution and the second one - from the analogous denominator in the distribution (4). In Refs. [3, 5], where the cross sections in PT regions were earlier calculated, quite different results have been obtained. The cross section in [3] grows more rapidly than the energy logarithm squared, while cross section [5] grows only as energy logarithm.

Testing the obtained energy asymptotics of charm cross section in terms of our model means to verify the universal "sea" ($\sim 1/x$) behaviour of $C(x)$ distribution.

Bearing in mind that our results are valid for $x_L > M_c/\sqrt{s}$ (e.g. at ISR energies for $x_L > 0.025$) in Table 1 we present the integrals over inclusive spectra taken from certain minimum $(x_L)_{\text{min}}$ values.

For contrast, Figs. 5, 6, 8 show also predictions of the gluon fusion model $gq \rightarrow c\bar{c}$ (diagrams of Fig.4a).

4. Nonperturbative Region of $c\bar{c}$ -Partons Excitation

In the region $|t| \leq Q_0^2$ c, \bar{c} -partons scattering occurs already not on separate gluons and quarks of projectile proton, but on constituents of larger scale (such as constituent quarks). Although we have no possibili-

ty to calculate this scattering in detail, it is natural to suppose that this process, just as any other "normal" strong interaction, has a peripheral character:

$$\frac{d\sigma^{NP}}{dt} = \frac{\sigma_0(sx)}{Q_0^2} e^{-b|t|} \quad (11)$$

where σ_0 weakly (logarithmically) depends on energy.

The slope parameter b may be estimated in the following way: the distribution over transverse momentum of Λ_c -baryons and D -mesons measured at ISR energies is [12]: $d\sigma/dp_\perp^2 \sim e^{-b p_\perp^2}$, where $b \sim 1.2 \text{ GeV}^{-2}$. As far as at small $|t|$, $p_\perp^2 \sim |t|$, we shall take simply $b = 1 \text{ GeV}^2$. Of course, such subtle details as variation of slope with energy cannot be determined within the accuracy of this model.

Normalization of cross section (11) on the corresponding value at the PT region boundary (the interpolation condition) yields

$$\sigma_0(sx) \approx 3.2 \text{ mb} \left[\ln \frac{sx}{M_c^2} - 2.4 \right]$$

at $b = 1 \text{ GeV}^2$, $Q_0^2 = 1 \text{ GeV}^2$, $\gamma = 3$, $\alpha_s(Q_0^2) = 0.4$.

Substituting (11) to the first term of (6) together with the distribution (4) and integrating over t , we arrive at the following expression for the contribution of nonperturbative region into C -quark production cross section

$$\sigma^{NP}(\sqrt{s}) = (\gamma+1) \langle C \rangle \int_{M_c/\sqrt{s}}^{1-M_c/\sqrt{s}} \sigma_0(sx) \left(\frac{Q_0^2 - t_0(x)}{Q_0^2} \right) \times \left\{ \frac{\exp[b(Q_0^2 - t_0)] - \frac{(1-x)^\gamma}{x} (1 + b(Q_0^2 - t_0) - \ln \frac{(1-x)^\gamma}{x})}{[b(Q_0^2 - t_0) - \ln \frac{(1-x)^\gamma}{x}]^2} \right\} dx \quad (12)$$

The representation in the form of integral over X is convenient since the integrand immediately gives the inclusive spectrum: $d\sigma/dx_L \approx d\sigma/dx$. Indeed, at small t , when C -quark scattering occurs not on gluons with average momentum fraction $y < M_c/\sqrt{s}$, but on constituent objects carrying a finite fraction of the projectile proton momentum, the approximation $X \sim X_L$ is valid within the accuracy of $\sim |t|/s$.

A distinctive feature of the inclusive spectrum obtained is its hardness at large X_L ($\sim \ln^{-2}(1-X_L)$ at $X_L \rightarrow 1$) as compared with the PT contribution yielding $d\sigma/dx_L \sim (1-X_L)^8/X$.

Such an unusual behaviour of the inclusive cross section is caused, as may be readily tested, just by the nonperturbative evolution of $C(x,t)$ in the region $t_0(x) \leq |t| \leq Q_0^2$ according to (4).

The $d\sigma/dx$ presented in (12) vanishes at small $x \sim M_c/\sqrt{s}$. It means that the asymptotics of nonperturbative part of total charm production cross section is determined entirely by the σ_0 asymptotics, i.e. $\sim \ln \sqrt{s}/M_c$, as our interpolation condition dictates.

Predictions for inclusive spectra generated by $C\bar{C}$ -partons excitation in NP or large-distance region are given in Figs.5-7, whereas a contribution of this region into the total cross section $\sigma(pp \rightarrow c\bar{c} + \dots)$ in Fig.8.

5. Discussion

Let us now compare the obtained predictions with the available data on charmed particle production in hadronic collisions.

The most complete measurements of cross sections and inclusive spectra have been carried out by the BCF group on ISR [12-14] at $\sqrt{s} = 60$ GeV. The main results of this experiment may be formulated as follows [1, 2]:

- i) total inclusive cross section of $C\bar{C}$ -production, i.e. the sum $\sigma(\Lambda_c\bar{D}) + \sigma(D\bar{D})$ approaches $\sim 1 \text{ mb} \pm 50\%$, where $\sigma(\Lambda_c\bar{D})$ is $\sim 200 \text{ mb}$, $\sigma(D\bar{D}) \sim 800 \text{ mb}$;
- ii) inclusive distribution of Λ_c -baryons is essentially hard $\sim (1-x)^{0.5}$
- iii) the inclusive spectrum for the events of D -meson production is steeper: $\sim (1-x)^3/x$

Our model is formulated for C -quark production itself. In order to compare our results with the measured charmed hadron yields, a well established picture of $C\bar{C}$ -pair hadronization is needed. Nevertheless it seems to us that we may use our results directly, taking into account the following circumstance.

The C -quark, being inside Λ_c or D , carries the main share of momentum of these hadrons ($\sim M_c/M_c + M$, where M is the characteristic mass of light hadron constituents). Therefore, spectrum of Λ_c or D -production in a good approximation reproduces that of its own C -quark. Besides, it is natural to assume that C -quark with large X_L turns mainly into Λ_c baryon, combining with the valence u, d quarks of the initial proton, whereas more slower C -quarks are to be combined with slow sea antiquarks forming D -mesons. At the same time, \bar{C} -quark turns predominantly into \bar{D} -meson at any X_L . Using these qualitative arguments, we are able to reproduce the main experimental results quoted above. Of particular importance is the fact that the observed hard Λ_c -production finds its explanation as a direct manifestation of C -quark nonperturbative excitation at large X_L (see Fig.8). No less important is that the PT region contribution corresponds to the observed D -meson pro-

duction inclusive spectra $\sim (1-x)^3/x$. These spectra are softer than those for Λ_c -baryons, but yield larger total contribution.

Fig.8 gives a comparison of the calculated $\sigma(pp \rightarrow c\bar{c} + \dots)$ cross section with the experimental data on charm hadroproduction taken from review [1] as well as with the cosmic ray data on the so-called X -particles [15, 16]. (The latter should be interpreted mainly as charmed particles). The agreement within the accuracy of the experiments is reasonable. It is at least seen that the excitation model of C -quarks yields a correct order of value for the $\sigma(pp \rightarrow c\bar{c} + \dots)$ cross section even at FNAL energies and reproduces the energy dependence from FNAL to ISR and higher.

Thus, we have demonstrated that the excitation mechanism of charm hadroproduction considered here explains the main experimental characteristics of these processes at least at sufficiently large X_L ($X_L > M_c/\sqrt{s}$). Of course, both the quantitative results and the values of model parameters chosen above must not be taken too seriously. The main result obtained is, to our mind, a rather qualitative answer to the following question. What features must have the C -quark distribution inside the nucleon in order to reproduce the observed pattern of charm hadroproduction? We claim that there are two distinct regimes of C -quark excitation. Besides usual hard scattering of the $C\bar{C}$ -fluctuation on the projectile gluons and light quarks which is described by QCD perturbation theory, there exists essentially large distance effect - soft excitation of long living $C\bar{C}$ -partons, which is beyond the perturbation theory. A natural question arises, whether it is possible to deduce this nonperturbative evolution of C -quark distribution using any nonperturbative method (e.g. QCD sum rules). Nevertheless we argue that it is already possible to extract this distribution using the charm hadroproduction data. It is important also that fixing

the C -quark distribution parameters in the accelerator region we may predict unambiguously the charm cross section at higher energies since the model formulated above yields a well defined asymptotic behaviour.

The calculations performed above may be easily adjusted also for πN -collisions by changing slightly the distribution functions of gluons and

C -quarks. (Somewhat less powers determining the behaviour at large x must be taken). Numerical estimates give for πN - collisions inclusive spectra close to those for pp ones and cross section

$$\sigma(\pi N \rightarrow c\bar{c} + \dots) \simeq 80\% \sigma(pp \rightarrow c\bar{c} + \dots)$$

To estimate the cross sections for heavier b, t -quarks, we suppose that $\langle b \rangle = (M_c^2/M_b^2) \langle c \rangle$, $\langle t \rangle = (M_c^2/M_t^2) \langle c \rangle$. All other parameters are unchanged. The results for the cross sections are shown in Fig.9. Note that, in general, the heavier is quark the less is NP contribution into its production cross section. In this sense c, \bar{c} -quarks viewed as a part of nucleon are intermediate between "really heavy" $b\bar{b}, t\bar{t}$ -quarks and light $s\bar{s}$ -quarks. For the latter the NP-mechanism is already dominant (indeed, strange particle production is a pure soft process).

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Table

The cross section $\int_{(X_L)_{min}}^1 d\sigma/dx_L (pp \rightarrow c\bar{c} + \dots) dx_L$
of charm production in pp-collisions integrated from
certain $(X_L)_{min}$ at different energies (in μb).

The PT region contribution is given in parentheses.

\sqrt{S} / $(X_L)_{min}$	60 GeV	540 GeV	$1.4 \cdot 10^3$ GeV	$1.4 \cdot 10^4$ GeV
0.15	120 (60)	310 (150)	430 (190)	710 (310)
0.10	160 (90)	440 (220)	600 (290)	1000 (460)
0.05	260 (140)	770 (370)	1000 (490)	1600 (790)

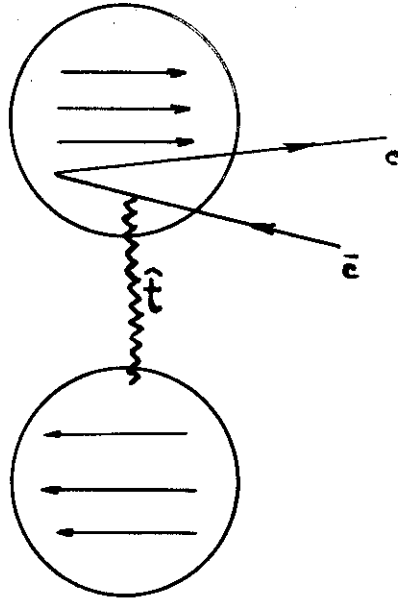


Fig. 1

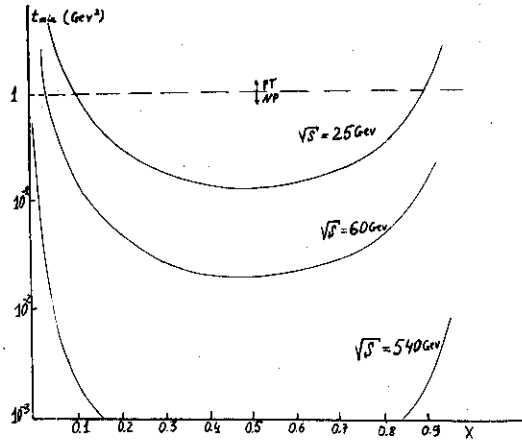


Fig. 2

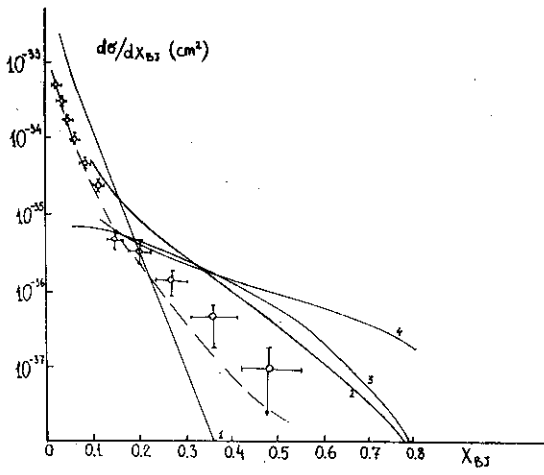


Fig. 3

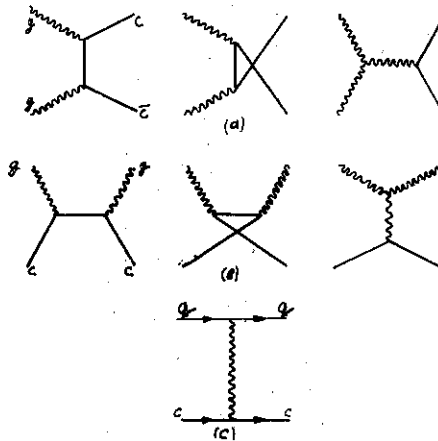


Fig. 4

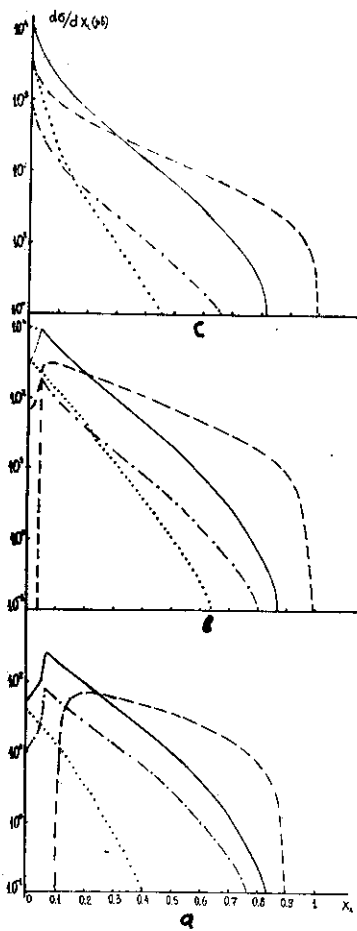


Fig. 5

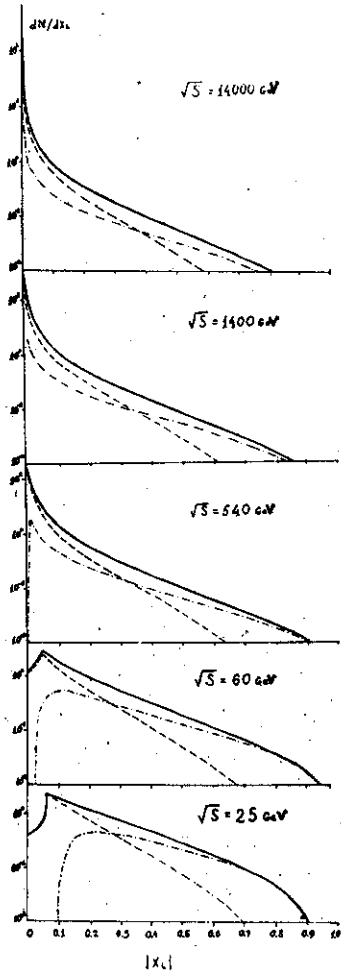


Fig. 6

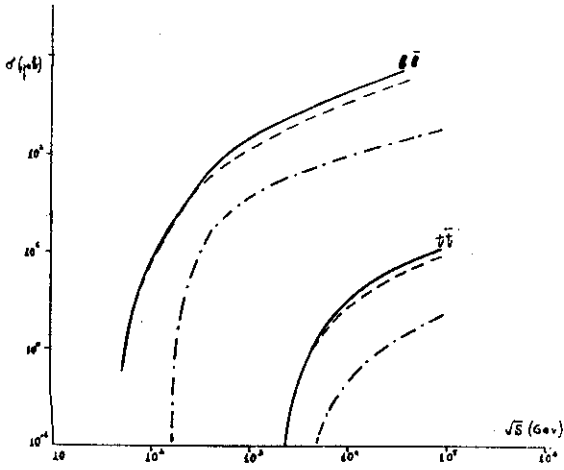


Fig. 9

FIGURE CAPTIONS

Fig.1. Excitation of $C\bar{C}$ -partons inside the nucleon.

Fig.2. The dependence of minimum momentum transfer t_{min} on C -quark-parton momentum fraction X at different energies. Above (below) the dashed line $Q_0^2 = 1 \text{ GeV}^2$ is the PT (NP) region of C -quark excitation.

Fig.3. The $d\sigma/dx_{Bj} (Mp \rightarrow M + C\bar{C}^+)$ cross section taken from Ref. [11]. Dotted line is the photon-gluon fusion contribution [11]. Solid lines 1, 3, 4 are the $C\bar{C}$ -parton "excitation" contributions at $Q_0^2 > 1 \text{ GeV}^2$ in models [3], [4], [5], respectively. Solid line 2 is our prediction obtained for C -quark distribution (4).

Fig.4. $O(\alpha_s^2)$ diagrams of C -quark production in QCD perturbation theory: (a) - fusion ($gg \rightarrow C\bar{C}$), (b), (c) - excitation ($gC \rightarrow gC, qC \rightarrow qC$).

Fig.5. The inclusive cross sections of C -quark production in pp-collisions at energies a) $\sqrt{S} = 25 \text{ GeV}$, b) 60 GeV , c) $\sqrt{S} = 540 \text{ GeV}$. The solid (dash-dotted) line is $gC \rightarrow gC$ ($qC \rightarrow qC$) scattering contribution in the PT region (Figs. 4b, c). The dashed line is the NP region contribution into the $C\bar{C}$ -parton excitation. The dotted line is the gluon-fusion contribution (Fig.4a).

- Fig.6. Inclusive spectra $dN/dx_L = \frac{1}{6} (d\sigma/dx_L)$ of C-quark production in pp-collisions. Dashed (dash-dotted) line is the PT (NP) region contribution.
- Fig.7. Total inclusive cross section $\sigma(pp \rightarrow c\bar{c} + \dots)$ (Crossed line). Solid (dash-dotted) line is the $gC \rightarrow gC$ ($qC \rightarrow qC$) scattering contribution in the PT region. Dashed line is the NP region contribution into the $c\bar{c}$ -parton excitation. Dotted line is the gluon-fusion contribution. The comparison is made with experimental data on Λ_c (\bullet) and \mathcal{D} (\square) production taken from Ref. [1] and on X-particle data in cosmic rays from Refs. [15, 16].
- Fig.8. The inclusive cross section $d\sigma/dx_L (pp \rightarrow c\bar{c} + \dots)$ at $\sqrt{S} = 60$ GeV as compared with the experimental data [13] on Λ_c -baryon production at ISR. Dash-dotted (dashed) line is the NP (PT) region contribution.
- Fig.9. $\sigma(pp \rightarrow b\bar{b} + \dots)$, $\sigma(pp \rightarrow t\bar{t} + \dots)$ cross sections of open b and t flavor production in pp-collisions ($m_t = 30$ GeV). Dash-dotted (dashed) line is the NP (PT) region contribution.

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