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CHARMED BARYON PRODUCTION IN HADRONIC COLLISIONS

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Abstract

Quautitative description of charmed baryon production in pp and $\pi^- p$ collisions is obtained in the framework of the soft, peripheral quark-gluon approach. The quark-gluon model, based on the topological expansion, is used for determination of the planar part of the multiperipheral diagrams. The parameters of the $D^* - D^{**}$ Regge trajectories and residues are estimated in this model. The total contribution of the peripheral mechanism is calcul-ted by substitution of this planar part to the cylinder-type multiperipheral diagram with π -meson exchange. The energy dependence, absolute value of the inclusive cross section for Λ_c production and its x_F and $p_\perp$ -distributions are calculated and found to be in an agreement with experimental data. Connection with other models of charm production is discussed.

I. Introduction

Experimental data on production of charmed particles in hadronic collisions have demonstrated that the naive perturbative QCD estimates could not explain the experimentally observed production cross sections of these particles (a review of the situation in this field can be found in ref. [1]). Even for nonrealistic values of the c -quark mass and coupling constant α_s theoretical values of the cross sections are considerably smaller than the experimental ones.

Recent experiments on charmed baryon Λ_c production [2] have shown that the discrepancy in the shape of inclusive spectra is even more drastic, - perturbative QCD calculations predict the spectrum, which decreases rapidly as x_F increases and is concentrated mainly in the region $x_F < 0.2 \div 0.3$, while the experimental spectrum decreases very slowly with x_F up to $x_F \approx 0.8 \div 0.9$. Fast decrease of the charmed particles spectra with x_F in the perturbative QCD calculations is connected to a fact that in this model charmed quarks are produced by gluons, whose distribution is peaked at $x \approx 0$.

In order to explain these data Brodsky et al. [3] have formulated a hypothesis of a substantial ($\sim 1\%$) admixture of c -quarks inside a proton ("intrinsic charm" of a proton). The intrinsic charm is understood in this model as the sea of c, $\bar{c}$ -quarks caused by the large-distance interaction, which is not connected with the perturbative evolution of quark-gluon distributions. The necessary value of the "intrinsic charm" for a proton has been estimated directly from the Λ_c -production data.

On the other hand, effects of large distance dynamics can be described quantitatively in different versions of peripheral models - Regge model, dual schemes, and etc. Let us note in this connection, that the characteristic features of the Λ_c -production data are very similar to those for inclusive spectra of strange Λ -hyperons (shape of the spectrum, small mean transverse momentum), which have been succesfully described in the multiperipheral model (see ref. [4]). The leading particle effect in this approach is explained quite naturally - ΛK -system ($\Lambda_c \bar{D}$ for charmed particles) is produced peripherally and takes the most part of the momentum of initial proton.

In the peripheral approach, however, it is difficult to obtain a large value of the cross section for charmed particle production due to low intercept of exchange - degenerate D^*-D^{**} trajectories, which determine the amplitude of this process. Estimates give $\alpha_{D^*(D^{**})}(0) = (-1) \div (-2)$, thus suppressing strongly charmed baryon production (for Λ -hyperon production K^*-K^{**} -trajectories with $\alpha_{K^*}(0) \simeq 0.35$ dominate). A large theoretical uncertainty is connected to estimates of residues for D^* -trajectory. Barger and Phillips [5] have proposed the form of residues, which follows from SU(4)-symmetry and Venesiano model and have obtained a very small cross section of Λ_c -hyperon production: $\sigma_{\Lambda_c} \sim (3 \div 60)$ nb.

The quark-gluon model, based on the topological expansion and string model interpretation of Feynman diagrams, has been developed in refs. [6,7] . A large number of relations between Regge trajectories and their residues have been obtained in the framework of this approach. (These relations enables one to calculate with a good accuracy masses and partial widths [7] of the corresponding families of resonances).

In the present paper this approach is used for evaluation of a planar part of peripheral diagrams for charmed baryon production. An estimate of the total contribution of the peripheral mechanism is obtained substituting this planar part into a diagram with pion exchange. The absolute value and energy dependence of the cross sections for charmed baryon production in πp and pp-collisions and inclusive distributions in x_F and $p_\perp^2$ are calculated. The results are in agreement with the experimental data. Connection with other models is discussed.

2. Formulation of the model

Our purpose is a calculation of peripheral diagrams of Fig.1 for the charmed baryon production in pp-collisions. An analogous mechanism for production of strange hyperons has been investigated in detail in ref. [4] and shown to play the main role in the fragmentation region. In this case the diagram of the type 1 a (with Λ and K-meson) is the dominant one up to energies $\sim$ 100 GeV; at ISR-energies the diagram of the type 1 b, corresponding to production of K^* and heavier strange resonances gives a comparable contribution. A parametrization of the upper blob of the diagram has been carried out in ref. [4], using experimental data on binary reactions $\pi p \to \Lambda K$ and $\pi p \to \Lambda K^*$. Close estimates can be obtained if, taking into account the arguments of duality, Regge-parametrization of amplitudes $\pi p \to K \Lambda$ with $K^* - K^{**}$ exchanges is used. Besides this, the diagrams of the type 1 c , 1 d give contributions at not too high energies.

For the case of the charmed baryon production a quantitative estimate of the cross sections, corresponding to diagrams of Fig.1 is more difficult than for strange hyperons. On the one hand, this is connected, as it was mentioned above, with our poor knowledge of the D^* -trajectory. On the other hand, a relative role of the diagram 1 b is strongly enhanced and production of charmed resonances with large masses becomes important (a rate of decrease of the cross section with increase of the mass of the shower is determined by the value of the intercept of the ρ -trajectory which lies much higher in j-plane than the D^* -trajectory. Thus, large masses of the upper blob of the diagram are connected to large masses of the shower, i.e. to production of heavy resonances). Finally, an estimate of absolute values of Regge-residues is a very complicated task, because even if approximate SU(4) symmetry is valid on the mass shell ($t = m_v^2$), the correct extrapolation of the SU(4) relationships to the physical region $t \leq 0$ is a serious problem.

Thus the main problem in calculations of the absolute value of the cross section for the reaction

$$p + p \to \Lambda_c + X \qquad (1)$$

is connected to an estimate of the cross section of the process

$$\pi + p \to \Lambda_c + \bar{D} \qquad (2)$$

$$\pi + p \to \Lambda_c + D_R \qquad (3)$$

where by D_R we denote a shower of particles, which includes D^*, D^{**} -resonances and also states with larger masses.

Let us emphasize that from the point of view of the topological expansion both amplitudes of the process (2) and process (3) will be described by the planar diagrams only (see Figs.2 and 3). This planarity property allows one to distinguish the upper and lower blocks of the diagram 1b, - the upper block contains a completely planar part, while the lower one corresponds to the discontinuity of the cylinder-type diagram, which is equivalent to the pomeron contribution at high energies.

3. Planar diagrams

In our calculations of planar Regge exchanges we will use the ideas of the quark-gluon model, developed in a series of papers [6,7] . In this model QCD diagrams are classified on the basis of the topological expansion (see, for example [8]), and then each class of diagrams (and, first of all, planar diagrams) are interpreted from the probabilistic point of view, considering a hadron as a string [6] . (The probabilities to find out in a hadron string valence quarks with given momentum fraction are calculated).

This approach leads to an extensive system of relations between contributions of different Regge exchanges. In the next section we will give the results for the D^* -trajectory and its residues in the binary process (2) and then, using this cross section for normalization we will calculate with a help of the finite-mass dispersion sum rules the contribution of the most important process (3).

4. Cross section of the process $\pi p \to \Lambda_c \bar{D}$

A contribution of a pair of exchange-degenerate D^*-D^{**} trajectories to the process $\pi p \to \Lambda_c \bar{D}$ is described by a planar diagram of Fig. 2a. It can be given the following interpretation: 1) the valence u -quark of a proton and $\bar{u}$ -quark of π meson have, with some small probability $w_{\pi p}$ close rapidities and annihilate. As a result, two initial hadronic states π and p transform into a single white object, which can be called a string or a colour-tube [6] ; 2) the hadronic string is an unstable object, and among its decay modes there is a two-body decay into Λ_c and $\bar{D}$, which corresponds to fission of the string with production of $c, \bar{c}$ -quarks. The string decays mainly with production of many particles and its two-body decay is a rare event with a probability $w_{\Lambda_c D}$, which decreases exponentially with increase of the rapidity difference of quarks at the ends of the string, i.e. with increase of $\ln \frac{s}{s_0}$.

Let us note that the same probabilities $w_{\pi p}$ and $w_{\Lambda_c D}$ determine planar parts of elastic processes $\pi p \to \pi p$ and $\Lambda_c \bar{D} \to \Lambda_c \bar{D}$, corresponding to the diagrams 2b with a=c, b=d. These processes (we will call them "diagonal", because initial and final hadrons have the same quark content) have been studied in detail in refs. [6,7] . It has been shown that Regge form of the scattering amplitude for hadrons a and b with exchange of a pair of secondary reggeons α_{ii}

$$A_{ab}(s,t) = \frac{\pi g^2_{ab}(t)}{\sin \pi\alpha_{ii}(t)} \left(-\frac{s}{s_0^{ab}}\right)^{\alpha_{ii}(t)-1} \cdot \left(-\frac{s}{\bar{s}}\right) \qquad (4)$$

(where $\bar{S} = 1\ \mathrm{GeV}^2$ is a universal scale factor) corresponds to the probability of annihilation of quarks i and $\bar{i}$ from hadrons a and b

$$W_{ab} \sim \exp\left[-(1-\alpha_{ii}(0))(\tilde{y}_{i/a}-\tilde{y}_{\bar{i}/b})\right] \qquad (5)$$

Here

$$\tilde{y}_{i/a} = \ln\left(\frac{2\tilde{p}^{\parallel}_{i/a}}{m_{\perp i}}\right) = \ln\left(\frac{2p_a\tilde{x}_{i/a}}{m_{\perp i}}\right)$$

$$\tilde{y}_{\bar{i}/b} = -\ln\left(\frac{2p_b\tilde{x}_{\bar{i}/b}}{m_{\perp\bar{i}}}\right)$$

are the mean values of rapidities of the quark i in the hadron a and of the antiquark $\bar{i}$ in the hadron b, $\tilde{x}_{i/a}$ and $\tilde{x}_{\bar{i}/b}$ are the average fractions of the momenta carried by the corresponding quarks. Thus we have

$$W_{ab} \sim \exp\left[-(1-\alpha_{ii}(0))\ln\frac{4p_ap_b}{(m_{\perp i}/\tilde{x}_{i/a})(m_{\perp\bar{i}}/\tilde{x}_{\bar{i}/b})}\right] = \left(\frac{s}{S_0^{ab}}\right)^{\alpha_{ii}(0)-1} \qquad (5a)$$

It follows from Eq. (5a) that the scale factor S_0^{ab} is determined in this model by the average transverse masses and the average fractions of the momenta of hadrons a, b carried by the quarks i and $\bar{i}$

$$S_0^{ab} = \left(\frac{m_{\perp i}}{\tilde{x}_{i/a}}\right)\left(\frac{m_{\perp\bar{i}}}{\tilde{x}_{\bar{i}/b}}\right) \qquad (6)$$

If the average fraction of the momenta of a fast hadron carried by a constituent quark is proportional to a transverse mass of the quark

$$\tilde{x}_{i/a} = \frac{m_{\perp i}}{(\sum_k m_{\perp k})_a} \qquad (7)$$

then the factor s_0^{ab} is proportional to sums of transverse masses of constituent quarks in hadrons a and b

$$s_0^{ab} = \left(\sum_k m_{\perp k}\right)_a \left(\sum_k m_{\perp k}\right)_b \qquad (8)$$

In particular, if we take $m_{\perp u} \simeq 0.5$ GeV *) , $m_{\perp s} \approx 0.6$ GeV, $m_{\perp c} \simeq 1.6$ GeV, then there is a substantial difference in values of the scale factors for the processes with usual hadrons and charmed particles

$$s_0^{\pi N} \simeq 1.5 \text{ GeV}^2 , \quad s_0^{K\Lambda} \simeq 1.9 \text{ GeV}^2, \quad s_0^{\bar{D}\Lambda_c} \simeq 5.5 \text{ GeV}^2 \qquad (9)$$

The t-dependence of residues $g_{ab}(t)$ has been chosen [7] in the form characteristic for dual models

$$\frac{\pi g_{ab}^2(t)}{\sin \pi \alpha_{ii}(t)} = C_{ab}\, g_0^2\, \Gamma(1 - \alpha_{ii}(t)) \qquad (10)$$

where g_0^2 is a universal constant, and C_{ab} is a coefficient dependent on quark content of colliding hadrons. It has been shown in ref. [7] that the form (10) for residues, combined with a nonuniversal form (8) of the factor s_0^{ab} (contrary to the universal factor of dual models $s_0 = (\alpha'_\rho)^{-1}$) allows one to obtain widths of resonances on vector and tensor trajectories, which are in a good agreement with experiment. The

*) For $\pi\pi$ -scattering we thus have $s_0 = 1$ GeV^2, in an agreement with the value $s_0 = (\alpha'_\rho)^{-1}$, used in ref. [5].

constant $g_0^2/4\pi = 2.7$ was determined from the ρ -meson width.

Using this results for diagonal processes we can write the amplitude of the reaction (2) in the form

$$A_{\pi N \to \Lambda_c \bar{D}}(s,t) = C_{\pi^- p} P_{\Lambda_c} g_0^2 \Gamma(1-\alpha_{uc}(t)) \left(-\frac{s}{s_0^{uc}}\right)^{\alpha_{uc}(t)-1} \cdot \left(-\frac{s}{\bar{s}}\right) . \quad (11)$$

The coefficient $C^2_{\pi^- p} = 2$ is connected to a number of planar diagrams in elastic $\pi^- p$ -scattering. The factor P_{Λ_c} corresponds to the projection of the quark state $[ud]c$, where $[ud]$ is diquark-spectator of the initial proton, to the state of Λ_c . Below this factor will be taken equal to 1, taking into account that nearly all charmed baryons in the final state, corresponding to $[ud]c$ -system decay into Λ_c .

In order to determine the parameters of the trajectory $\alpha_{D^*}(t) \equiv \alpha_{uc}(t)$ and the factor s_0^{uc} we will use the probabilistic interpretation [6] , according to which asymptotically at $s \to \infty$ and small $|t|$ inside the Regge-cone , $|t| \lesssim \left(\alpha'_{uc} \ln \frac{s}{s_0^{uc}}\right)^{-1}$ the cross section of the process $\pi N \to \Lambda_c \bar{D}$ can be written in a factorized form in terms of the probabilities $W_{\pi N}$ and $W_{\Lambda_c D}$ (Eq. (5)), i.e.

$$\left(\frac{s}{s_0^{\Lambda c}}\right)^{2(\alpha_{uc}(0)-1)} = W_{\pi N} W_{\Lambda_c D} = \left(\frac{s}{s_0^{\pi N}}\right)^{\alpha_{uu}(0)-1} \cdot \left(\frac{s}{s_0^{\Lambda_c D}}\right)^{\alpha_{cc}(0)-1} \quad (12)$$

From Eq. (12) follows the relation among intercepts of Regge-trajectories, obtained previously in ref. [6]

$$\alpha_{uc}(0) = \frac{\alpha_{uu}(0) + \alpha_{cc}(0)}{2} \quad (13)$$

and the relation among the scale factors

$$\left(s_0^{uc}\right)^{2(\alpha_{uc}(0)-1)} = \left(s_0^{\pi N}\right)^{\alpha_{uu}(0)-1} \cdot \left(s_0^{\Lambda_c D}\right)^{\alpha_{cc}(0)-1} . \qquad (14)$$

The relation among slopes of Regge-trajectories has been obtained in ref. [6] from the s -channel factorization in the b-impact parameter space

$$\left(\alpha'_{uc}\right)^{-1} = \left[\left(\alpha'_{uu}\right)^{-1} + \left(\alpha'_{cc}\right)^{-1}\right]/2 \qquad (13a)$$

The ρ -trajectory $\alpha_\rho(t) \equiv \alpha_{uu}(t)$ is rather well known

$$\alpha_\rho(t) = 0.46 + 0.9t \qquad (15)$$

The trajectory $\alpha_\psi(t) \equiv \alpha_{cc}(t)$ is known with much less accuracy. Its parameters $\alpha_\psi(0)$ and $\alpha'_\psi(0)$ can be found assuming its linearity and exchange degeneracy and using masses of ψ -meson ($J^P = 1^-$) $m_\psi = 3.1$ GeV and χ -meson (2^+) $m_\chi = 3.554$ GeV

$$\alpha_\psi(t) = -2.18 + 0.33t \qquad (16a)$$

Another way to determine the parameters of ψ -trajectory is connected to an assumption that ψ' -meson with mass $m_{\psi'} = 3.686$ GeV lies on a daughter trajectory, parallel to the ψ -trajectory. This gives

$$\alpha_\psi(t) = -3.8 + 0.5t \ . \qquad (16b)$$

Equations (13), (13a) and (15), (16a), (16b) give two sets of parameters for the trajectory $\alpha_{D^*}(t) \equiv \alpha_{uc}(t)$

$$\alpha_{D^*}(t) = -0.86 + 0.5t \tag{17a}$$

$$\alpha_{D^*}(t) = -1.67 + 0.69t \tag{17b}$$

Let us note that for both cases $m_{D^*} \approx 2$ GeV in an agreement with experiment. These two versions are markedly different, so in the following we will make calculations for both sets of parameters.

Equations (14) and (9) give for the scale factor the values

$$s_0^{uc} = 4.9 \text{ GeV}^2 \tag{18a}$$

$$s_0^{uc} = 5.2 \text{ GeV}^2 \tag{18b}$$

Thus the differential cross section of the process $\pi p \to \Lambda_c \bar{D}$ is described by the formula

$$\frac{d\sigma_{\pi N\to\Lambda_c\bar{D}}}{dt} = \frac{1}{16\pi s^2}\left|A_{\pi N\to\Lambda_c\bar{D}}(s,t)\right|^2 = \frac{g_0^4}{8\pi \bar{s}^2}\left[\Gamma(1-\alpha_{D^*}(t))\right]^2\left(\frac{s}{s_0^{uc}}\right)^{2(\alpha_{D^*}(t)-1)} \tag{19}$$

where $g_0^2/4\pi = 2.7$, $\bar{s} = 1$ GeV^2 and $\alpha_{D^*}(t)$, s_0^{uc} are determined by Eqs. (17a), (17b) and (18a), (18b).

Several comments in conclusion of this section:

1) Our parametrization (11) of the two-body process $\pi p \to \Lambda_c \bar{D}$ is similar to one, used by Barger and Phillips in ref. [5]. In particular, Eq. (10) coincides with prescription of ref. [5]. The main difference is in nonuniversal scale factor s_0^{uc} and, because of low intercept $\alpha_{D^*}(0)$, this leads to strong difference in the absolute value of the cross section.

2) The hypothesis of the form of the residue and relations among trajectories, made in this section, have been confirmed in refs. [6,7] by comparing with experiment theoretical predictions for masses, widths of resonances and differences of total cross sections of hadronic interactions. These calculations involve t-region from zero to the mass square of the corresponding resonance.

3) It will be shown below that the diagram 1a, which contains the subprocess $\pi p \to \Lambda_c \bar{D}$, gives very small contribution to the inclusive cross section of Λ_c -production. However, the form and the absolute cross section of this binary process obtained in this section will serve as a basis for normalisation of the cross section $\pi p \to \Lambda_c D_R$, which determines the main contribution of the diagram 1b.

B. Cross section of the process $\pi p \to \Lambda_c D_R$

The hadronic string produced after annihilation of u and $\bar{u}$ quarks of proton and pion can decay, due to production of $c\bar{c}$ -pair, into two heavy parts, which, being unstable themselves, transform into Λ_c , $\bar{D}$ and extra mesons (made mainly of light u,d -quarks). We are interested in the fastest Λ_c , so in this case the $c\bar{c}$ -pair is the fastest of the quark pairs spontaneously produced from vacuum (see Fig.3). The Λ_c -baryon is produced in association with heavy charmed resonances D^*, D^{**} etc. Applying the finite mass sum rules, summary contribution of these resonances to the cross section can be expressed in terms of the contribution of the triple Regge diagram $D^* D^* R$. From the point of view of duality, the contribution of the triple-Regge diagram averages the cross sections of resonances over some mass interval (see Fig. 4), i.e.

$$\int_0^{M_1^2} \frac{d\sigma_{Res}}{dt\, dM^2} dM^2 = \int_0^{M_1^2} \frac{d\sigma_{TR}}{dt\, dM^2} dM^2 \qquad (20)$$

where $\frac{d\sigma_{Res}}{dt\, dM^2}$ is the cross section of $\Sigma^*, D^{**}, \dots$ resonance production, and $\frac{d\sigma_{TR}}{dt\, dM^2}$ is the cross section corresponding to the planar triple-Regge diagram. The triple-Regge cross section can be written in the form

$$\frac{d\sigma_{TR}}{dt\, dM^2} = F(t)\left(\frac{s}{M^2}\right)^{2(\alpha_{D^*}(t)-1)} \cdot \left(M^2\right)^{\alpha_R(0)-2} \qquad (21)$$

where the residue $F(t)$ is some phenomenological function. For normalization of the cross section (21) we take as the interval of duality in Eq. (20) the region of D -meson $(M_D < M_1 = 1.95\,\text{GeV} < M_{D^*})$. Thus we have

$$\frac{d\sigma(\pi p \to \Lambda_c D)}{dt} = \int_0^{M_1^2} dM^2 \frac{d\sigma_{TR}}{dt\, dM^2} . \qquad (22)$$

Comparing Eqs. (22) and (19) at t=0 we obtain

$$F(0) = \frac{g_0^4}{16\pi s_0^2}\left(\alpha_R(0) - 2\alpha_{D^*}(0) + 1\right)\left[\Gamma(1-\alpha_{D^*}(0))\right]^2 \frac{\left(s_0^{\pi c}\right)^{2(1-\alpha_{D^*}(0))}}{\left(M_1^2\right)^{\alpha_R(0) - 2\alpha_{D^*}(0) + 1}} \qquad (23)$$

or for versions (17a), (18a) and (17b), (18b)

$$F(0) = 660\ \text{GeV}^{-6} \qquad (24a)$$

$$F(0) = 5320 \text{ GeV}^{-6} \ . \tag{24b}$$

This method allows us to normalise the cross section of the process (3) at $t \simeq 0$. It would be not justified to determine the t-dependence of the cross sections (19) and (21) at large negative t using duality arguments, because the functional dependence on t in Eq. (19) in the region $s \sim s_{thresh} = (m_{D_R} + m_{\Lambda_c})^2$ and at large $|t|$ is unreliable. So, having fixed the value F(0) by Eqs. (24a) and (24b), we will approximate the t-dependence of the function F(t) at negative t by the exponent $F(0)\exp(R^2 t)$ and will consider R^2 as a free parameter. The value of this parameter will be fixed from a comparison of the theoretical calculation with $p_\perp$ -distribution of Λ_c produced in pp-collisions. The comparison shows that the parameter R^2 can be put equal to zero. Thus we will use the following form for the differential cross section

$$\frac{d\sigma(\pi p \to \Lambda_c D_R)}{dt\, dM^2} = F(0) e^{R^2 t} \left(\frac{s}{M^2}\right)^{2(\alpha_{D^*}(t)-1)} (M^2)^{\alpha_R(0)-2} \tag{25}$$

with F(0), determined by Eqs. (24a), (24b).

Let us compare the cross sections of direct production of D and D^* -mesons. Taking into account in the left-hand part of Eq. (20) both D and D^* -mesons and fixing $M_1 = 2.2$ GeV we obtain $(\sigma_D + \sigma_{D^*})/\sigma_D = (2.4 \div 3.8)$ (in versions (a) and (b)), i.e. the cross section of the vector D^* -meson is 2÷3 times larger than the one for the pseudoscalar D -meson. This seems quite natural.

Cross sections of the processes $\pi p \to K\Lambda$ and $\pi p \to K_R \Lambda$, where K_R denotes the series of strange resonances $K^*, K^{**},\ldots$ are described by equations, analogous to Eqs.(19), (25) with substitution $\alpha_{D^*}(t) \to \alpha_{K^*}(t)$ with the parameters [6]

$$\alpha_{K^*}(0) \simeq 0.35\,, \qquad \alpha'_{K^*} \simeq 0.85\ \mathrm{GeV}^{-2} \tag{26}$$

This corresponds to the following values of the constants S_0^{us} and F(0)

$$S_0^{us} = 1.7\ \mathrm{GeV}^2 \tag{27}$$

$$F(0) = 150\ \mathrm{GeV}^{-6} \tag{28}$$

(In the sum rule (20) the value $M_1^2 = 0.5\ \mathrm{GeV}^2$ has been used in this case).

4. Reaction $pp \to \Lambda_c X$. Numerical results.

The contribution of the planar diagrams to the production of charmed particles in πp collisions has been considered in the previous section. There are no such diagrams in proton-proton collisions. Moreover, even for πp -collisions at sufficiently high energies the contribution of planar diagrams decreases $(\sim 1/\sqrt{s})$ and contributions of nonplanar diagrams, which do not decrease with energy starts to dominate. The diagrams of the cylinder type corresponding to the imaginary part of the Pomeron are the most important. They correspond to multiperipheral configuration of final hadrons with the density of particles in the rapidity space being twice higher than in the planar case.

It is known that inelastic production of particles at high energies is well described by the multiperipheral π -exchange model [9]. The π -exchange contribution, being mainly real, is not dual to the sum of s -channel resonances. Thus we will avoid double counting and will obtain reliable estimate of the cross section, if we assume that the planar and nonplanar parts of the diagram Ib are devided by π -meson exchange and substitute as the lower blob the total cross section of πp -interaction (see Fig. 5). From the point of view of the quark diagrams the contribution of the neutral $u\bar{u}$ -system is equal to the one for $\bar{u}d$. This means that the summary (π^0, η^0, η') -exchange gives the same contribution as π^- -exchange *). Contribution of the diagram Ib can be written in the form

$$d\sigma = \frac{1}{4p_0\sqrt{s}}\, 2\left[128\pi^2 p_1^2 s_1 \frac{d\sigma(\pi p\to\Lambda_c D_R)}{dt_1\, dM^2}\right]\cdot\left(4p_2\sqrt{s_2}\,\sigma_{\pi N}^{(tot)}(s_2)\right)\times$$

$$\times \frac{e^{R_\pi^2 t}}{(t-\mu^2)^2}\,\frac{d^3p_{\Lambda_c}}{(2\pi)^3 2E_{\Lambda_c}}\,\frac{dM^2}{2\pi}\,\frac{ds_2}{2\pi}\, d\tau_2(s_{12}, M^2, s_2) \qquad (29)$$

where p_{Λ_c}, E_{Λ_c} are the momentum and energy of Λ_c , M is the mass of the shower D_R; s_1, t_1 are, respectively, the square of mass of the $(\Lambda_c D_R)$ -system and the square of the momentum transfer in the upper block, s_2 is the square of mass of the lower block, $d\tau_2(s_{12}, M^2, s_2)$ is the two-body phase space of the system, containing D_R and the lower shower of particles, at fixed square of mass s_{12} of this system (calculation of τ_2 includes integration over the square of mass t of the virtual pion).

The factor 2 before the square brackets is due to the sum over $u\bar{u}$ and $d\bar{u}$ quark states.

*) This "effective" pion exchange takes into account at $|t| \gg \mu^2$ also twisted reggeon contributions with $\alpha(0) \simeq 0.5$.

The pion off-mass-shell effects are described by the function $\exp(R_\pi^2 t)$, where the parameter $R_\pi^2 = 0.1$ GeV^2 is chosen in such a way as to forbid very large values of $|t| \gtrsim 10$ GeV^2, which are not connected to the peripheral mechanism .

Integration was carried out numerically with exact phase space. A lower limit on the mass M of the system D_R was chosen to be equal to 2 GeV. For the case of the diagram 1a Eq.(29) is also valid with $M = m_D$, and the factor $\frac{dM^2}{2\pi}$ is absent.

Relative contribution of the diagram 1a is small. The calculation shows that it equals $\approx 30\%$ at $p_L = 50$ GeV/c and $\lesssim 2\%$ at $p_L = 1500$ GeV.

The diagram 1d gives noticable contribution only at not too large energies. In particular, it substantially increases the cross section of Λ_c production at momenta $p_L \simeq 20 \div 100$ GeV for np -collisions. The corresponding formfactor differs, generally speaking, from the one for the diagrams 1a, 1b. In calculations the formfactor of ref. [10] has been used.

The energy dependence of the inclusive cross section of Λ_c production in pp-cillisions is shown in Fig. 6a. Experimental data are from refs. [2,11] (see reviews [12,13]). The curves (a) and (b) in this Figure correspond to the calculation with the sets of parameters (17a), (18a), (24a) and (17b), (18b), (24b), respectively. Despite a big difference in the values of F(0), the final results for the cross sections at large energies are not very different. The cross section quickly increases up to ISR energies and then it flattens.

Let us note that experimental values of the cross sections in the most cases have uncertainty, connected to the assumptions onthe shapes of x_F and $p_\perp$ distributions of charmed particles. The numbers in Fig. 6 correspond to the most realistic version with a flat distribution for Λ_c: $\frac{d\sigma_{\Lambda_c}}{dx_F} \sim const$ and central production of associated $\bar{D}$ -meson: $\frac{d\sigma_{\bar{D}}}{dx_F} \sim (1-x_F)^n$, $n=3$.

The theoretical predictions for the Λ_c cross section in np and $\pi^- p$ -collisions, obtained with an account of the diagram 1d, are shown in Fig. 6b for versions (a) and (b). For $\pi^- p$ -case the contribution of the planar block, which dominates up to $p_L \sim$ 400 GeV is also shown.

The distribution on the Feynman variable of Λ_c -particle is shown in Fig. 7a. Experimental data is from ref. [2]. Both theoretical versions gives flat x_F -distributions. The x_F --distribution for the shower D_R is shown in Fig. 7b. As it was explained above, Λ_c and D_R carry the most part of the momentum of the beam particle. Because the $\bar{D}$ -meson carries the main part of the momentum of the shower D_R, the distribution 6b is similar to the spectrum of $\bar{D}$ -mesons, produced in association with Λ_c.

The $p_\perp^2$ distribution from ref. [2] is compared with theoretical calculation in Fig. 8. This distribution is sensitive to the parameter R^2 in Eq. (25) for the cross section of the upper block. Both versions are in an agreement with experiment within the errors for $R^2 = 0$.

Thus theoretical calculations are in an agreement with experimental data both for the absolute value of the cross sections and for the form of x_F and $p_\perp^2$ distributions. Theoretical predictions have the following uncertainties:

1) There is no reliable information on D^* -trajectory. However, it occurs that even for strong difference of parameters of the trajectory the values of residues, in the framework of this model, compensate to some extent this difference, and the final results for the cross sections are rather close (versions (a) and (b)).

2) A possible D -exchange contribution to the amplitudes of the processes (2) and (3) is not taken into account (contrary to π and ρ or K and K^* -exchanges, the contributions of D and D^* can be rather close). An account of this contribution can increase the cross section by 1.5 ÷ 2 times. Besides, the charmed baryon exchanges can be important at small values of x_F.

3) Account of Regge-cuts in reactions (2) and (3) can lead to ~ double decrease of the corresponding cross sections.

4) We have already pointed out that the calculated cross section corresponds to production of $[ud]c$ -system of quarks, but not of a Λ_c -baryon. In principle, a factor arising from a projection of $[ud]c$ onto Λ_c system should be taken into account. However, experimentally measured cross section include both direct Λ_c production and its production due to a decay of heavier charmed baryons of the type Σ_c^+, Λ_c^*, ... So in the comparison with experiment it is rather safe to put the projection factor P_{Λ_c} equal to one. For strange Λ hyperon projecting the $[ud]s$ onto Λ -state is more important.

5) It should be taken into account discussing the total cross sections of charmed particles production that there is another

independent mechanism connected to the short distances, which gives the main contribution at small x_F .

Role of the factors, discussed in (3) and (4) can be estimated by comparison of theoretical calculations with experimental data on strange hyperon production. Inclusive cross section of Λ -production is described by equations of the type of Eqs. (19), (25), (29) with parameters (26)-(28). The calculation shows that the results should be multiplied by a factor $F \sim 1/3$, in order to describe $d\sigma_\Lambda/dx_F$ in the fragmentation region. This factor characterize a role of the effects, discussed in (3) and (4). The contributions of the diagrams 1a and 1b for Λ - hyperons are of the same order of magnitude.

For charmed baryon production the effects, discussed in (2), and (3), and (4) to large extent compensate each other.

Conclusions

The comparison of the predictions of the peripheral quark--gluon model with experimental data on charmed baryon production gives an evidence in favor of this mechanism.

What is the relation between the proposed peripheral model and the hypothesis of the "intrinsic charm", suggested in ref. [3] ? Peripheral effects, connected to a mesonic cloud (containing charmed particles) around the proton, are the important consequences of nonperturbative mechanism. In the inifinite momentum frame peripheral diagrams can be interpreted as an admixture of mesonic states ($q\bar{q}$-pairs) in a nucleon. On the other hand, the interpretation of the peripheral interaction as production and subsequent fission of a hadronic string allows another possibility. Fission of the string due to spontaneous production of $c\bar{c}$ -pair from vacuum happens in time later, than the quark-antiquark annihilation. This does not correspond to "intrinsic charm" in proton. Thus our model is more general than the "intrinsic" charm hypothesis and can be valid also in the case when there are no $c\bar{c}$ -pairs in the fast moving proton and all charmed quarks are produced in the process of interaction via decay of a string.

In addition to the "intrinsic charm" hypothesis an extra assumption on the diffractive character of charmed particle production has been made in ref. [3] . In this connection, we make several comments. First, in this case it is more consistent to estimate an admixture of charm as a ratio $\sigma_{\Lambda_c}/\sigma_{dd}$, where σ_{dd} is the cross section of diffraction dissociation, but not as a ratio $\sigma_{\Lambda_c}/\sigma_{NN}^{(tot)}$ [3] . This would considerably increase the estimate of "intrinsic charm" made in ref. [3] . Second, it was assumed in ref. [3] that dependence on the mass of a shower for diffraction dissociation into charmed particles is the same as for a shower of usual hadrons, $-\ \frac{d\sigma}{dM^2} \sim 1/M^2$. This is true only for a triple-pomeron contribution, when a number of particles in a shower is not fixed and rises logarithmically with its mass M. For dissociation of a proton into nucleon and pion, for example, $\frac{d\sigma}{dM^2} \sim 1/(M^2)^3$, and for $\Lambda_c\bar{D}$ we can expect that this dependence is determined by the exchange of D^* -trajectory: $\frac{d\sigma}{dM^2} \sim 1/(M^2)^{3-2\alpha_{D^*}(0)}$. This sharp decrease with M^2 leads to the cross section, which practically does not depend on energy in the Fermilab - ISR energy region. This contradicts to experimental data.

However, the assumption on the diffraction character of charmed particles production is unnecessary for the hypothesis of intrinsic charm. For usual multiperipheral mechanism both arguments, mentioned above, are not valid.

Production of the $c\bar{c}$ -pair by gluon fusion (described by QCD perturbation theory) is a mechanism competing to the peripheral mechanism, considered in this article. While in the light hadron production the peripheral mechanism dominates, the charmed particle production is an intermediate case, where both mechanisms can give comparable contributions. The detailed experimental investigation of different kinematical regions (small x_F, large $p_\perp$), probably, will give a possibility to separate contributions of these mechanisms. A contribution of the peripheral mechanism fastly decreases with a mass of a quark, because firstly the intercepts of the corresponding trajectories become lower and, secondary, the value of t_{min} (minimal momentum transfer) increases for heavier particles. So, we expect that production of particles with b-quarks is mainly described by the perturbation theory diagrams.

In conclusion we note that the most straightforward test of the model, proposed in this paper, can give experiments of charmed baryon production in πp -collisions, where planar diagrams give important contribution.

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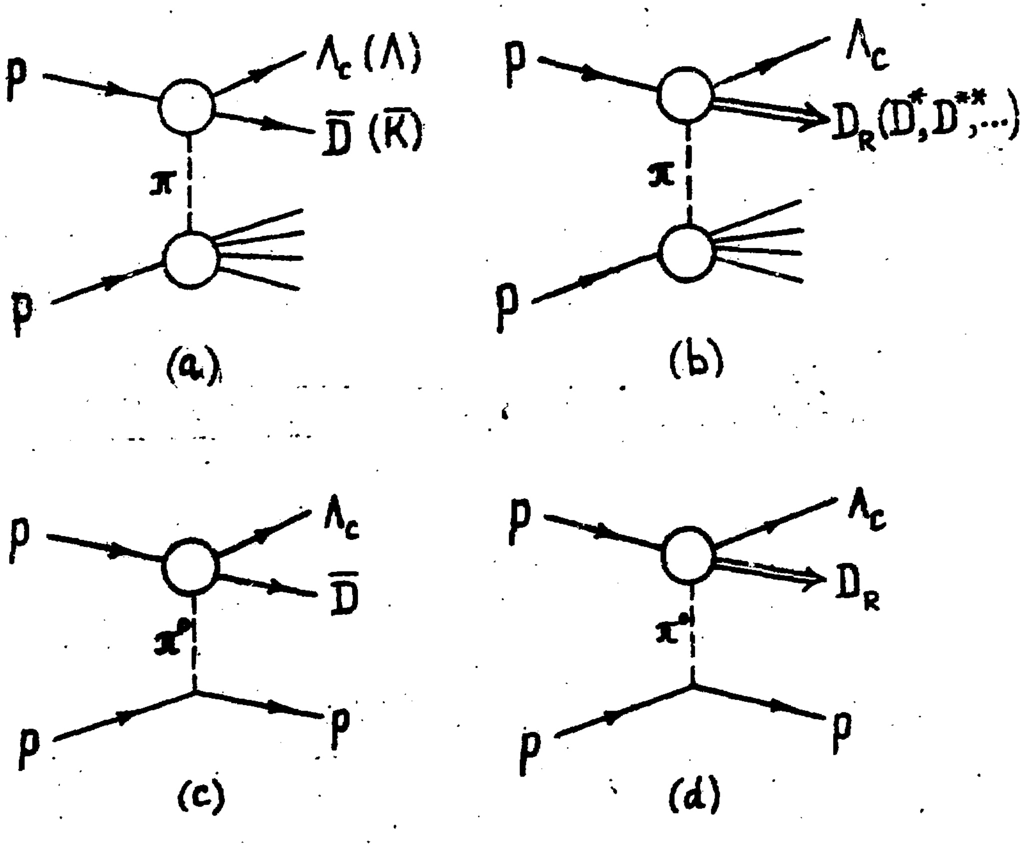

Fig. 1. Diagrams for production of $\Lambda_c\,(\Lambda)$ baryons in pp collisions.

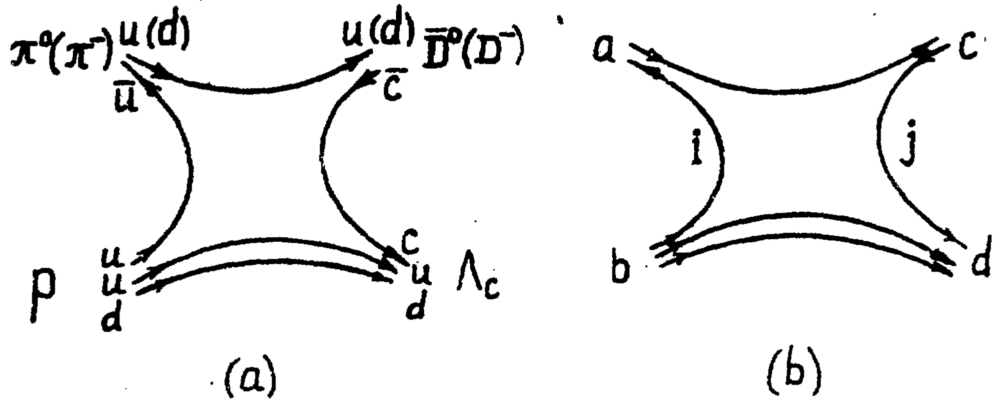

Fig. 2. Planar quark diagrams for two-particle processes.

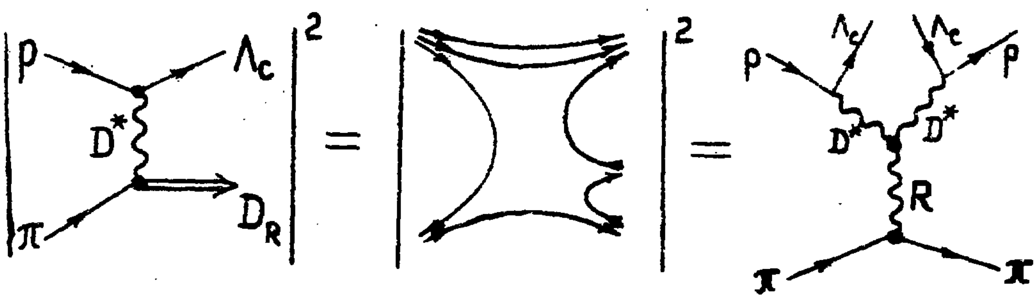

Fig. 3. Relation between the cross section of the jet planar production and the reggeon diagram.

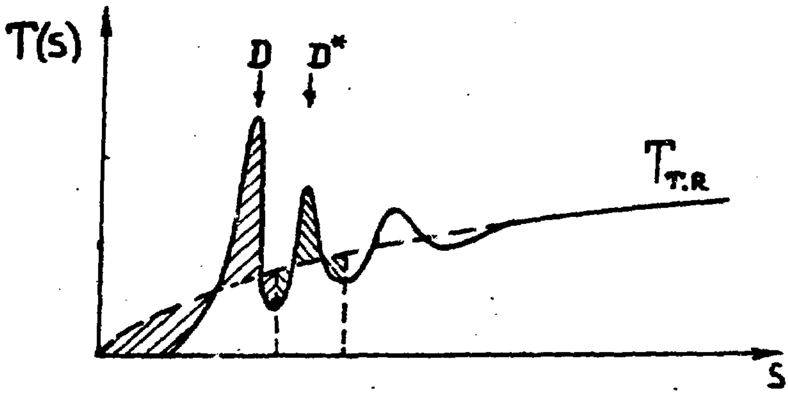

Fig. 4. Duality of the resonance and reggeon contributions.

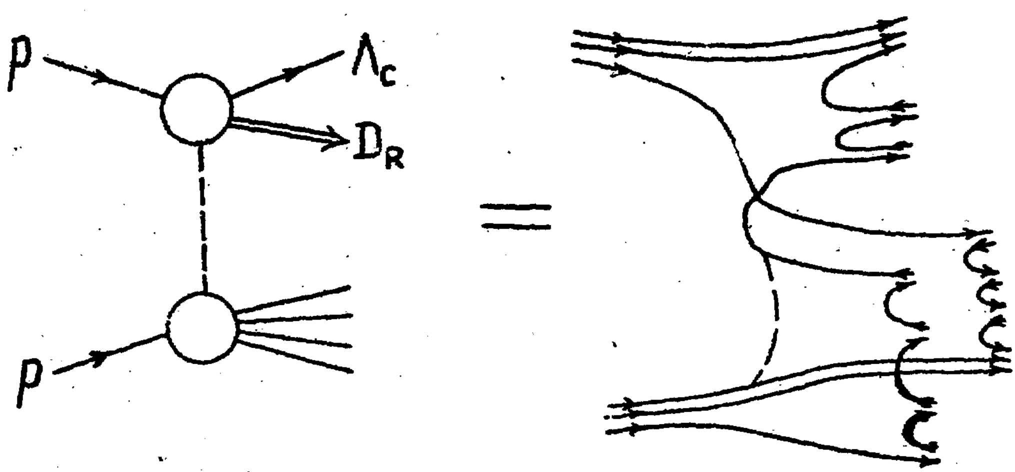

Fig. 5. Correspondence between the quark non-planar diagram and pion-exchange diagram.

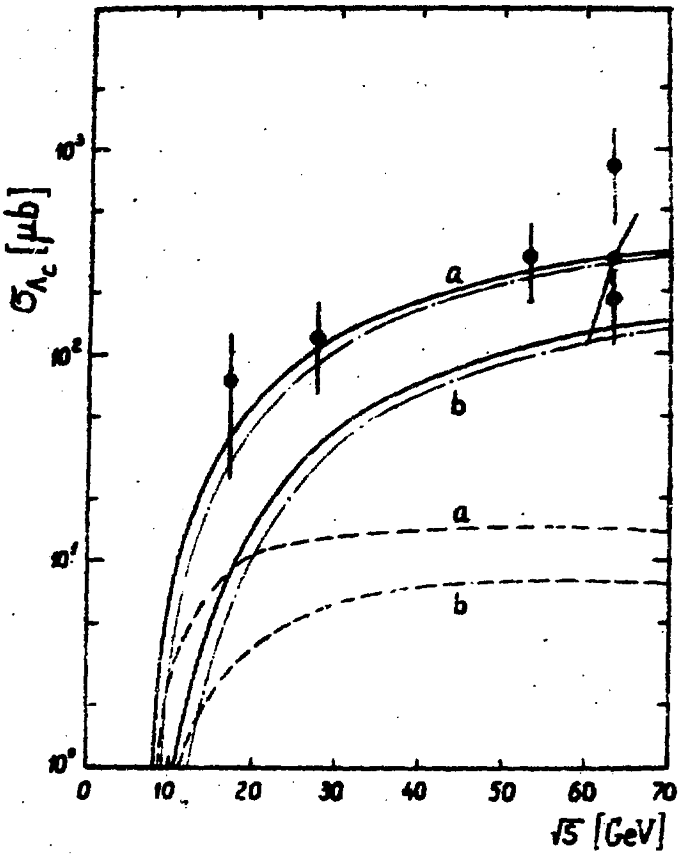

Fig. 6. Energy dependence of Λ_c -baryon production in hadron-hadron collisions.

a) pp interaction. The experimental data are from ref. [2,22] . The theoretical predictions correspond, respectively, to the variants (a) and (b) (see the text). The dashed-dotted curves describe the contribution given by the diagram 1b; dashes are the same for the diagram 1d.

b) Predicted cross sections for the processes $np \to \Lambda_c X$ and $\pi^- p \to \Lambda_c X$ for the variants (a) and (b). The dashed curves correspond to the planar diagram contribution.

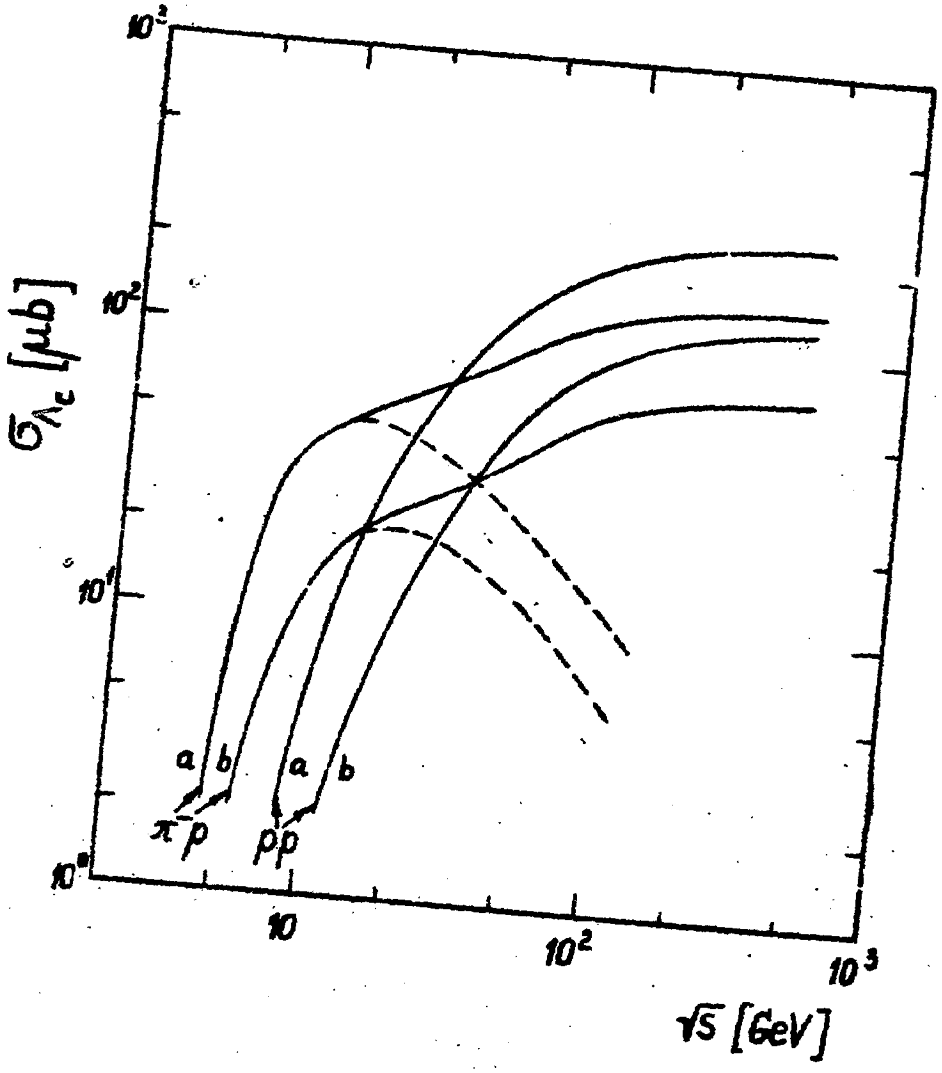

Fig. 6b

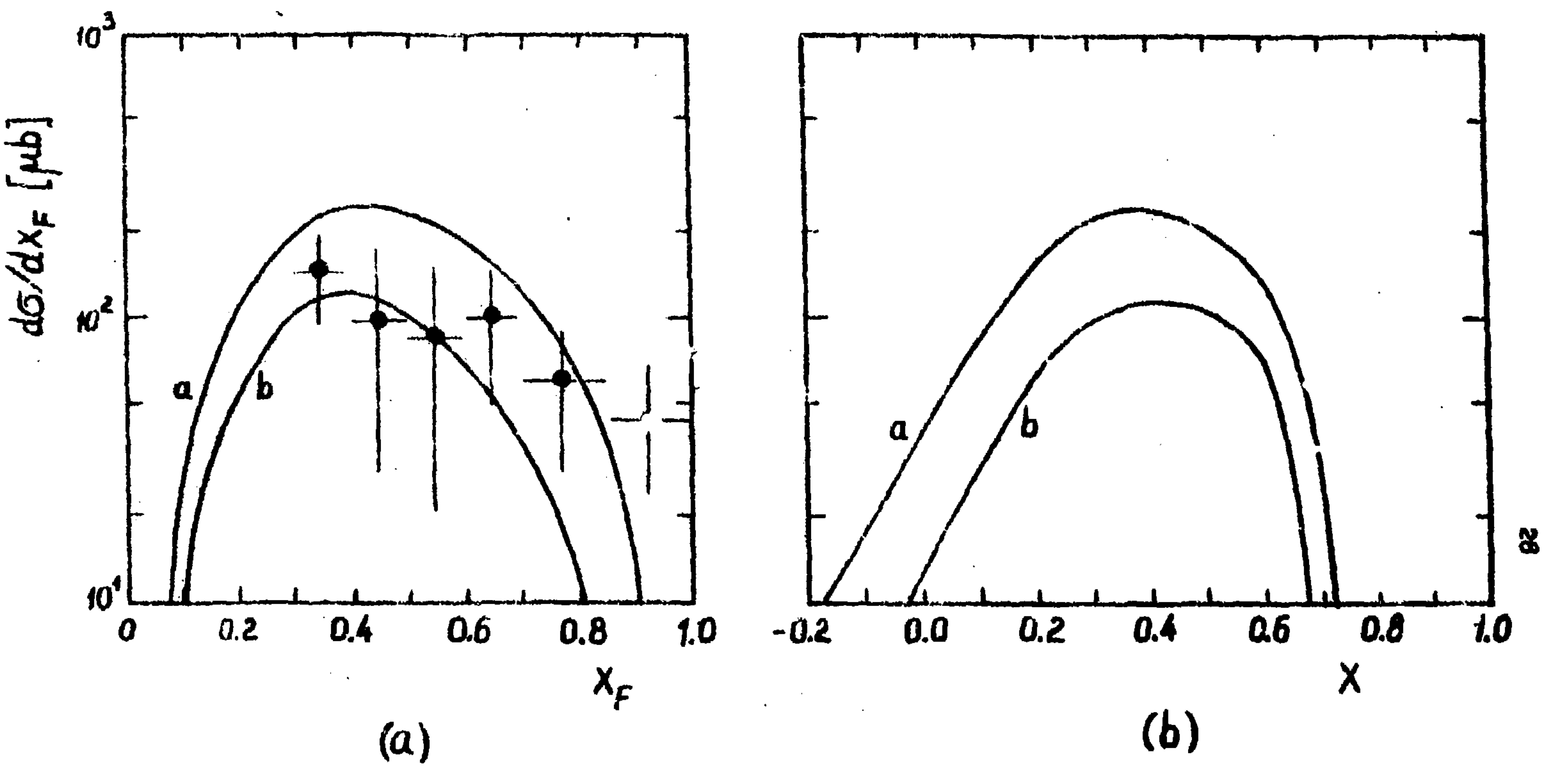

Fig. 7. a) The distribution in the Feynman variable x_F for Λ_c hyperons in the $pp \to \Lambda_c X$ [2] process. The theoretical curves correspond to the variants (a) and (b).

b) Distribution in the Feynman variable for system D_k

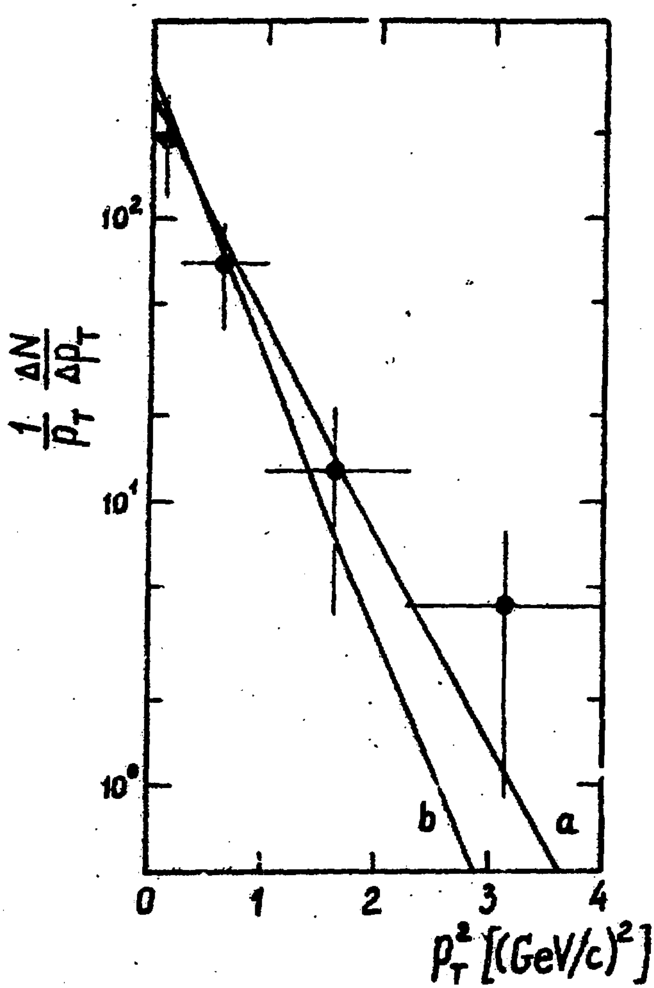

Fig. 8. The $p_\perp^2$ distribution for the $pp \to \Lambda_c X$ process. The data are from ref. [2] . The theoretical curves correspond to the variants (a) and (b).

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