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ON LEADING CHARMED MESON PRODUCTION IN π-NUCLEON INTERACTIONS

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О рождении лидирующих очарованных мезонов в π-нуклонных взаимодействиях

Показано, что лишь D-мезон, легкий кварк которого является валентным кварком пиона, а очарованный кварк рожден в аннигиляции валентных кварков начальных адронов и имеет достаточно большой импульс, является лидирующим мезоном в реакции типа $\pi^- p \to DX$. Если такой аннигиляции валентных кварков из начальных адронов произойти не может, то не должно быть и ярко выраженного эффекта лидирования.

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On Leading Charmed Meson Production in π-Nucleon Interactions

It is shown that the D-meson, whose light quark is the initial-pion valence quark and whose charmed quark is produced in annihilation of valence quarks and has got a large enough momentum, is really a leading meson in reactions like $\pi^- p \to DX$. If such annihilation of valence quarks from initial hadrons is impossible, there must be no distinct leading effect.

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

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Recently the E769 collaboration [1] has reported confirmation of previously obtained [2] enchanced leading production of $D^{\pm}$- and $D^{*\pm}$-mesons in 250 GeV $\pi^{\pm}$–nucleon interaction. A leading charmed meson is considered to be one with the longitudinal momentum fraction $x_F > 0$, whose light quark (or anti-quark) is of the same type as one of the quarks in the beam particle. At large x_F significant asymmetry was found:

$$A(x_F) \equiv \frac{\sigma(\text{leading}) - \sigma(\text{non-leading})}{\sigma(\text{leading}) + \sigma(\text{non-leading})}. \qquad (1)$$

Such asymmetry for the production of charmed hadrons is not expected in perturbative quantum chromodynamics.

Some years ago a simple non-perturbative mechanism of leading charmed mesons production was considered [3] for data analysis of CERN experiment on D-mesons production in π^-p-collisions [4]. It was demonstrated that presence of a valence quark from the initial pion (so-called leading quark state) in the final charmed meson is a necessary but insufficient condition for the meson to be a leading one. Actually, those D are leading mesons whose light quarks are valence quarks of the pion *and* charmed quarks are produced in annihilation of valence quarks and carry a large momentum x_c.

The leading effect is a characteristic property of inclusive production of charmed hadrons [5]. A hadron H produced in the reaction $a + b \to H + \ldots$ and carrying the largest portion of the momentum, $p_H = O(\sqrt{s}/2)$, is regarded as a leading hadron. The corresponding momentum spectrum dN/dx_F usually parametrized in the form $(1 - x_F)^n$ at a large Feynman variable $x_F = \frac{2}{\sqrt{s}}P_{\|}$ is "hard" for leading hadrons ($0 < n \lesssim 3$) and "soft" for non-leading ones ($n \gtrsim 5$).

In the quark-parton approach the leading charmed meson H is a result of recombination of the spectator valence quark q_v with the charmed quark produced in a parton subprocess. Owing to the large momentum of the valence quark x_v H turns to be a leading meson, its momentum is large enough $x_H = x_v + x_c > x_v$.

From this point of view $D^-(d\bar{c})$ and $D^\circ(\bar{u}c)$ directly produced in the reaction $\pi^-(d\bar{u}) + p \to D(d\bar{c}; \bar{u}c) + X$ must be both leading mesons, i.e., yields of $D^-(d\bar{c})$ and $D^\circ(\bar{u}c)$ have to be practically the same at large momentum (say, $x_F > 0.5$).

On the other hand, let us assume for a moment that hadrons consist of valence quarks alone. This picture takes place, for instance, in deep inelastic phenomena at quite large x_F, when all non-singlet parton distribution functions vanish.

In this case $D^\circ(\bar{u}c)$–mesons can by no means result form the reaction $\pi^-(d\bar{u}) + p(uud) \to D + X$ because there is no parton subprocess which can ensure c-quark creation. On the other hand, the $\bar{c}$–quark appears due to valence quarks annihilation $\bar{u}_v^\pi u_v^p \to c\bar{c}$, providing the $D^-(d\bar{c})$–meson in the final state. It is clear that some difference in π^--nucleon production of leading $D^\circ(\bar{u}c)$ and $D^-(d\bar{c})$–meson has to take place at sufficiently large x_F. To demonstrate this feature quantitatively let us follow briefly the work [3].

The invariant differential cross section for the process $\pi^-p \to DX$ in the centre-of-mass system at the energy $\sqrt{s}$ and $x_F > 0$ can be written down in the form [6]:

$$x^* \frac{d\sigma}{dx\, dp_T^2} = \exp\{-2p_T^2/\sqrt{s}\} \int R(x_{sp}, x_c; x) \frac{dx_{sp}}{x_{sp}} \frac{dx_c}{x_c^*} \left\{ \frac{x_c^* x_{sp} d\sigma}{dx_{sp} dx_c dp_T^2} \right\}. \qquad (2)$$

Here $x \equiv x_F$, x_{sp}, x_c are the Feynman variables of $D^-(D^\circ)$–meson, spectator $d(\bar{u})$- and produced $\bar{c}(c)$–quark; $x^* = 2E_D/\sqrt{s}$, $x_c^* = 2E_c/\sqrt{s}$.

The phenomenological recombination function [6], [7] $R(x_{sp}, x_c; x) \sim \delta(x - x_{sp} - x_c)$ provides a probability of producing a $D^-(D^\circ)$–meson (with the momentum x) by means of a $d(\bar{u})$–quark (x_{sp}) and a $\bar{c}(c)$–quark (x_c).

The probability of existence of spectator $d(\bar{u})$-quark and charmed $\bar{c}(c)$–quark is determined by the expression:

$$\frac{x_c^* x_{sp}\, d\sigma}{dx_{sp} dx_c dp_T^2} = x_{sp} \int dx_L dx_R \sum_{i=q,\bar{q},g} f^\pi_{d(\bar{u})i}(x_{sp}, x_L) f_i^p(x_R) \frac{x_c^* d\sigma}{dx_c dp_T^2}. \qquad (3)$$

Here $\frac{x_c^* d\sigma}{dx_c dp_T^2}$ is the quantum–chromodynamics cross section for the charm production parton subprocess $i\bar{i} \to c\bar{c}$ [8]. The single-particle proton distribution functions, $f_i^p(x_R)$, are extracted from deep inelastic lepton-proton scattering [9]. The analytical form of two-particle pion distribution functions, $f^\pi_{vi}(x_{sp}, x_L)$, is given in the statistical parton model [6], [10]. The free parameters of these analytical forms can be fixed via comparison with the data.

It is clear from relation (3) that the above-mentioned difference in yields of $D^\circ(\bar{u}c)$ and $D^-(d\bar{c})$- mesons mainly arises due to different contributions of distribution functions: $\sum f^\pi_{vi} \cdot f_i^p$.

For a D°–meson the sum is

$$\sum D^\circ = f^\pi_{vv} \cdot f_s^p + f^\pi_{vs} \cdot (3f_v^p + 6f_s^p). \qquad (4)$$

For a D^-–meson we have

$$\sum D^- = f^\pi_{vv}\cdot f^p_s + f^\pi_{vs}\cdot(3f^p_v + 6f^p_s) + 2f^\pi_{vv}\cdot f^p_v = \sum D^\circ + 2f^\pi_{vv}\cdot f^p_v, \qquad (5)$$

where index v corresponds to valence quarks and s to sea quark. For simplicity flavour symmetric distributions were used and the gluon contribution was omitted.

Therefore the total momentum spectrum of D^- and D°–meson production in $\pi^- p$-collisions can be put down in the form

$$\frac{d\sigma}{dx}(D^- + D^\circ) = 2\frac{d\sigma}{dx}(D^\circ) + \frac{d\sigma}{dx}(v). \qquad (6)$$

This formula was used for fixing distribution functions f^π_{vi} by means of comparison with the data on leading D–meson production in $\pi^- p$–collisions at $\sqrt{s} = 26$ GeV [4].

It was obtained that the "valence" component, $\frac{d\sigma}{dx}(v)$, due to "hard" shape of valence distributions, ensured the non-vanishing total spectrum for $x_F \gtrsim 0.5$. At low x_F the total spectrum was saturated by the other component – $\frac{d\sigma}{dx}(D^\circ)$.

The term $\frac{d\sigma}{dx}(v)$ makes no contribution to the spectrum of D°–mesons (see formula (4)), therefore the yield of neutral D°–mesons at large x_F is small enough.

Figure 1 shows the ratio:

$$R(x_F) = \frac{\frac{d\sigma}{dx}(\pi^- p \to D^\circ X)}{\frac{d\sigma}{dx}(\pi^- p \to D^- X)}, \qquad (7)$$

which quantitatively illustrates the suppression of the D° yield as compared with the D^- one. The experimental points are recalculated from combined data on asymmetry A (1) measured on nuclei [1]. The curves obtained in paper [3] and considered as predictions successfully fit the new data [1].

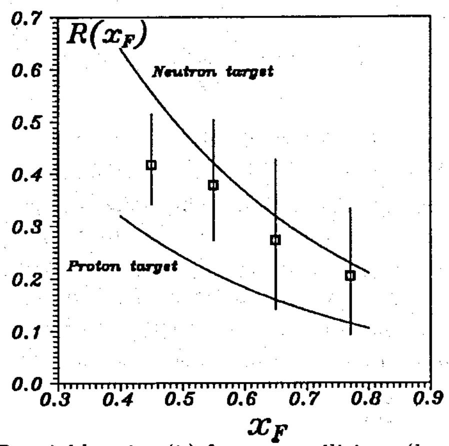

Fig. 1. D°-to-D^- yield ratios (7) for $\pi^- p$-collisions (lower curve) and $\pi^- n$-collisions (upper curve). The points are recalculated from the data on asymmetry A [1]

Figure 2 shows two curves for asymmetry A (1), calculated on the basis of the ratio (7). The curves also describe the data well.

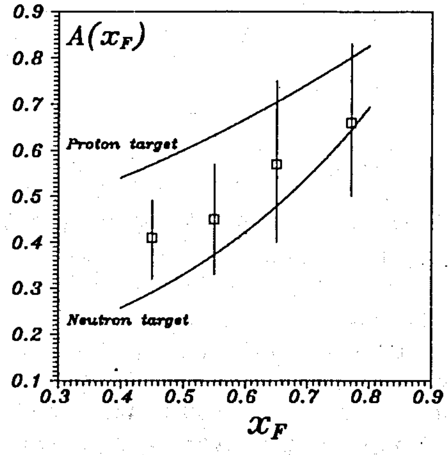

Fig. 2. Asymmetry A (1) on the proton target (upper curve) and the neutron target (lower curve) calculated on the basis of the ratio (7). The data from ref. [1]

Thus it is demonstrated that presence of a valence quark from the initial hadron (as a spectator) in the final charmed meson is a necessary but insufficient condition for the meson to have a "hard" momentum spectrum (i.e., to be a leading meson).

Actually, the D-meson is a "real" leading meson whose light quark is a spectator valence quark and charmed quark (anti-quark) is produced in annihilation of valence quarks from initial hadrons.

In addition, it is easy to construct relations like (7) for reactions similar to $\pi^- p \to DX$. Thus we have for $x_F > 0.5$ (denominators show the leading mesons):

$$\frac{\sigma(\pi^+ n \to D^+ X)}{\sigma(\pi^+ n \to D^\circ X)} = \frac{\sigma(\pi^+ \bar{p} \to D^\circ X)}{\sigma(\pi^+ \bar{p} \to D^+ X)} = \frac{\sigma(\pi^- \bar{n} \to D^- X)}{\sigma(\pi^- \bar{n} \to D^\circ X)} = R(x_F);$$

$$\frac{\sigma(K^- p \to D^\circ X)}{\sigma(K^- p \to D^-_s X)} = \frac{\sigma(K^+ p \to D^\circ X)}{\sigma(K^+ p \to D^+_s X)} = R(x_F);$$

$$\frac{\sigma(\pi^-\bar{p} \to D^- X)}{\sigma(\pi^-\bar{p} \to D^\circ X)} = \frac{\sigma(\pi^+ p \to D^+ X)}{\sigma(\pi^+ p \to \bar{D}^\circ X)} = \frac{\sigma(\pi^- n \to D^\circ X)}{\sigma(\pi^- n \to D^- X)} = 2R(x_F);$$

$$\frac{\sigma(\pi^+\bar{n} \to \bar{D}^\circ X)}{\sigma(\pi^+\bar{n} \to D^+ X)} = \frac{\sigma(K^- n \to \bar{D}^\circ X)}{\sigma(K^- n \to D_s^- X)} = \frac{\sigma(K^+ \bar{n} \to \bar{D}^\circ X)}{\sigma(K^+ \bar{n} \to D_s^+ X)} = 2R(x_F).$$

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