On leading charmed meson production in $\pi$-nucleon interactions

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Abstract

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 $\pi^- p \rightarrow DX$. If such annihilation of valence quarks from initial hadrons is impossible there must be no distinct leading effect.

Recently the E769 collaboration [1] has reported confirmation of previously obtained [2] enhanced leading production of $D^\pm$- and $D^{\ast\pm}$-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:

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

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 $\pi^- p$-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 $a + b \rightarrow H + \ldots$ 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 parametrised in the form $(1 - x_F)^n$ at a large Feynman variable $x_F = \frac{2}{\sqrt{s}}P_\parallel$ 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 $x_H = x_v + x_c > x_v$. 

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From this point of view $D^-(d\bar{c})$ and $D^0(\bar{u}c)$ 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 $D^0(\bar{u}c)$ 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 $D^0(\bar{u}c)$–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 $\bar{u}_v^s u_v^p \to c\bar{c}$, providing the $D^-(d\bar{c})$–meson in the final state. It is clear that some difference in $\pi^-$–nucleon production of leading $D^0(\bar{u}c)$ 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 [3]:

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

Here $x \equiv x_F$, $x_{sp}$, $x_c$ are the Feynman variables of $D^-(D^0)$–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 [3], [7] $R(x_{sp}, x_c; x) \sim \delta(x - x_{sp} - x_c)$ provides a probability of producing a $D^-(D^0)$–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:

$$x^*_s x_{sp} \frac{d\sigma}{dx_{sp} dx_c dp_T^2} = x_s \int dx_L dR \sum_{i=q, u, d} f_{v i}^p(x_{sp}, x_L) f_{v i}^R(x_R) \frac{x^*_s d\sigma}{dx_c dp_T^2}. \quad (3)$$

Here $\frac{x^*_s d\sigma}{dx_c dp_T^2}$ is the quantum–chromodynamics cross section for the charm production parton subprocess $\bar{u}u \to c\bar{c}$ [3]. The single-particle proton distribution functions, $f_{vi}(x_R)$, are extracted from deep inelastic lepton-proton scattering [5]. The analytical form of two-particle pion distribution functions, $f_{vi}^p(x_{sp}, x_L)$, is given in the statistical parton model [3], [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 $D^0(\bar{u}c)$ and $D^-(d\bar{c})$–mesons mainly arises due to different contributions of distribution functions: $\sum f_{v i}^\pi f_{v i}^p$.

For a $D^0$–meson the sum is

$$\sum D^0 = f_{v v}^\pi f_{v v}^p + f_{v s}^\pi f_{v s}^p (3 f_{s}^p + 6 f_{s}^p). \quad (4)$$
For a $D^-$ meson we have

\[ \sum D^- = f_{v\pi}^v \cdot f_s^p + f_{v\pi}^v \cdot (3f_{v}^p + 6f_{v}^p) + 2f_{v\pi}^v \cdot f_v^p = \sum D^0 + 2f_{v\pi}^v \cdot f_v^p , \tag{5} \]

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 $D^0$ meson production in $\pi^- p$-collisions can be put down in the form

\[ \frac{d\sigma}{dx}(D^- + D^0) = 2\frac{d\sigma}{dx}(D^0) + \frac{d\sigma}{dx}(v) . \tag{6} \]

This formula was used for fixing distribution functions $f_{v\pi}^v$ 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 $-\frac{d\sigma}{dx}(D^0)$.

The term $\frac{d\sigma}{dx}(v)$ makes no contribution to the spectrum of $D^0$–mesons (see formula (4)), therefore the yield of neutral $D^0$–mesons at large $x_F$ is small enough.

Figure 1 shows the ratio:

\[ R(x_F) = \frac{\frac{d\sigma}{dx}(\pi^- p \rightarrow D^0 X)}{\frac{d\sigma}{dx}(\pi^- p \rightarrow D^- X)} , \tag{7} \]

which quantitatively illustrates the suppression of the $D^0$ 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 a predictions successfully fit the new data [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.

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 $\pi^- p \rightarrow DX$. Thus we have for $x_F > 0.5$ (denominators show the leading mesons):

\[ \frac{\sigma(\pi^+ n \rightarrow D^+ X)}{\sigma(\pi^+ n \rightarrow D^0 X)} = \frac{\sigma(\pi^+ \bar{p} \rightarrow \bar{D}^0 X)}{\sigma(\pi^+ \bar{p} \rightarrow D^0 X)} = \frac{\sigma(\pi^- \bar{n} \rightarrow D^0 X)}{\sigma(\pi^- \bar{n} \rightarrow D^+ X)} = R(x_F) ; \]
\[
\frac{\sigma(K^-p \to \bar{D}^0X)}{\sigma(K^-p \to D^-sX)} = \frac{\sigma(K^+\bar{p} \to D^0X)}{\sigma(K^+\bar{p} \to D^+sX)} = R(x_F);
\]

\[
\frac{\sigma(\pi^-p \to D^-X)}{\sigma(\pi^-p \to D^0X)} = \frac{\sigma(\pi^+p \to D^+X)}{\sigma(\pi^+p \to D^0X)} = \frac{\sigma(\pi^-n \to D^0X)}{\sigma(\pi^-n \to D^-X)} = 2R(x_F);
\]

\[
\frac{\sigma(\pi^+\bar{n} \to \bar{D}^0X)}{\sigma(\pi^+\bar{n} \to \bar{D}^+X)} = \frac{\sigma(K^-n \to \bar{D}^0X)}{\sigma(K^-n \to \bar{D}^-sX)} = \frac{\sigma(K^+\bar{n} \to \bar{D}^0X)}{\sigma(K^+\bar{n} \to \bar{D}^+sX)} = 2R(x_F).
\]

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Figure Captions

Fig. 1. $D^0$–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 $A(1)$.

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].
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