DEUTERON DISINTEGRATION IN QUARK-PARTON MODEL

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Abstract

The deuteron disintegration process with the emission of fast proton in the vicinity of the kinematical boundary of the reaction, when Feynman variable \( x \to 2 \), is studied. The consideration is fulfilled in the framework of the quark-parton model of cumulative phenomena based on perturbative QCD calculations of the corresponding quark diagrams near the thresholds, at which some quarks ("donors") in the nuclear flucton transfer all their longitudinal momenta to the distinguished active quarks and become soft. The presence of the multi-quark \( 6q \)-configuration in a deuteron is essentially exploited in the consideration. The different versions of hadronization mechanisms of the produced cumulative quarks into cumulative particles are analyzed. It is shown that in the case of the production of cumulative protons from deuteron the hadronization through the coalescence of three cumulative quarks is favorable and leads to the \( (2 - x)^5 \) cross section threshold behavior whereas the usual hadronization through one cumulative quark fragmentation into proton the same as the calculations predicts for the deuteron structure function \( F_2^d(x) \) at \( x \to 2 \) in DIS processes. The results of the calculations are compared with the available experimental data.

1 Introduction

The paper is devoted to the investigation of the cumulative phenomena on deuteron at \( x \to 2 \) in terms of scaling variable \( x \), defined for the interaction with single nucleon. This limit is of especial interest as in the vicinity of the kinematical boundary of the reaction the quantity \( 2 - x \) can be considered as a small parameter on which some perturbative scheme can be developed. Note the uniqueness of deuteron in this respect, it is practically impossible to hope to reach experimentally the vicinity of the kinematical boundary \( x \to A \) for any other nucleus.
It is clear that in this limit we have to use $6q$-language for the description of deuteron, as in this case the typical internucleon distances are smaller than the mean nucleon radius. The attempts to stay at the nucleon level of analysis lead to the uncertainties in the so-called relativization procedure for the $NN$ wave function. The origin of these difficulties is well known: it is the principal impossibility to develop the self-consistent theory of the relativistic bound state with fixed number of interacting constituents as in this case the particle number operator do not commutate with the Hamiltonian.

The quark approach to the description of the processes on nuclei is being developed during the long period of time (see, for example [1]-[6]). In the paper [7] it was pointed out on the possibility to use the perturbative QCD calculations near the threshold, at which quarks transfer all their longitudinal momenta to the distinguished active quark and become soft. In papers [8]-[10] we have applied this idea for the description of the cumulative phenomena at large $x$, $x \gg 1$.

2 Obtained results

In this paper we compare two mechanisms of the fast ($x \to 2$) cumulative particle production in the deuteron disintegration process. The first mechanism is the production of one fast quark and its subsequent fragmentation into cumulative particle. This mechanism was studied in our papers [8]-[10], as one responsible for the cumulative meson production. For the process of deuteron fragmentation into pion with $x_\pi \to 2$ it corresponds to the diagram of the type shown in Fig. 1. Recall it’s just the process from which the intensive experimental investigations of cumulative phenomena have been started [11]. As $x_\pi \to 2$ then for the longitudinal momentum of the fast quark we also have $x \to 2$. In result, all $x_i \to 0$ for $i \geq 2$, which enable to apply the perturbative QCD scheme of [4] for the calculation of this process. As a result we find for the behavior of the inclusive cross section integrated over the transverse momentum in the vicinity of the kinematical boundary of the reaction:

$$I_{\text{frag}}^d(x) \sim (2 - x)^9 \quad \text{at} \quad x \to 2$$

(1)

It’s the same as for the behavior of the deuteron structure function in the DIS process:

$$F_2^d(x) \sim (2 - x)^9 \quad \text{at} \quad x \to 2$$

(2)
The second mechanism is the production of several fast quarks and their coalescence into cumulative particle. It was pointed out in our paper [10], that in the case of the production of cumulative protons the hadronization through the coalescence of three cumulative quarks is favorable than the usual hadronization through one cumulative quark fragmentation into proton. For the process of deuteron fragmentation into proton with $x \to 2$ it corresponds to the diagram in Fig. 2. As $x = x_1 + x_2 + x_3 \to 2$ then all $x_i \to 0$ for $i \geq 4$, which enable again to apply the perturbative QCD scheme of [7] for the calculation of the process. As a result we find for the behavior of the inclusive cross section of the cumulative proton production in the vicinity of the kinematical boundary of the reaction:

$$I_{\text{coal}}^d(x) \sim (2 - x)^5 \quad \text{at} \quad x \to 2$$

Preliminary comparison with the experimental data [12] on the process of deuteron fragmentation into proton in the vicinity of the kinematical boundary of the reaction, at $x$
close to 2, shows that the behavior (3) of the inclusive cross section corresponding to the coalescence mechanism is compatible with the data and the behavior (1) of the inclusive cross section corresponding to the fragmentation mechanism is incompatible with the data on cumulative proton production.

3 Used approach and details

First of all we shortly review the approximations made in the process of diagram calculations. In Fig. 1 $\psi_f(x'_i, k'_{i\perp})$ is the soft parton wave function of the 6$q$-flucton. Following [7] we use hard gluon exchanges to calculate the asymptotic behavior of the parton wave function at $x_1 = x \to 2$ and $x_i \to 0$, for $x_i \geq 2$. Following [7] we choose the Coulomb gauge in which transverse part of gluon exchanges is damped at low $x_i$ and the dominating Coulomb part is

$$x'_1 \frac{x_1}{x'_2} x_2 = 4\pi \alpha (x_1 + x'_1)(x_2 + x'_2) \frac{(x_1 - x'_1)^2}{(x_1 - x'_1)^2}.$$  

For these light cone QCD calculations "old" time ordered perturbation scheme is convenient. In this scheme we have for the "internal" (between the gluon exchanges) quark propagators:

$$\frac{x'_i}{x_i} = \frac{1}{x_i}$$

As a result in the framework of this scheme (or integrating over $k'_{i\perp}$ and $k_{i\perp}$ momentum components in the usual Feynman diagram approach) we find for the diagram in Fig. 1:

$$I^d_{\text{frag}}(x) = \frac{4\pi^4}{9!} (2 - x)^9 w_2 J_5 \left| \int \varphi_t(x'_1 \ldots x'_6)W_{\text{frag}}(x'_1 \ldots x'_6)\delta \left( \sum_{1}^{6} x'_i - 2 \right) \prod_{1}^{6} \frac{dx'_i}{2x'_i} \right|^2$$  

(4)

Here

$$\varphi_t(x'_i) \equiv \int \psi_t(x'_i, k'_{i\perp})\delta \left( \sum_{1}^{6} k'_{i\perp} \right) \prod_{1}^{6} \frac{dk'_{i\perp}}{(2\pi)^3}$$  

(5)

The normalization condition is

$$\int |\psi_t(x'_i, k'_{i\perp})|^2 \delta \left( \sum_{1}^{6} x'_i - 2 \right) \prod_{1}^{6} \frac{dx'_i}{2x'_i} \delta \left( \sum_{1}^{6} k'_{i\perp} \right) \prod_{1}^{6} \frac{dk'_{i\perp}}{(2\pi)^3} = 1$$  

(6)
$W_{\text{frag}}$ includes gluon exchanges and the "internal" quark propagators (see above). $w_2$ is the probability to find the $6q$-state in deuteron. $J_p$ describes the interactions of $p$ soft partons ("donors") with the target.

$$J_p = C^{-1} \int d^2B \left[ 4\pi m^2 j(B) \right]^p$$

(7)

$C$ is the quasi-eikonal factor, $m$ is the constituent quark mass and the function $j(B)$ has been calculated in [3] with eikonal and in [4, 5] with quasi-eikonal parametrization of the partonic amplitude. It was demonstrated in [3] that all donors have to interact with the target.

Following [7] we assume that the soft partonic wave function have the sharp maximum at $x_1' = ... = x_6' \equiv x_0' = 2/6 = 1/3$. Then taking in (4) the function $W_{\text{frag}}$ in this point we find the following approximation for $I_{\text{frag}}^d(x)$:

$$I_{\text{frag}}^d(x) = \frac{4\pi^4}{9!}(2 - x)^9 w_2 J_5 W_{\text{frag}} \int \varphi_1(x_1'...x_6')\delta\left(\sum_{1}^{6} x_i' - 2\right) \prod_{1}^{6} \frac{dx_i'}{2x_i'}$$

(8)

where

$$W_{\text{frag}} = W_{\text{frag}}(x_1' = ... = x_6' \equiv x_0' = 1/3) = \frac{(4\pi\alpha)^5}{x_0^d} X_5$$

(9)

and $X_5$ is the sum of about $10^2$ diagrams (in units of $x_0'$):

In [8] we have developed the method of these diagram summation based on the recurrence relation for the arbitrary number of quarks $X_p \equiv f_{p+1}(p + 1)!$:

$$f_n = \frac{1}{n(n - 1)} \sum_{k=1}^{n-1} \frac{n + k}{n - k} f_k f_{n-k}$$

(10)

with the initial condition $f_1 = 1$. The recurrence relation (10) enables easy calculate $f_n$ for an arbitrary $n$ starting from $f_1 = 1$. For large $n$ (10) evidently admits asymptotical solutions of the form

$$f_n \simeq ((6/5) n + o(n)) \exp(-an)$$

(11)

where $a$ is arbitrary. Numerical studies reveal that with $f_1 = 1$

$$a = 0.24421...$$
and also show that the asymptotical expression (11) approximates the true solution quite well starting from \( n = 3 \), i.e. for all physically interesting values. In particular for
\[ n = p + 1 = 6 \]
we have
\[ X_5 = 6! f_6 = 6! \frac{36}{5} \exp(-1.464) \]

The calculations of the diagram in Fig. 2 corresponding to the mechanism of the coalescence of three fast quarks into cumulative proton are very similar. As a result, we find
\[ I_{\text{coal}}^d(x) = \frac{16\pi^2}{5!} (2 - x)^5 w_2 J_3 \int \varphi_1(x'_1, ..., x'_6) W_{\text{coal}}(x'_1, ..., x'_6, x_1, x_2, x_3) \phi^*_p(x_1, x_2, x_3) \times \]
\[ \times \delta \left( \sum_{i=1}^6 x'_i - 2 \right) \prod_{i=1}^6 \frac{dx'_i}{2x'_i} \delta \left( \sum_{i=1}^3 x_i - 2 \right) \prod_{i=1}^3 \frac{dx_i}{2x_i} \right)^2 \]

We see that the interference takes place. The result (13) is not reduced in general to the product of two probabilities: the probability to find three quarks with momenta \( x_1, x_2, x_3 \) multiplied by the probability of the coalescence of quarks with these momenta. We have to sum amplitudes not cross sections. In (13) at first we have to integrate over \( x_i \) and only then to calculate \( |...|^2 \).

The idea that in QCD a quark can hadronize by coalescing with a comoving spectator parton was suggested in the paper [13]. It was used later for the description of the fragmentation of protons and pions into charm and beauty hadrons at large \( x \) [14, 15]. It was shown that the coalescence or recombination of one or both intrinsic charm quarks with spectator valence quarks of the Fock state leads in a natural way to leading charm and beauty production. But the interference effects were not taken into account in these papers.

Again assuming that the soft partonic wave functions have the sharp maximum at \( x'_1 = ... = x'_6 \equiv x'_0 = 2/6 = 1/3 \) and \( x_1 = x_2 = x_3 \equiv x_0 = 2/3 \) we have:
\[ I_{\text{coal}}^d(x) = \frac{16\pi^2}{5!} (2 - x)^5 w_2 J_3 W_{\text{coal}}^2 \times \]
\[ \times \left| \int \varphi_1(x'_1, ..., x'_6) \delta \left( \sum_{i=1}^6 x'_i - 2 \right) \prod_{i=1}^6 \frac{dx'_i}{2x'_i} \right|^2 \times \left| \int \varphi_p(x_1, x_2, x_3) \delta \left( \sum_{i=1}^3 x_i - 2 \right) \prod_{i=1}^3 \frac{dx_i}{2x_i} \right|^2 \]

where
\[ W_{\text{coal}} = W_{\text{coal}}(x'_1 = ... = x'_6 \equiv x'_0 = 1/3, x_1 = x_2 = x_3 \equiv x_0 = 2/3) = 3!(4\pi\alpha X_1) \]
and $X_1$ is the simplest diagram (in units of $x'_0$):

$$X_1 = \frac{1}{1} \frac{2}{3} = 3$$

$3!$ corresponds to the time ordering of the gluon exchanges in "old" perturbative scheme and no "internal" quarks propagators enter in $W_{coal}$.

Note that related approach was successfully applied in [10] for the description of the behavior of the nuclear structure functions but in non cumulative $x < 1$ region (the EMC effect). In the paper the existence of a multi-quark cluster ($6q$) was postulated and its structures functions were simply approximated using the quark counting rules [17] and normalization conditions.

We would like to emphasize that both the intrinsic mechanism of the cumulative quark production when the quarks of several nucleons concentrated in one nuclear flucton transfer their longitudinal momenta to the distinguished quark and the hadronization through the cumulative quarks coalescence break the QCD factorization theorem.

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