QCD and nuclear reactions at large momentum transfer

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The QCD diagrams, which give a parametrically larger contribution than the quark counting diagrams to the high-momentum component of the wave function of a nuclear deuteron, are shown and calculated. The results of the calculation are in reasonable agreement with the momentum dependence of the cumulative particle yields.

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The important QCD diagrams, which determine the wave function of a NN system in the $1\ \text{GeV}/c > k > 0.5\ \text{GeV}/c$ nucleon momentum region, are shown and calculated in this paper. The contribution of these diagrams to the indicated region is parametrically greater than that from the six-quark configuration in a deuteron, which is described by quark counting[1,2] by the so-called democratic-chain (DC) diagrams.[1] This results in the elimination of the apparent contradiction of the QCD with data for deep inelastic scatering, where in an experiment $F_{2D}(x) \sim (2-x)^7$ for $1 < x < 1.5$ (Ref. 3), instead of the $(2-x)^{10}$ predicted by the DC[4] and by the data for fragmentation of a deuteron into a proton[5]: $xd^3\sigma/dxd^2p_\perp|_{p_\perp=0} \sim (2-x)^3$, instead of $(2-x)^6$ in the DC[1]).[6]

To calculate the deuteron wave function in the $k > 0.5$ GeV/c region in terms of QCD, we must find a process which is rigid at finite α and which simultaneously can be described in terms of the wave function of the deuteron as a system of two nucleons ($\alpha/2$ is the fraction of the deuteron momentum removed by a nucleon in a system where the deuteron is fast).

Such a process is a reaction of the type: $e + D \to e' + p + x$ at $x = -q^2/2m_N q_0$, established by Bjerken, and $\alpha \to 2-x$ in the region of moderate $x \sim 0.2 - 0.3$ ($\alpha = 2-x$ is the edge of the phase volume for this reaction). In the following discussion we assume that the nucleon with large α is produced before the interaction of γ^* with D (this hypothesis is usually used in analyzing the preconfinement state in QCD). In this case the scattering by a deuteron configuration with a finite number of partons—the $6q$ configuration—predominates because of the limited phase volume.

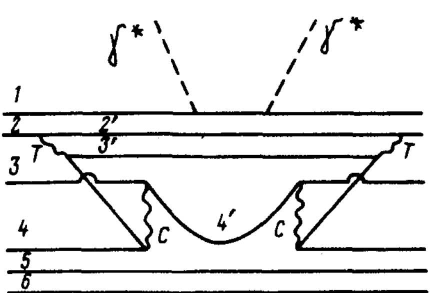

FIG. 1.

Within the framework of these assumptions, the space-time evolution of the process is described by the diagrams of the old perturbation theory in the infinite-momentum frame (Fig. 1). In the initial state the quarks (1, 2, 3) and (4, 5, 6) form two nucleons in the average configuration ($x_i \sim 0.2 - 0.3$). Only the rigid gluon exchanges are designated in diagram 1. The indices C and T refer to the Coulomb and transverse gluon exchanges. These exchanges must alternate, as determined by the selection rules in QCD.[4] A calculation of diagram 1 in the limit $\alpha \to 2-x$, $k_\perp = 0$ gives

$$F_2^{D/N}(x, \alpha) \sim (2 - x - \alpha)^3 = \left(1 - \frac{x}{2-\alpha}\right)^3 (2-\alpha)^3. \tag{1}$$

Here, $F_2^{D/N}(x,\alpha)$ describes the α distribution for a specified x of the (4′, 5, 6) system of quarks. The factor $(2-x-\alpha)^6$ arose from the six energy denominators, the factor $(2-x-\alpha)^{-2}$ from the four vertices for the transverse gluon interaction, and the factor $(2-x-\alpha)^{-1}$ from the phase volume. The $F_2^{D/N}(x,\alpha)$ calculation is reasonable in the interval $1.5 < \alpha < 1.7 - 1.8$. The inequality $\alpha < 1.7$–1.8 follows from the requirement that quark 1 must be in the average configuration, otherwise an additional suppression factor must be taken into account. At $\alpha < 1.5$ the gluon exchanges are not rigid.

To estimate the proton yield with large α, we must evaluate the overlap integral of the dominant quark configuration with the hadronic state. The upper three quarks 1′, 2′, 3′ are almost in the same configuration as in a nucleon in which one quark carries $\tilde{x} = x/(2-\alpha)$. The probability of this configuration is proportional to F_{2N} $[x/(2-\alpha)]$. (We note that this probability is of the same order of magnitude for a $N^*(1400)$-type baryon resonance. Therefore, in order to obtain an unambiguous interpretation of the hadronic state, we must calculate the overlap integral with the baryon resonances. This problem falls outside the scope of this paper.) Analogously, the overlap integral for quarks (4′, 5, 6) and for the baryon resonances, which is proportional to $\alpha F_{2N}[(\alpha - 2/3)/\alpha]$, is weakly dependent on α for $1.5 < \alpha < 1.8$, which can be disregarded. (We note that this estimate exaggerates somewhat the α dependence of the overlap integral, since more complex configurations than $3q$, whose contribution decreases faster with x, contribute to F_{2N}.)

Expanding the $6q$ configuration in terms of intermediate hadron states and assuming, in accordance with the small value of the inelasticities in the S and D phases, the the two-nucleon intermediate state dominates, we can estimate the α dependence of the nucleon distribution density matrix $\rho_D^N(\alpha)$. In the two-nucleon approximation[7]:

$$F_2^{D/N}(x, \alpha) = F_{2N}\left(\frac{x}{2-\alpha}\right)\rho_D^N(\alpha, k_\perp = 0). \tag{2}$$

A comparison of Eqs. (1), and (2) gives

$$\rho_D^N(\alpha, 0) \sim (2-\alpha)^3 \quad \text{for} \quad 1{,}5 \leqslant \alpha \leqslant 1{,}7 \div 1{,}8. \tag{3}$$

It is useful to compare this estimate with that predicted by a dimensional analysis[4,6] $(2-\alpha)^6$ (allowance for the overlap integral leads to an additional decrease of this contribution with α), which is also suppressed by a factor α_s^2 compared with the contribution being discussed.

A calculation of the $F_{2D}(x)$ structure function by means of Eq. (3) for ρ_D^N leads to $F_{2D}(x) \sim (2-x)^7$ for $1 < x < 1.5$, in reasonable agreement with experiment.[3]

By using Eq. (3) we can also estimate the cross section for backward nucleon production in pD scattering

$$\alpha \left. \frac{d\sigma(p + D \to p + X)}{d\alpha d^2 p_\perp} \right|_{p_\perp = 0} \sim \rho(\alpha, 0) \sim (2-\alpha)^3 \quad \text{for} \quad 1{,}5 < \alpha < 1{,}8. \tag{4}$$

Experimentally,[5] the cross section in this region behaves like $(2-\alpha)^{3\pm 0.2}$ (see Fig. 2).

As shown in Ref. 8, the use of realistic D-type wave functions of the Hayman-Johnston wave function makes it possible to describe the $p + D \to p + X$ reaction to $\alpha \sim 1.7$. Thus, the regime (3) is softly joined to the standard deuteron wave functions in a wide momentum range $0.5 < k < 0.8$ GeV/c.

As shown in Ref. 9, the yield of cumulative nucleons, pions, and deuterons from heavy nuclei is determined by the escape of nucleons from short-range, few-nucleon correlations and the α dependence of the wave functions of these correlations can be

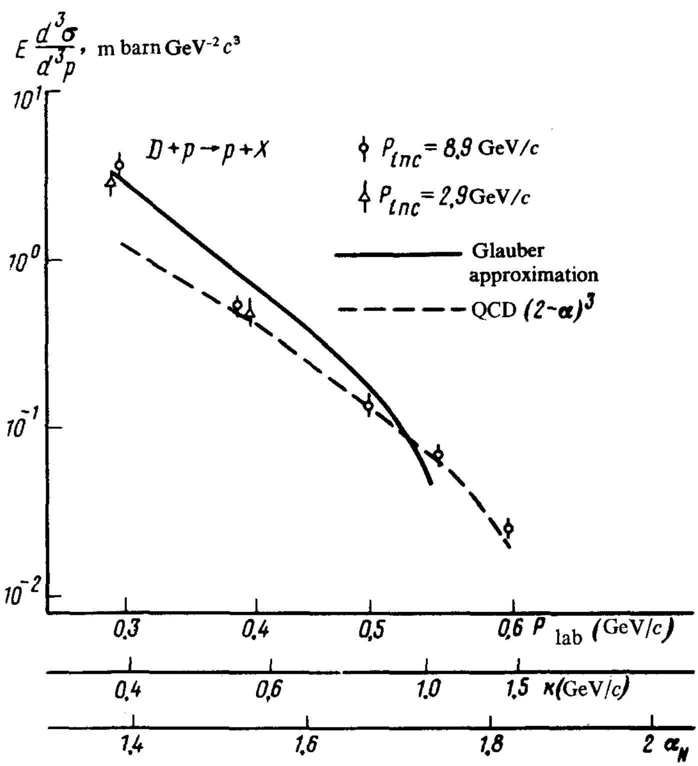

FIG. 2. GeV/c

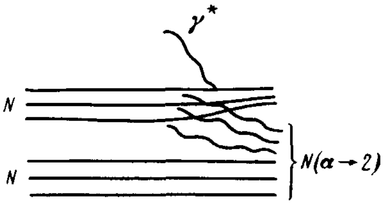

FIG. 3.

estimated from the behavior of $\rho_D^N(\alpha)$ in the region $1.5<\alpha<1.8$, in agreement with experiment. Thus, the analysis presented above shows that the production of cumulative nucleons from nuclei is essentially a QCD effect.

For rare components of the impurity type $\bar{q}$ the predictions of the two-nucleon approximation with ρ_D^N from (3) and from the QCD perturbation theory give different results:

$$F_{\bar{q}}^{D/N} \sim (2-\alpha-x)^7 \qquad \text{in QCD}$$

$$F_{\bar{q}}^{D/N} \sim \left(1-\frac{x}{2-\alpha}\right)^7 (2-\alpha)^3 \quad \text{in two-nucleon approximation}$$

i.e., according to QCD, as the nucleons come together, the number of antiquarks in them is smaller than that in the two free nucleons. At the same time $F_{\bar{q}}^{D}(x)$ agrees with the two-nucleon approximation. Thus, a soft transition between the two-nucleon approximation and the quark approach can occur only for the main quark configurations in a deuteron.

We note that the calculation of diagram 1 shows that a cumulative nucleon is formed in a special compressed configuration—with almost no gluon field. As a result, the interaction of such a nucleon with the nucleus is suppressed until the gluon field increases. Thus, then nucleus is more transparent for cumultive particles than for free hadrons.

For a fixed $\alpha \gtrsim 1.8$ and $x/(2-\alpha)$ the contribution of diagrams such as Fig. 1, with allowance for a rigid exchange between quarks 5 and 6, gives a parametrically small contribution $F_2^{D/N}(x,\alpha)\sim(2-x-\alpha)^6\alpha_s^{10}$, i.e., $\rho_D^N(\alpha)(\alpha,0)\sim(2-\alpha)^6$. Since $\alpha\to 2$ corresponds to $x\to 0$, in this limit large longitudinal distances are important in the formation of the leading particles. An example of this is the formation of nucleons due to diagrams such as those in Fig. 3, where the system of fast $3q+3g$ is converted into a nucleon due to an interaction after the γ^* impact. Thus,

$$F_2^{D/N}(x,\alpha)\sim(2-\alpha-x)^2 \tag{4}$$

i.e., for the hadron reaction

$$\alpha\frac{d\sigma(p+D\to p+X)}{d\alpha d^2k_\perp}(2-\alpha)^2. \tag{5}$$

The qualitative difference between Eq. (5) and the predictions of quark counting (DC) is attributable to the fact that the contribution of long longitudinal distances does not contain the smallness associated with the presence of slow partons. Equation (5) joins softly with the three-reggeon limit as $a \to 2$, which is predicted at a sufficiently high energy

$$a \frac{d\sigma}{da\, d^2 k_\perp} \sim (2 - a)^{1 - 2a_N(0)} \approx (2 - a)^{1.8}. \tag{6}$$

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[1)]Here, we give the predictions of quark counting with allowance for the QCD selection rules which are due to vector coupling of gluons with the quarks.[4]

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