Deep inelastic eD scattering in the region forbidden for scattering by one nucleon

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A description is proposed for the effects of small distances in the deuteron, based on the space–time picture of G. West (Annals of Physics **74**, 464, 1972) for the scattering of high-energy hadrons. The structure function of the deuteron in a region forbidden to scattering by one nucleon is calculated in accord with experiment.

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Processes of scattering by a deuteron in the kinematic region forbidden to scattering by one nucleon (the F region) have recently attracted attention.[1–3] The decisive role in the theoretical description of these effects is played by the method used to take relativistic effects into account[3] (for example, when estimating the process $D+p\to\pi+X$ in the F region, the virtuality of the nucleon reaches 1 GeV^2).[2] We construct here a relativistic impulse approximation, in which, in contrast to the standard approximation,[1,2,4] there enter only the scattering amplitudes on the mass shell and the relativistic wave functions (WF) of the deuteron. The method of constructing relativistic WF was investigated in[5] and subsequently in[6], and therefore will not be discussed here.

It is well known[7] that a lucid semi-quantitative (and frequency also quantitative) description of the properties of hadrons is obtained by using the old perturbation theory (but not the Feynman diagrams) in the infinite momentum frame (IMF), for in this case the ordering of the processes in space–time is taken into account in natural fashion.[7,8] We shall therefore base our analysis on the dispersion approach (DA) proposed by Gribov[8] for the description of the scattering of high-energy γ quanta by nuclei; an approach equivalent to a description with the aid of the IMF. In the case of the scattering of a high-energy deuteron, the DA reduces to a dispersion representation of the scattering amplitude in terms of the deuteron mass, i.e., in the DA the deuteron consists of real hadrons: NN, $NN\pi$, $\cdots$, from which the scattering takes place in fact. Since the inelastic processes at low energies are connected mainly with production of nucleon resonances, it is reasonable to expect, inasmuch as the isospin of the deuteron is zero, that up to the threshold of the production of two $\Delta(1240)$ (i.e., up to nucleon momenta $k \sim \sqrt{m_\Delta^2 - m_N^2} \sim 0.8$ GeV/c) the main contribution is made by a configuration wherein the deuteron consists of two nucleons.[1] Phase-shift analysis data seem to indicate that the $^1S_0$ and $^3S_1$ nucleon-nucleon scattering phase shifts are practically real in an even wider range[9]).

The WF of a zero-spin deuteron ($D \to NN$ vertex function) depends in the DA only on the η-invariant mass of the system of two nucleons: $4m^2 + 4k^2$.[2] Here k is the momentum of one of the nucleons in the deuteron rest system. (The usefulness of introducing k is indicated in[6,10].) It will be convenient to use the variable

$$a = \frac{1}{2}\left(1 + \frac{k_3}{\sqrt{m^2 + k^2}}\right)$$

which is the fraction of the deuteron momentum carried away by one of the nucleons in the IMF (see also[10]). The WF is normalized by the condition $\int \phi^2(k)\, d^3k = 1$.

In the DA, the structure function of the deep-inelastic eD scattering at $|q^2| \to \infty$ and at a fixed $x = -q^2/2q_0 M_D$ takes in the impulse approximation the form

$$\int d^3k\, \phi^2(k)\left(F_{2p}\left(\frac{x}{a}\right) + F_{2n}\left(\frac{x}{a}\right)\right) = F_{2D}(x). \tag{1}$$

Here F_2 is equal to νW_2 for any target in the scaling limit. The derivation of Eq. (1) follows the method of[8]. The appreciable simplification is due to the fact that in the IMF the structure function of the nucleon depends only on the fraction of the deuteron momentum carried away by the interacting parton. For (1) to be valid, it is important that the nonconservation of the energy in this approach be immaterial in the IMF in the case of scaling for F_{2N}.[11] Formula (1) differs from the formulas of the parton model only in that account is taken of the structure function of the nucleon.

Allowance for the spin of the deuteron in (1) reduces to the replacement of $\phi^2(k)$ by $u^2(k) + w^2(k)$,[10] where u and w are the analogs of the quantum-mechanical wave functions S and D waves. For a rough estimate we can identify u and w with the nonrelativistic WF, say of[12], since they describe fairly well the form factor of the deuteron. (We note that allowance for the relativistic effects leads to a slowing down of the decrease of the form factor of the deuteron at large momentum transfers in comparison with the quantum-mechanical calculation,[13] and consequently to an improvement of the agreement with experiment.) Measurements of deep-inelastic eD scattering at small ω ($\omega = 1/2x$) have been published recently.[14] The results of the calculation with the aid of formula (1) and the WF of[12] are shown in Fig. 1. For F_{2p} we used the standard parametrization,[15] while F_{2n} was assumed to be equal to $F_{2p}(x) \times (1 - 3x/4)$. The results of the calculation does not contradict. In the range $0.55 < \omega < 1$, the theoretical curve can be approximated by the formula $F_{2D}(x)$

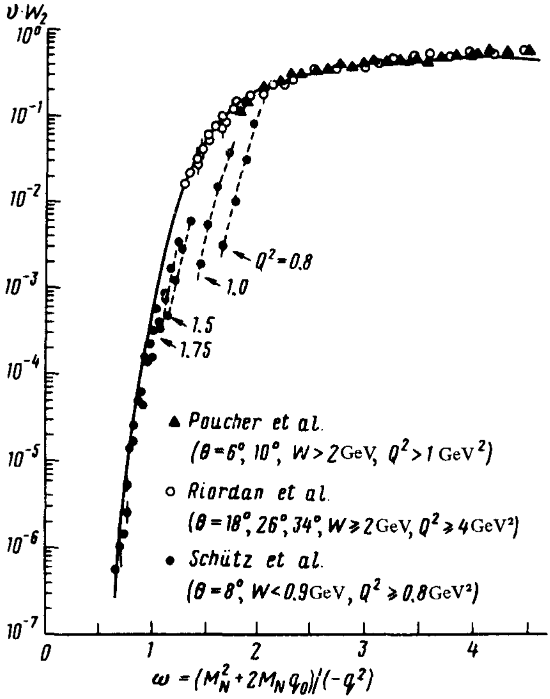

FIG. 1.

$= 0.12(\omega - 1/2)^n$, where $n = 5.7$. A fit to the experimental data yields $n = 6 \pm 0.5$.[14]

It was noted in[14] that the observed behavior of F_{2D} contradicts the predictions of the quark calculation ($n = 9$). A weaker dependence of F_{2D} on ω at $\omega > 0.6$ was expected in the composite model of the deuteron[3] as a result of the large Fermi momenta of the quarks (~ 0.4 GeV/c).

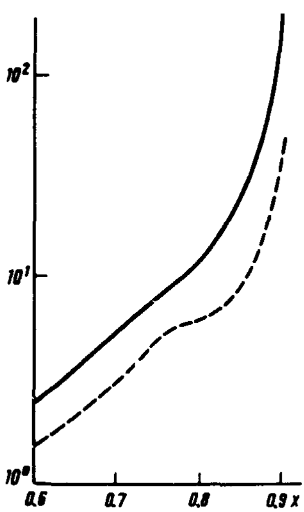

FIG. 2.

Figure 2 shows the ratio of the results of the calculation by formula (1) and by the formulas of[4] (solid curve), which are analogous to the formulas used in[1,2]. The difference between the calculation results at large x (small ω) is due mainly to the fact that in the DA the interacting nucleon and the spectator enter symmetrically, just as in quantum mechanics, whereas in[1,2,4] the spectator carries away a larger fraction of the momentum. In other words, the connection between α and **k** is different here than in the cited papers. Following the method of[8] we can also calculate the amplitude of the reaction $D+p \to \pi+X$ in the region F:

$$\rho_D^{\pi}(x, p_{\perp}) = \int (\rho_p^{\pi}(\frac{x}{\alpha}, p_{\perp}+k_{\perp}) + \rho_n^{\pi}(\frac{x}{\alpha}, p_{\perp}+k_{\perp}))\,(u^2(k)+w^2(k))d^3k. \qquad (2)$$

Here x is the fraction of the deuteron momentum carried away by the pion. In (2), scaling is assumed for $\rho_N^{\pi}(x,p_{\perp}) = (1/\sigma_{tot})(d\sigma/dxd^2p_{\perp})$. Since $\rho_N^{\pi}(x,p_{\perp})$ decreases as $x \to 1$ more slowly that $F_{2N}(x)$, the enhancement for the discussed reaction is smaller than for eD scattering (see the dashed curve in Fig. 2). It appears that this enhancement does not contradict the experimental data.

The reaction $D+p \to p+X$ in the F region will be considered in detail in later papers. We note only that the cross section of this reaction is expected here to be less than in the formalism of[1,2] (at equal WF). A study of this reaction makes it possible to verify the hypothesis that a core is present in the wave function of the deuteron. For example, in the region $k \sim 0.4$ GeV/c, where the S wave passes through zero, one expects a strong dependence of the cross section on the deuteron polarization.

Since the wave functions enter in the discussed phenomena at large momenta (for example, at $\omega = 0.65$, which is the smallest value of ω in the experiment of[14], the significant values in the calculation are $k \sim 0.7$—1.3 GeV/c), a natural question arises: what is the physical meaning of an analysis based on a two-nucleon wave function of a deuteron at these momenta? In addition to the arguments given at the beginning of the article, there exist supplementary arguments based on the quark model. In processes where the quark additivity gives good account of itself, one quark takes part in the interaction, and consequently, for a consistent description of all these processes it suffices that the two-nucleon WF describe correctly the single-particle distribution of the quarks in the deuteron (the electromagnetic form factor of the deuteron).

From this point of view, the wave function concept is not as clearly defined in hadronic reactions of the type $D+p \to p+X$, since there is no one-to-one correspondence between the quarks and the hadrons. For example, the presence of a $\Delta+\Delta$ configuration in the WF deuteron in the DA does not contradict the quark model. It is therefore of interest to study experimentally the production of Δ, N^*, etc. in the F region.

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1) This reasoning is equivalent to the assumption that in the deuteron rest system the probability of any configuration decreases with increasing distance from the energy shell.

2) In the light-cone formalism this result follows from the "angle condition."[10]

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