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Description of deep inelastic processes in the compound quark model

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Deep-inelastic lepton–hadron scattering processes are considered within the compound quasi-nuclear quark model. Both incoherent processes of scattering by individual quarks and coherent processes of scattering by bound systems of quarks (diquarks and triquarks) are taken into account. Scattering by diquarks is dominant for $x \approx 2/3$, and by triquarks for $x \approx 1$. The total contribution of diquarks to the structure functions is estimated to be approximately 10%, and that of triquarks to be about 1%.

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1. INTRODUCTION

The study of deep-inelastic lepton-hadron scattering processes makes it possible to obtain valuable information on the structure of hadrons. The most striking experimental fact has been the Bjorken scale invariance,[1] which can be explained in the framework of Feynman's parton picture.[2] According to the parton ideas a hadron consists of structureless particles—partons, each of which carries a definite fraction x of the total hadron momentum. We may consider quarks as the partons, and such a quark-parton model gives a fairly good description of deep-inelastic processes.[3–6]

There are, however, fairly serious indications that the quarks in a hadron exist not only as carriers of quantum numbers but also as real spatially separated objects. Such a quasi-nuclear nonrelativistic model of hadrons enables us to give a good description of their static properties,[7,8] makes the successes of $SU(6)$ symmetry comprehensible, and leads to a number of relations, in agreement with experiment,[9] between the total hadron cross sections. The spatial separation of the quarks in a hadron is indicated by the presence of dips in the differential cross sections for pp-scattering at high energies[10] and by the symmetry of the inclusive spectra in the center-of-mass frame of the colliding quarks in meson-nucleon interactions.[11] In a model with spatially separated quarks each quark carries, on average, $\frac{1}{3}$ of the momentum of the nucleon. Therefore, deep-inelastic processes in the region $x > \frac{1}{3}$ can arise as a result of coherent scattering of the lepton by several quarks.[12,13]

It is obvious that, in the given case, in the scattering of a lepton with a large momentum-transfer squared q^2, we can disregard the coherent interaction with quark-partons only when they are positioned at the same impact-parameter distance: the contribution of such processes falls rapidly for $-q^2R^2 \gg 1$, where R is the hadron radius ($R^2 \approx 2$ GeV^{-2}). For $-q^2 > 1$ GeV^2 the lepton interacts coherently with quarks separated by relatively small distances of the order of their radius r_0. The lepton can begin to "feel" the structure of such formations of quarks (two quarks form a diquark and three quarks a triquark) only when $-q^2 r_0^2 \gg 1$. (The quark-parton picture for strong interactions makes it possible to estimate the square of the quark radius: $r_0^2 \sim 0.25$ GeV^{-2}; see below, and also in[10,14].) For small transfers $-q^2 \lesssim r_0^{-2} \approx 4$ GeV^2, the lepton interacts with diquarks and triquarks as with a single whole. The problem of the interaction of a lepton with diquarks and triquarks for $-q^2 > 4$ GeV^2 cannot be solved uniquely *a priori* at the present time. Here it is possible that there is a rapid decrease of the form factors of the diquarks and triquarks and equally possible that there is a rather long delay before the onset of the fall-off regime (if the intrinsic radii of the diquarks and triquarks are less than the quark radius). The interactions between the quarks can also be such that the form factors of the diquarks or triquarks will not fall with increasing q^2. In this case, the corresponding diquark or triquark can be regarded as a new type of parton.

In the present paper we consider the coherent interaction of leptons with quarks, when they are at comparatively short distances of the order of r_0. We analyze the type of interaction of leptons with diquarks and triquarks that conserves the scale invariance in deep-inelastic processes. This requires that the form factors of the diquarks fall like $1/|q|$, and that the triquarks be point particles. (In this case it seems natural to assume that they have no anomalous magnetic moment.) Certainly, this is one of the possible variants for taking the coherent interaction into account. The problem of whether this or some other type of interaction is realized must be solved experimentally. In any case, however, it must be kept in mind that in a quasi-nuclear quark model the coherent-interaction phenomenon is an entirely natural way of describing lepton-scattering processes in the region $x > \frac{1}{3}$ and should, therefore, be investigated quantitatively.

It should also be stressed that the interaction of leptons with diquarks and triquarks leads to definite relations between the structure functions for protons and neutrons for $x \approx \frac{2}{3}$ and $x \approx 1$. These can serve as a good criterion for elucidating the question of whether the coherent interaction with quarks is important in hadrons.

2. DESCRIPTION OF THE COMPOUND MODEL

We shall start from the fact that a baryon at rest consists of three spatially separated quarks, just as tritium consists of three nucleons. Each of the three quarks is surrounded by its own cloud of virtual particles: a cloud of quark-antiquark pairs. Thus, by the concept "quark" we shall mean a virtual valence quark together with a sea of quark-antiquark pairs that has zero total quantum numbers. In a fast-moving nucleon the momenta p_i of all three quarks ($i=1, 2, 3$) are large. In this case the nucleon consists of three quark-parton clouds, each of which consists of a valence quark-parton and a sea of quark-partons and antiquark-partons. The total momentum of each of the clouds is approximately equal to one-third of the baryon momentum. Thus, the quark-partons of these clouds have $x \lesssim \frac{1}{3}$. Here the valence quark-parton has the highest average value of x: the maximum of its distribution lies near $x=\frac{1}{3}$. The probability of finding a quark-parton with $x > \frac{1}{3}$ in spatially separated clouds decreases sharply with increase of x. Values $x \approx \frac{2}{3}$ are realized for sufficiently strong overlap of two clouds. Closely spaced valence quark-partons have a resultant x close to $\frac{2}{3}$ and can interact as a single entity with a lepton. We shall call such a system a valence diquark. A diquark can be surrounded by its own cloud of quark-partons. The probability of overlap of clouds and formation of a diquark is comparatively small (of order $(r_0/R)^3$). However, for $x \approx \frac{2}{3}$, interaction with diquarks gives the principal contribution to the structure functions. The value $x \approx 1$ is realized when three valence quarks are closely spaced and form a single system—a valence triquark. A triquark can also be surrounded by its cloud of quark-partons.

Diquarks and triquarks can also be formed by quark-partons from the sea. However, these diquarks and triquarks have small values of x. Below we shall disregard them, assuming that, in the region of small x, their contribution to the structure functions is small compared with that of the quark-partons.

The momentum distributions of the quark-partons in the cloud depend on the ratio $x_i = k/p_i$ of the parton momentum to the total momentum of the quark (k is the parton momentum). We denote the distribution of the valence quark-parton in the cloud by $v(x_i)$ and the distributions of the nonstrange quark-partons from the sea by $c(x_i)$. Strange quark-partons are produced with a certain suppression parameter λ, so that their distribution function is $\lambda\tilde{c}(x_i)$. The suppression of the probability of creation of strange quarks in the sea follows from the fact that the total cross sections with participation of strange particles are relatively suppressed. In the quark-parton picture the relative smallness of the cross section with participation of the strange quark implies that the strange valence quark emits a multiperipheral "comb" with lower probability than does a nonstrange quark. The same suppression of the probability of the development of a multipheripheral comb also occurs in the case of creation of a strange quark-parton within the comb. Thus, the quantity λ can be estimated from the ratio of the total cross sections in kaon-nucleon and in pion-nucleon collisions at high energies: $\lambda \approx 2\sigma_{KN}/\sigma_{\pi N} - 1$.[15] This value agrees well with that obtained by direct comparison of the predictions of the quark-parton model for multiple production of particles in hadron-hadron collisions with the experimental data.[14,16]

Since the baryon is a weakly bound system, the relative momenta of the three quarks are not great. In the following we shall assume that the wavefunction of the quarks in the nucleon falls off exponentially as their relative momenta p_{il} ($i, l=1, 2, 3$) increase:

$$\psi \sim \exp\left(-\frac{b}{m_q^2}\sum_l p_{il}^2\right), \tag{1}$$

where m_q is the quark mass. The distribution function of an individual quark at high nucleon momenta

$$p = \sum_{i=1}^{3} p_i$$

depends only on $z_i = p_i/p$ and can be calculated starting from (1). To within slowly varying pre-exponential factors,

$$\Phi_v(z) \approx \text{const}\cdot\exp\left[-b\left(\frac{1}{z}+\frac{4}{1-z}\right)\right]; \tag{2}$$

$\Phi_v(z)$ is a maximum at $z=\frac{1}{3}$ and falls rapidly as z approaches zero or unity. The quark-parton momentum distributions in the variables $x=k/p$ are

$$v(x) = \int_x^1 \Phi_v(z)\,\tilde{v}\left(\frac{x}{z}\right)dz, \tag{3}$$

$$c(x) = \int_x^1 \Phi_v(z)\,\tilde{c}\left(\frac{x}{z}\right)dz. \tag{4}$$

From the same wavefunction (1) we can obtain the diquark distribution function. For this we must put the relative three-momentum of the pair of quarks equal to zero and, having fixed $z = p_{\parallel}^{d}/p$ ($p_{\parallel}^{d}$ is the longitudinal component of the momentum of the pair), integrate over

TABLE 1.

Particle-parton	Proton	Neutron	Particle-parton	Proton	Neutron
q_1	$2v(x)+c(x)$	$v(x)+c(x)$	$d_v^{(1/3)}$	$1/2\, d_v(x)$	$1/2\, d_v(x)$
q_2	$v(x)+c(x)$	$2v(x)+c(x)$	$d_v^{(-2/3)}$	0	$d_v(x)$
q_3	$\lambda c(x)$	$\lambda c(x)$	$d_s^{(1/3)}$	$3/2\, d_s(x)$	$3/2\, d_s(x)$
$\bar{q}_1$	$c(x)$	$c(x)$	$t^{(1)}$	$t(x)$	0
$\bar{q}_2$	$c(x)$	$c(x)$	$t^{(0)}$	0	$t(x)$
$\bar{q}_3$	$\lambda c(x)$	$\lambda c(x)$	g	$g(x)$	$g(x)$
$d_v^{(4/3)}$	$d_v(x)$	0			

Note: d_v, d_s and t denote the vector and scalar diquarks and triquark, the charges of the particles are indicated in brackets, and g denotes the neutral gluons.

the remaining variables. As a result we have

$$\Phi_d(z) \approx \text{const}\cdot\exp\left[-b\left(\frac{4}{z}+\frac{1}{1-z}\right)\right]. \qquad (5)$$

The distribution of diquarks in the nucleon is equal to

$$d(x)=\int_x^1 \Phi_d(z)\,\tilde{d}\left(\frac{x}{z}\right)dz, \qquad (6)$$

where $\tilde{d}(x)$ is the distribution function of the diquark in the cloud surrounding it. For triquarks, naturally, we have $t(x)=\tilde{t}(x)$.

The behavior of $\tilde{c}(x)$ for small x is determined by the Pomeranchuk pole, and $\tilde{c}(x)\sim x^{-1}$. The behavior of $\tilde{v}(x)$ for small x is due to the nonvacuum Regge trajectories having intersection $\alpha(0)\approx\frac{1}{2}$. Therefore, in this region, $\tilde{v}(x)\sim x^{-\alpha}$. This is the essential feature of the small value that arises when one quark diffuses along the multiperipheral comb. The behavior of $\tilde{d}(x)$ for small x is connected with diffusion of two quarks along the multiperipheral comb, and, therefore, $\tilde{d}(x)\approx x^{1-2\alpha}$ here. The distribution of triquarks for small x behaves like $t(x)\approx x^{2-3\alpha}$. The behavior of $t(x)$ as $x\to 1$ determines the behavior of the form factor of the nucleon. If it falls off like q^{-4}, then $t(x)\sim(1-x)^3$ as $x\to 1$. We shall assume that $\tilde{v}(x)$ and $\tilde{d}(x)$ behave in the same way as $x\to 1$. The character of the fall-off of $\tilde{c}(x)$ as $x\to 1$ cannot be determined uniquely. It is necessary to keep in mind, however, that the behavior of $c(x)$, $v(x)$ and $d(x)$ as $x\to 1$ is principally determined by the behavior of the functions $\Phi_v(z)$ and $\Phi_d(z)$ (cf. formulas (3), (4) and (6)).

Diquarks can be either scalar or vector. Triquarks have spin $\frac{1}{2}$. Using the compound quark model, it is not difficult to obtain the composition of the proton and neutron (see Table 1). The distributions $v(x)$, $d_v(x)$, $d_s(x)$ and $t(x)$ should satisfy the following normalization condition:

$$\int_0^1 dx[v(x)+d_v(x)+d_s(x)+t(x)]=1. \qquad (7)$$

Here all the additive quantum conservation laws are fulfilled automatically.

3. INTERACTIONS OF LEPTONS WITH DIQUARKS AND TRIQUARKS. THE STRUCTURE FUNCTIONS

We turn now to discuss the form of the interaction of leptons with diquarks and triquarks and to write out their contribution to the structure functions.

A scalar diquark can have only the vector interaction

$$V_\mu=f_s(q^2)\,(k_\mu^{(1)}+k_\mu^{(2)}), \qquad (8)$$

where $f_s(q^2)$ is the form factor of the scalar diquark. A vector particle has three vector form factors and one axial-vector CP-invariant form factor.[17] However, if we assume that a vector diquark does not have anomalous magnetic and quadrupole moments, its vector current can be written in the form[2)]

$$V_\mu=f_v(q^2)\,[(e_\alpha^{(1)}e_\alpha^{(2)})(k_\mu^{(1)}+k_\mu^{(2)})-(e_\alpha^{(1)}k_\alpha^{(2)})e_\mu^{(2)}-(e_\alpha^{(2)}k_\alpha^{(1)})e_\mu^{(1)}], \qquad (9)$$

where $e^{(1)}$ and $e^{(2)}$ are the polarization vectors of the initial and final diquarks, $k^{(1)}$ and $k^{(2)}$ are their momenta before and after the interaction, and $q=k^{(2)}-k^{(1)}$ is the momentum transfer.

The axial-vector current of a vector particle has the form

$$A_\mu=if_a(q^2)\,\varepsilon_{\mu\alpha\beta\gamma}e_\alpha^{(1)}e_\beta^{(2)}(k_\gamma^{(1)}+k_\gamma^{(2)}). \qquad (10)$$

To satisfy scale invariance for $x\approx\frac{2}{3}$ it is necessary that the form factors $f_v(q^2)$ and $f_a(q^2)$ fall like $1/|q|$ with increasing q^2 and that the form factor $f_s(q^2)$ be constant:

$$f_v(q^2)=\frac{\gamma_v m_d}{|q|},\quad f_a(q^2)=\frac{-\gamma_a m_d}{|q|},\quad f_s(q^2)=\gamma_s, \qquad (11)$$

where m_d is the diquark mass and the γ are constants. We shall also assume here that scale invariance is also satisfied in the interaction of leptons with triquarks. In this case it is natural to assume that the vector current of the triquarks is analogous to a current of point particles and that they have no anomalous magnetic moment. Thus, we take the vector and axial-vector currents for the triquarks in the form

$$V_\mu=F_v(q^2)\,\bar{u}_2\gamma_\mu u_1, \qquad (12)$$
$$A_\mu=F_a(q^2)\,\bar{u}_2\gamma_\mu\gamma_5 u_1, \qquad (13)$$

and assume that the form factors $F_v(q^2)$ and $F_a(q^2)$ are independent of q^2 and equal to

$$F_v(q^2)=F_a(q^2)=\gamma_t. \qquad (14)$$

The structure assumed here for the triquark current leads to constancy of the ratio of the electric and magnetic form factors of the proton at large q^2. The ratio G_M^n/G_M^p of the neutron and proton magnetic form factors should then tend to zero.

The electron-nucleon scattering cross-section is equal to

$$d\sigma=\frac{\alpha^2}{4\pi q^4}\frac{L_{\mu\nu}W_{\mu\nu}}{((l_1p)^2-m_e^2m^2)^{1/2}}\frac{d^3l_2}{l_{20}}, \qquad (15)$$

$$L_{\mu\nu}=2[l_{1\mu}l_{2\nu}+l_{2\mu}l_{1\nu}-(l_1l_2)\delta_{\mu\nu}+m_e^2\delta_{\mu\nu}], \qquad (16)$$

$$W_{\mu\nu}=4\pi m(q_\mu q_\nu/q^2-\delta_{\mu\nu})W_1(q^2,\nu)$$
$$+\frac{4\pi}{m}\left(p_\mu-\frac{(pq)}{q^2}q_\mu\right)\left(p_\nu-\frac{(pq)}{q^2}q_\nu\right)W_2(q^2,\nu). \qquad (17)$$

Here l_1 and l_2 are the momenta of the electron before and after the scattering, p is the momentum of the nucleon in the initial state, and $q = l_1 - l_2$. The electron and nucleon masses are equal to m_e and m. The structure functions W_1 and W_2 depend on the momentum-transfer squared q^2 and on $\nu = (p \cdot q)/m$. The quantity ν is expressed as usual in terms of the electron energy loss in the laboratory frame: $\nu = E_1 - E_2$. The scaling variable x is defined as $x = -q^2/2m\nu$.

The structure functions W_1 and νW_2, which, in the case of scale invariance, depend only on x, can be written in the following form:

$$W_1 = \sum_a e_a^2 \omega_{1a} p_a(x), \quad \nu W_2 = \sum_a e_a^2 \omega_{2a} p_a(x), \tag{18}$$

where the summation is taken over all the kinds of parton appearing in the nucleon. Here $p_a(x)$ is the parton distribution in the nucleon (see Table 1) and e_a is the parton charge in electronunits. The quantities ω_{ia} depend on the type of parton and for quark-partons are equal to

$$\omega_{1q} = 1/2m, \quad \omega_{2q} = x. \tag{19}$$

For scalar diquarks,

$$\omega_{1s} = 0, \quad \omega_{2s} = x\gamma_s^2. \tag{20}$$

For vector diquarks,

$$\omega_{1v} = \gamma_v^2/12m, \quad \omega_{2v} = x\gamma_v^2/6. \tag{21}$$

For triquarks,

$$\omega_{1t} = \gamma_t^2/2m, \quad \omega_{2t} = x\gamma_t^2. \tag{22}$$

The cross section for scattering of a neutrino by a nucleon has the form

$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{dx\,dy} = \frac{G^2 mE}{\pi}\left[(1-y)F_2^{\nu,\bar{\nu}}(x) + \frac{y^2 x}{2} 2F_1^{\nu,\bar{\nu}}(x) \pm \left(1 - \frac{y^2}{2}\right) yxF_3^{\nu,\bar{\nu}}(x)\right], \tag{23}$$

where m is the nucleon mass, E is the lepton energy before scattering, $y = \nu/E$, and the plus sign refers to the neutrino and the minus sign to the antineutrino. The structure functions $F_i^{\nu,\bar{\nu}}$ can then be written in the following way:

$$F_i^{\nu,\bar{\nu}} = \sum_a (g_a^{\nu,\bar{\nu}})^2 f_{ia} p_a(x), \tag{24}$$

where, as in formula (18), the summation is taken over all the kinds of parton appearing in the nucleon. In the interaction of a neutrino (antineutrino) with quark-partons or antiquark-partons, the quantities $g_a^{\nu,\bar{\nu}}$ are equal to

$$g_1^{\bar{\nu}} = g_{\bar{1}}^{\nu} = 1, \quad g_2^{\nu} = g_{\bar{2}}^{\bar{\nu}} = \cos\theta_C, \quad g_3^{\nu} = g_{\bar{3}}^{\bar{\nu}} = \sin\theta_C,$$

$$g_1^{\nu} = g_2^{\bar{\nu}} = g_3^{\bar{\nu}} = g_{\bar{1}}^{\bar{\nu}} = g_{\bar{2}}^{\nu} = g_{\bar{3}}^{\nu} = 0.$$

In the interaction of a neutrino (antineutrino) with a diquark or triquark.

$$g_{d,t}^{\nu,\bar{\nu}} = \sum_a g_a^{\nu,\bar{\nu}}$$

depending on their composition. For quark-partons the quantities f_{ia} are equal to

$$f_{1q} = 1, \quad f_{2q} = 2x, \quad f_{3q} = 2; \tag{25a}$$

for antiquark-partons,

$$f_{1\bar{q}} = 1, \quad f_{2\bar{q}} = 2x, \quad f_{3\bar{q}} = -2; \tag{25b}$$

for scalar diquarks,

$$f_{1s} = 0, \quad f_{2s} = x\gamma_s^2, \quad f_{3s} = 0; \tag{26}$$

for vector diquarks,

$$f_{1v} = (\gamma_v^2 + \gamma_a^2)/12, \quad f_{2v} = [(\gamma_v^2 + \gamma_a^2)/6]x, \quad f_{3v} = \gamma_v\gamma_a/3; \tag{27}$$

for triquarks,

$$f_{1t} = \gamma_t^2, \quad f_{2t} = 2x\gamma_t^2, \quad f_{3t} = 2\gamma_t^2. \tag{28}$$

It is impossible to determine the constants γ separately, since they appear in the measurable quantities in the form of a product with the distribution of the corresponding partons.

It should be noted that the absence of an anomalous magnetic or quadrupole moment of the vector diquark leads to the result that the ratio of the cross sections for absorption of photons with longitudinal and transverse polarizations tends to zero with increase of q^2:

$$\frac{\sigma_L}{\sigma_T} = \frac{W_2(1 - \nu^2/q^2) - W_1}{W_1} \to 0. \tag{29}$$

In this case the ratio of the total cross sections for scattering of an antineutrino and a neutrino by the vector diquarks that appear in the structure of a nucleus with an equal number of protons and neutrons is equal to

$$\frac{\sigma^{\bar{\nu}}}{\sigma^{\nu}} = \frac{1}{\cos^2\theta_C} \frac{\gamma_v^2 + \gamma_a^2 - \gamma_v\gamma_a}{\gamma_v^2 + \gamma_a^2 + \gamma_v\gamma_a}. \tag{30}$$

Its minimum value is reached for $\gamma_v = \gamma_a$ and coincides with the ratio of the cross sections for the valence quark-partons:

$$\sigma^{\bar{\nu}}/\sigma^{\nu} = 1/3\cos^2\theta_C. \tag{31}$$

For scalar diquarks the same ratio is equal to

$$\sigma^{\bar{\nu}}/\sigma^{\nu} = 1/\cos^2\theta_C. \tag{32}$$

4. PARAMETRIZATION AND RESULTS

The structure function νW_2^{ep} in deep-inelastic electroproduction at the proton, the ratio of the structure functions $\nu W_2^{en}/\nu W_2^{ep}$, and σ^{ν}, $\sigma^{\bar{\nu}}$, for the freon-filler of the Gargamelle chamber (the ratio of the number of neutrons to the number of protons is 1.19), have been fitted in accordance with the experimental data. The functions $\tilde{v}(x)$, $\tilde{d}(x)$, $t(x)$ and $\tilde{c}(x)$ were taken in the form

$$\tilde{v}(x) = v_1\left[1 + \frac{v_2}{\sqrt{x}}\right] \Big/ \left[1 + \left(\frac{\rho}{1-x}\right)^3\right],$$

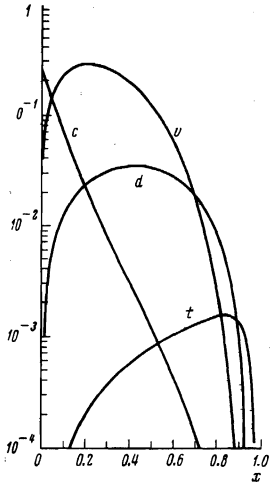

FIG. 1. Contributions to the structure function νW_2^{ep} from the valence quark-partons $xv(x)$ (curve v), diquarks $11\gamma_v^2 xd(x)/6$ (curve d), triquarks $\gamma_t^2 xt(x)$ (curve t) and the sea of partons (quarks and antiquarks) $11xc(x)/9$ (curve c).

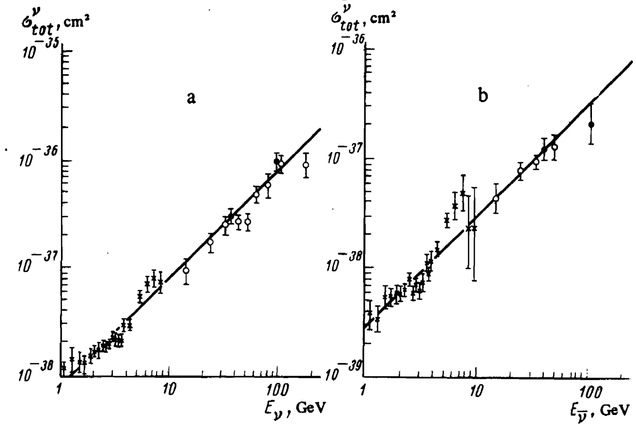

FIG. 3. Total cross sections for scattering of a neutrino (a) and antineutrino (b) by a nucleon[20] (× – Gargamelle, o – Harvard-Pennsylvania-Wisconsin, ● – Caltech-NAL). The straight lines are plotted for freon, $\sigma^\nu = 0.74 E_\nu$ and $\sigma^{\bar\nu} = 0.29 E_{\bar\nu}$.

$$\tilde d(x) = d_1 \Big/ \left[1 + \left(\frac{\rho}{1-x}\right)^3\right],$$
$$t(x) = t_1\sqrt{x} \Big/ \left[1 + \left(\frac{\rho}{1-x}\right)^3\right], \qquad (33)$$
$$\tilde c(x) = \frac{c_1}{x}\exp(-c_2 x).$$

This form satisfies the requirements mentioned in Sec. 2. Satisfactory agreement with the experimental data was obtained for $v_2 = 1$, $c_2 = 5.52$, $\rho = 0.076$ and with the constant b equal to 0.066 in formulas (2) and (5). In order to make $\sigma^{\bar\nu}/\sigma^\nu$ close to the experimentally observed value, near $\frac{1}{3}$, we put $\gamma_s = 0$.

At high energies, $\lambda \approx \frac{2}{3}$. At low energies it is substantially smaller: $\sim\frac{1}{3}$.[15,16] Here the mean value $\lambda = \frac{1}{2}$ was taken. The quantities $xv(x)$, $11\gamma_v^2 xd(x)/6$, $\gamma_t^2 xt(x)$ and $11xc(x)/9$, which are the contributions of the valence quark-partons, diquarks, triquarks and the quark-partons from the sea to the structure function νW_2^{ep}, are given in Fig. 1. The values of νW_2^{ep} and $\nu W_2^{en}/\nu W_2^{ep}$ are given in Fig. 2. The agreement is good, except in the region $x \approx 0.1 - 0.2$. This is connected with the need to have a comparatively small contribution from the antiquark–parton sea in order that $\sigma^{\bar\nu}/\sigma^\nu$ be close to $\frac{1}{3}$. The deviations from the experimental values in this region are common to all comparisons of quark-parton models with experiment (cf., e.g.,[6]). In the region $x \sim 0.6$, the ratio $\nu W_2^{en}/\nu W_2^{ep}$ can be varied easily in the range of values $0.3 - 0.6$ by changing the relative contributions of the valence quark-partons and diquarks.

In the calculation of the weak interactions we put $\sin\theta_C = 0.23$. The value of γ_a/γ_v was taken to be 1.5. This value gives $\sigma^{\bar\nu}/\sigma^\nu = 0.395$ (for freon). The ratio $\sigma^{\bar\nu}/\sigma^\nu$ varies weakly with change of γ_a/γ_v in the region $\gamma_a/\gamma_v \approx 1 - 2$. The slope σ^ν/E of the neutrino cross section varies more strongly: $\sigma^\nu/E = 0.69\,[10^{-38}\ \mathrm{cm^2/GeV}]$ for $\gamma_a/\gamma_v = 1$, and $\sigma^\nu/E = 0.74\,[10^{-38}\ \mathrm{cm^2/GeV}]$ for $\gamma_a/\gamma_v = 1.5$. For $\gamma_a/\gamma_v = 1.5$ the dependence of σ^ν and $\sigma^{\bar\nu}$ on the energy is given in Fig. 3. For the given choice of parameters, the dependence of $\langle Q^2\rangle^\nu$ and $\langle Q^2\rangle^{\bar\nu}$ (here $Q^2 = -q^2$) on the energy and the form of the functions $F_2(x)$ and $xF_3(x)$ are shown in Figs. 4 and 5. The predictions for the dependence of the differential cross-sections for scattering of a neutrino by a proton and a neutron are given in Figs. 6 and 7, and the predictions

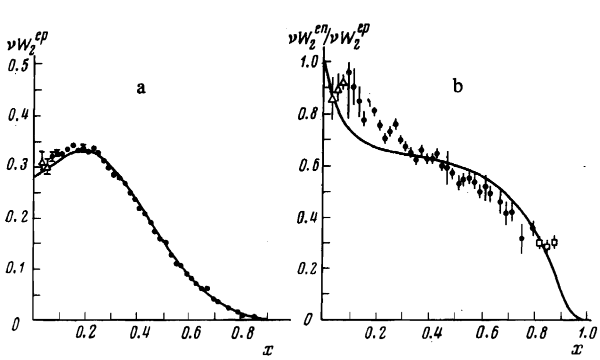

FIG. 2. Structure function γW_2^{ep} for the proton (a), and the ratio $\nu W_2^{en}/\nu W_2^{ep}$ of the structure functions for the neutron and proton (b); the points ● are from[6] and the references given there; Δ are from[22] and □ are from[23].

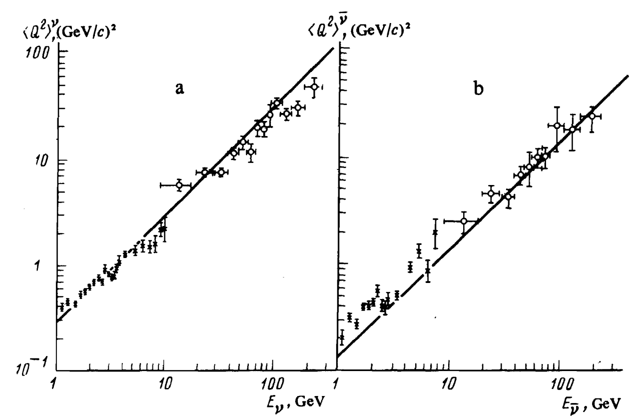

FIG. 4. Dependence of $\langle Q^2\rangle$ on the energy for scattering of a neutrino (a) and an antineutrino (b) by a nucleon[18,19] (× – Gargamelle, o – Harvard-Pennsylvania - Wisconsin). The straight lines are plotted for freon; $\langle Q^2\rangle^\nu = 0.28E_\nu$ and $\langle Q^2\rangle^{\bar\nu} = 0.13E_{\bar\nu}$.

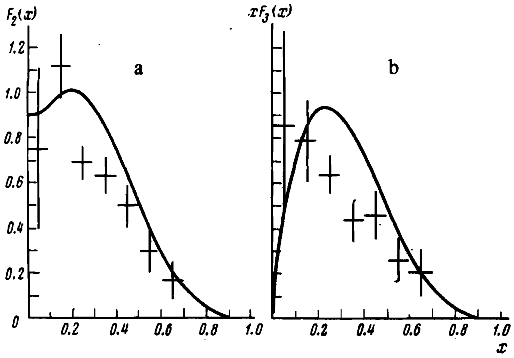

FIG. 5. Structure functions $F_2(x)$ (a) and $xF_3(x)$ (b) for scattering of a neutrino by a nucleon (freon target).[24]

for the values of σ^{ν}, $\sigma^{\bar{\nu}}$ and $\langle Q^2\rangle^{\nu}$, $\langle Q^2\rangle^{\bar{\nu}}$ are given in Table 2.

If we assume that $d_v(x)=d_s(x)$, then, with the values obtained for the parameters, the normalization condition (7) can be written in the form

$$0.92+0.066/\gamma_v^2+0.0013/\gamma_t^2=1. \qquad (34)$$

The probability of formation of diquarks should be proportional to the probability of overlap of two clouds of quarks, and is $\sim(r_0/R)^3$ (r_0 is the radius of the quark cloud and R is the hadron radius), and the probability of formation of a triquark is $\sim(r_0/R)^6$. The quark radius should be $\sim r_0\approx\sqrt{\alpha'}$,[14] where $\alpha'=0.25\ \text{GeV}^{-2}$ is the slope of the Pomeranchuk trajectory, and the hadron radius is of the order of the inverse ρ-meson mass: $R\approx m_\rho^{-1}=1.4\ \text{GeV}^{-1}$. It follows from this that $(r_0/R)^3\sim 0.04$, $(r_0/R)^6\sim 0.0016$. Comparison with (34) shows that we can put $\gamma_v=\gamma_t=1$. This means that the triquark can be regarded as a point particle.

In the analysis performed it was assumed that $SU(6)$ symmetry is not violated and $d_v(x)=d_s(x)$: the absence of interaction with a scalar diquark is due to its rapid fall-off with increase of momentum-transfer. Another variant in which the leptons do not interact with the scalar diquark ($d_s(x)=0$) is also possible. In this case, because of the normalization condition (7), the ratio between the distributions of the first and second valence

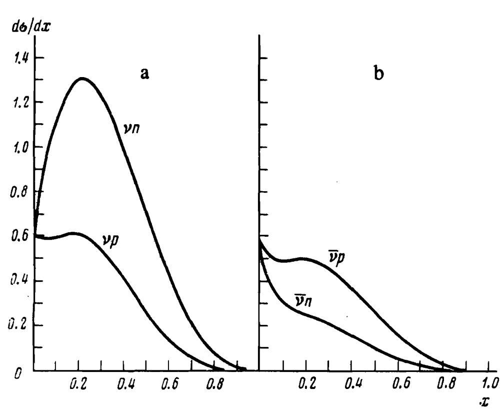

FIG. 6. Cross section $d\sigma/dx$ in units of G^2mE/π for scattering of a neutrino (a) and antineutrino (b) by a proton and neutron.

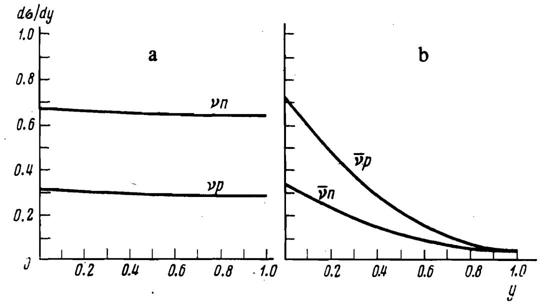

FIG. 7. Cross section $d\sigma/dy$ in units of G^2mE/π for scattering of a neutrino (a) and antineutrino (b) by a proton and a neutron.

quarks is slightly changed (by an amount ~ 0.03). Of course, such a small violation of the relationship between the valence quarks does not have any appreciable effect on the results of the model.

5. RELATIONS BETWEEN THE STRUCTURE FUNCTIONS-CRITERION FOR THE EXISTENCE OF DIQUARKS AND TRIQUARKS

In the construction of the model considered here, apart from the hypothesis of the existence of diquarks or triquarks within hadrons a number of definite assumptions have been made, such as the form of the distribution functions of the partons, the type of axial interaction of the diquarks, and the character of the behavior of the form factors of the diquarks and triquarks at large q^2. It is desirable, however, to have criteria which would not depend on these, more particular, assumptions, and which would give the possibility of determining whether diquarks or triquarks exist in hadrons. Relations between the structure functions in the interaction of leptons with neutrons and protons can serve as such tests for the existence of diquarks and triquarks. Diquarks make the principal contribution in the region $x\approx\frac{2}{3}$, and the ratio of the structure functions here is determined entirely by their charges. For electroproduction, with allowance for vector diquarks only, we have $\nu W_2^{en}(\frac{2}{3})/\nu W_2^{ep}(\frac{2}{3})\approx 3/11$. If for $x\to 1$ the principal contribution is given by triquarks, then $\nu W_2^{en}(1)/\nu W_2^{ep}(1)=0$. The valence quark-partons, which dominate for $x\approx\frac{1}{3}$, give $\nu W_2^{en}(\frac{1}{3})/\nu W_2^{ep}(\frac{1}{3})\approx\frac{2}{3}$.

Analogous predictions can also be made for neutrino reactions. If we introduce the ratios

$$r_\nu(x)=\frac{d\sigma^{\nu n}}{dx}\Big/\frac{d\sigma^{\nu p}}{dx},\qquad r_{\bar{\nu}}(x)=\frac{d\sigma^{\bar{\nu}p}}{dx}\Big/\frac{d\sigma^{\bar{\nu}n}}{dx},$$

then, in the region of dominance of vector diquarks, $r_\nu(\frac{2}{3})\approx r_{\bar{\nu}}(\frac{2}{3})\approx 9$, and in the region of dominance of triquarks, $r_\nu(1)=r_{\bar{\nu}}(1)\approx 4$. The valence quark-partons give

TABLE 2.

Reaction	σ_{tot}/E, $10^{-38}\ \text{cm}^2/\text{GeV}$	$\langle Q^2\rangle/E$, GeV/c
νp	0.44	0.25
$\bar{\nu}p$	0.40	0.14
νn	0.99	0.29
$\bar{\nu}n$	0.20	0.12

$r_\nu(\frac{1}{3}) = r_{\bar\nu}(\frac{1}{3}) \approx 2$. Such characteristic behavior of $r_\nu(x)$ and $r_{\bar\nu}(x)$ can serve as a good criterion for determining the role of coherent processes in nucleons.

The ratio $(d\sigma^{\bar\nu p}/dx)/(d\sigma^{\nu p}/dx)$ depends in an essential way on the relative contribution of the axial interaction. For the chosen form of the axial interaction, it is equal to 3.6 for $x \approx \frac{2}{3}$ and 1.3 for $x \approx 1$.

6. CONCLUSION

The compound quark-parton model with allowance for diquarks and triquarks gives, as we have seen, a good description of deep-inelastic processes. It leads to ratios $\nu W_2^{en}/\nu W_2^{ep}$ in agreement with experiment, with $x = \frac{1}{3}$ and $x = \frac{2}{3}$. At the present-day not-too-high energies, this is a completely natural result in the compound model, since for $-q^2 \lesssim 4\ \mathrm{GeV}^2$ we have every reason to expect large contributions from coherent processes. As already mentioned in the Introduction, the question of the role of coherent processes at realizable high energies requires further experimental study.

In constructing the model here we have assumed the absence of interaction between leptons and scalar diquarks (or, which is the same thing, the absence of scalar diquarks in the nucleon). This was dictated by the small experimental value of the ratio $\sigma^{\bar\nu}/\sigma^\nu = 0.38 \pm 0.02$.[18] The introduction of scalar diquarks led to $\sigma^{\bar\nu}/\sigma^\nu = 0.41$. This value does not contradict the experimental values obtained at high energies: $\sigma^{\bar\nu}/\sigma^\nu = 0.33 \pm 0.08$,[19] $\sigma^{\bar\nu}/\sigma^\nu = 0.41 \pm 0.11$.[20]

Thus, if we are guided only by the data at high energies, the possibility of the introduction of scalar diquarks is not closed. When scalar and vector diquarks are introduced with equal probability (as is required by $SU(6)$ symmetry), the ratio $\nu W_2^{en}(\frac{2}{3})/\nu W_2^{ep}(\frac{2}{3})$ is practically unchanged and will be equal to $\frac{1}{3}$. However, the quantities $r_\nu(\frac{2}{3})$ and $r_{\bar\nu}(\frac{2}{3})$ are extremely sensitive to the existence of an admixture of scalar diquarks in the nucleon. For scalar diquarks, $r_\nu = r_{\bar\nu} = 1$, whereas for vector diquarks $r_\nu = r_{\bar\nu} = 9$.

Naturally, the hypotheses of the existence of diquarks and triquarks in the nucleon are independent. The present experimental data do not give any special indications of the existence of triquarks. Their introduction into the present model is based only on a possible analogy between systems of two and three quarks at relatively small spacings. The hypothesis of the existence of triquarks also enables us to see that the vanishing of $\nu W_2^{en}/\nu W_2^{ep}$ as $x \to 1$ does not contradict the quark-parton structure of hadrons. In the framework of the parton picture the existence of point triquarks should lead to the same dependence of the magnetic and electric form factors of the proton on q^2 at large transfers: $G_E^p(q^2)/G_M^p(q^2) = \mathrm{const}$, and this is in agreement with experiment, right up to large q^2 (see the review[21]). In addition, the neutron form factors should fall off faster than the proton form factors: $G_M^n(q^2)/G_M^p(q^2) \to 0$ as $q^2 \to \infty$. The existing experimental data for $G_M^n(q^2)$ for comparatively small transfers ($-q^2 < 2\ \mathrm{GeV}^2$) do not point to a rapid decrease of the neutron form factor. However, the experimental data for $2\ \mathrm{GeV}^2 < -q^2 < 7\ \mathrm{GeV}^2$ give only an upper bound on $G_M^n(q^2)$ and do not contradict $G_M^n/G_M^p \to 0$.[21]

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2)This structure for the current arises if we assume the diquark to be a compound system of two quark-partons. Transfer of a large momentum to the diquark occurs in the case when, in the Breit system, the whole of its momentum is carried by one of the quark-partons. The interaction with this quark-parton leads, after summation over all possible spin states, to formulas (9) and (10).

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