INTERNAL HADRON STRUCTURE AND HIGH ENERGY HADRON COLLISIONS

By L. Van Hove

CERN-Geneva*

(*Received February 28, 1976*)

This paper continues recent work by Pokorski and the present author on the description of high energy hadron collisions by means of the quark-glue model of hadron structure. It gives a concrete example of joint distribution $g(x_1, x_2, x_3)$ of the nucleon valence quarks which reproduces the deep inelastic structure functions of both proton and neutron for $x \gtrsim 0.2$–0.3 and gives at the same time a realistic leading particle spectrum for non-diffractive pp collisions. Additional contributions to the structure functions are discussed, in particular, the physical reasons for their concentration at small x. The extension of the quark-glue model to hadron-nucleus collisions is briefly discussed.

1. *Introduction*

In previous papers in collaboration with Pokorski [1], [2], nondiffractive hadron-hadron collisions at high energy were discussed in terms of the quark-glue model of internal hadron structure, which is known to describe successfully deep inelastic lepton-nucleon scattering. The present paper completes Ref. [2] on various aspects of the model.

One of the most interesting conclusions extracted from the quark-glue model analysis of lepton-nucleon processes is that, on the average, about half the momentum of a high energy nucleon is carried by neutral stuff (the "glue") deprived of leptonic interactions in the deep inelastic region, the other half being carried almost entirely by the valence quarks. Whereas the glue is thereby recognized, energetically speaking, to be as important a constituent of the nucleon as the quarks, it has only a passive role of spectator in deep inelastic lepton-nucleon scattering.

The situation is reversed in our model of non-diffractive hadron-hadron collisions [1], [2], where the active role is attributed to the glue, the quarks being treated as spectators. More precisely: in a common non-diffractive collision (i.e., a small p_T collision) at high energy ($E_{cm} \gtrsim 20$ GeV), the glue of one incident hadron interacts strongly with the glue

* Address: CERN, Geneva 23, Ch-1211, Switzerland.

of the other and the resulting high state of excitation of the glue field is at the origin of the pionization observed in the central region of rapidity. The quarks, on the other hand, are assumed to fly through with their original share of c.m. momentum, after which they dress up again with glue and give rise to the "leading" hadrons emerging from the collisions (protons or proton isobars in the case of proton-proton collisions).

As was shown in Ref. [2], the quark-glue model of high energy hadron-hadron collisions establishes a direct relation between the p_L distribution of the leading hadrons emerging from non-diffractive collisions and the x distribution of the valence quarks in the incident hadrons. The rather flat p_L distribution of the leading hadrons was shown to be naturally related to the steeply falling x distribution of valence quarks derived from the deep inelastic lepton-nucleon scattering experiments. Our treatment in Ref. [2] was only qualitative; it neglected the difference between the x distribution of p- and n-type quarks in the nucleon, and it did not work out the absolute normalization of the distributions.

The first aim of the present paper is to deal with these questions. Section 2 describes and discusses an example of joint distribution $g(x_1, x_2, x_3)$ of the valence quarks in the nucleon which reproduces the x distributions of p- and n-quarks for $x \gtrsim 0.2$–0.3 and has the correct absolute normalization.

Section 3 is devoted to the region of small x, where the valence quarks do not account for the full amount of observed deep inelastic scattering. We discuss in the framework of our model the two additional mechanisms of scattering on quark-antiquark pairs and diffractive vector meson production, in particular, the reasons for their concentration at small x. The last section comments on two further points: the case where quarks carry a colour quantum number, and the extension of our model to high energy hadron-nucleus collisions. It ends with a brief summary.

2. *The valence quark distribution function of the nucleon*

Neglecting quark-antiquark pairs, we regard the nucleon to consist of 3 (valence) quarks and glue, and we denote by $g(x_1, x_2, x_3)$ the joint distribution function of the 3 quarks in a high energy nucleon, x_i being the fraction of nucleon momentum carried by the i-th quark. The index assignment is the following:

$i = 1$: unlike quark (n-type in proton, p-type in neutron)

$i = 2, 3$: like quarks (p-type in proton, n-type in neutron).

We go beyond the simplifying assumption of full symmetry made in Ref. [2] and take the proton-neutron difference into account, which means that we have only symmetry between like quarks

$$g(x_1, x_2, x_3) = g(x_1, x_3, x_2). \tag{1}$$

The normalization of g is

$$\int_T g(x_1, x_2, x_3) dx_1 dx_2 dx_3 = 1. \tag{2}$$

The integration domain T is defined by

$$0 < x_1, x_2, x_3, \quad x_1+x_2+x_3 < 1. \tag{3}$$

It is the tetrahedron OABC in Fig. 1 of Ref. [2].

The single quark distribution functions are

$$f_l(x) = \int_T g(x_1, x_2, x_3)\delta(x-x_i)dx_1\,dx_2\,dx_3, \quad i = 2 \text{ or } 3, \tag{4}$$

$$f_u(x) = \int_T g(x_1, x_2, x_3)\,\delta(x-x_1)dx_1\,dx_2\,dx_3, \tag{5}$$

for the like and unlike quarks, respectively. The contributions of the 3 (valence) quarks to the deep inelastic structure functions νW_2 of proton and neutron are

$$f_p(x) = (8f_l(x)+f_u(x))x/9, \quad f_N(x) = (2f_l(x)+4f_u(x))x/9, \tag{6}$$

with the usual incoherent approximation and quark charge assignments ($\frac{2}{3}$, $-\frac{1}{3}$). We want to find a function g such that (6) will give a good approximation to the full νW_2 for $x \gtrsim 0.2-0.3$ (it is known that the valence quarks alone cannot account for the full νW_2 at small x).

In our quark-glue picture of purely hadronic collisions, the distribution of leading hadrons emerging from non-diffractive nucleon-nucleon collisions is related to $g(x_1, x_2, x_3)$ by the simple equation [2]

$$F(x) = \int_T g(x_1, x_2, x_3)\,\delta(x-x_1-x_2-x_3)dx_1\,dx_2\,dx_3, \tag{7}$$

where x is the centre-of-mass Feynman variable $x = |p_L|p_{cm}^{-1}$ of either leading hadron. We have only indirect experimental information on $F(x)$, even in the best known case of pp collisions. Firstly, in our picture, the leading hadron emerging from the collision is not always a proton but may be an excited proton part of the time. Secondly, the separation of non-diffractive collisions from diffraction dissociation processes is ambiguous.

Nevertheless, as argued in Ref. [1], it seems reasonable to take $F(x)$ as given approximately by the outgoing proton spectrum ($\propto d\sigma/dx$) of ISR collisions for $0.2 \lesssim x \lesssim 0.8$. The data suggest a rather flat spectrum over this interval. For our discussion, we shall adopt for $F(x)$ the parametrization

$$F(x) = (1-x^n)\,(n+1)/n, \tag{8}$$

with n large ($n \simeq 13$), giving a flat $F(x)$ for $0 < x \lesssim 0.8$, with a rapid drop to 0 for $x \to 1$.

The question is then to make a reasonable guess for the function g so as to fulfil (7) and (8) while obtaining for (4) to (6) values agreeing at $x \gtrsim 0.25$ with the experimental data on νW_2. The problem has of course an infinity of solutions. We try to find a simple one by considering a limited class of functions:

$$g(x_1, x_2, x_3) = F(x_1+x_2+x_3)\,\bar{g}(x_1, x_2, x_3), \tag{9}$$

with $\bar{g}$ homogeneous of degree -2 and normalized to 1. Eq. (7) is then automatically fulfilled.

By trial and error we found the interesting fact that the regions $x \simeq 0.2$–0.3 and $x \gtrsim 0.5$ tend to impose opposite conditions on $\bar{g}$. To make the single quark distributions f_u, f_l drop for $x \to 1$ as fast as required by the deep inelastic data, one is led to concentrate $\bar{g}$ toward the central region of the domain T (the region where $x_1 \simeq x_2 \simeq x_3$). This, however, makes f_u and f_l large at $x \simeq 0.25$. The expressions (6) then even tend to exceed the experimental values of the structure functions, which is impossible if the contributions of the valence quarks and other mechanisms add up incoherently. This constraint is a consequence of our requirement to have $F(x)$ flat for $x \lesssim 0.8$. In fact, our approach would get into difficulties if the leading hadron spectrum of non-diffractive pp collisions would increase with x for, say, $0.4 \lesssim x \lesssim 0.8$. On the contrary, a certain decrease of the spectrum in this interval (as suggested by the data, see Fig. 2a of Ref. [1]) would be easy to accomodate.

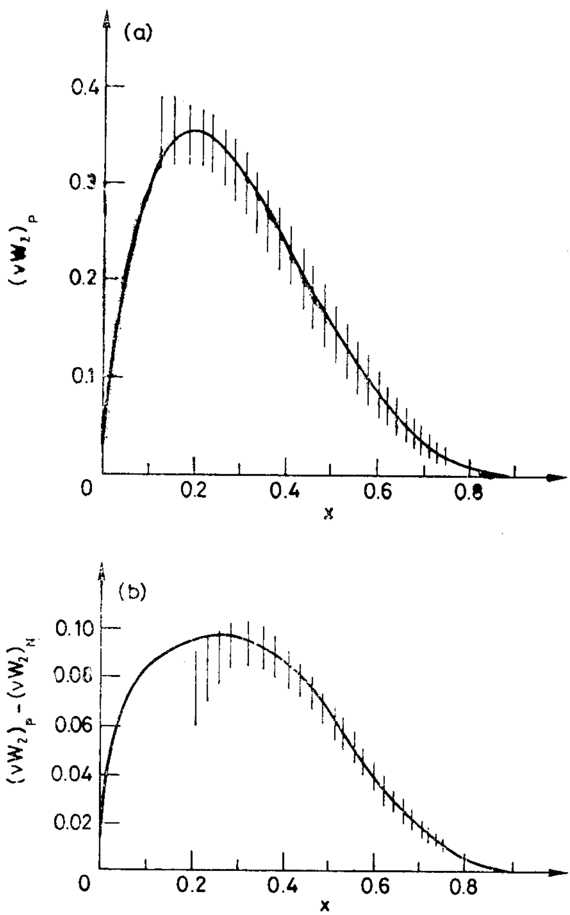

Fig. 1. The solid lines represent, for the ansatz of Eqs. (8)–(10), the valence quark contributions to the proton structure function (a), and the difference of proton and neutron structure functions (b). The shaded bands indicate the trend of the data; for (a) it is the same as in Fig. 2 of Ref. [2], for (b) the data used are from Fig. 1b of Ref. [3]

For the value $n = 13$ mentioned above, it turns out that the very simple function

$$\bar{g}(x_1, x_2, x_3) = 20x_1(x_2+x_3)^2/(x_1+x_2+x_3)^5 \tag{10}$$

gives a satisfactory description of $(\nu W_2)_P$ for $x \gtrsim 0.2$ and of $(\nu W_2)_N$ for $x \gtrsim 0.3$. This is illustrated in Figs. 1a and 1b where the solid lines correspond to the valence quark contributions and the shaded bands indicate the trends of the data. The main characteristics of (10) and of the resulting function g is that the ratio $g(1-\varepsilon-\varepsilon, \varepsilon, \varepsilon')/g(\varepsilon, \varepsilon', 1-\varepsilon-\varepsilon')$ tends to zero for $\varepsilon, \varepsilon' \to 0$, corresponding to the physical property that nucleon configurations with an unlike quark carrying most of the nucleon momentum are much less likely than those where a like quark does.

The discrepancies between theoretical curves and data in Fig. 1 are such that

$$f_P(x) < (\nu W_2)_P \quad \text{for} \quad x \lesssim 0.2, \quad f_N(x) < (\nu W_2)_N \quad \text{for} \quad x \lesssim 0.3.$$

Hence, the additional contributions to the structure functions are positive as they should be and are concentrated at small x. It would be more satisfactory if one could achieve $f_N \simeq (\nu W_2)_N$ for x down to 0.2, i.e., for the same x range as in the proton case. While this is undoubtedly possible by making $\bar{g}$ non-zero near the points $x_1 = 0$, $x_2 = x_3 \neq 0$, we have not found a simple ansatz giving a clear improvement of f_N for $0.2 \lesssim x \lesssim 0.3$. For $x \to 1$, our functions f_P, f_N approach zero as $(1-x)^4$, i.e., faster than predicted by the Drell–Yan relation. The trend of the data seems to go in the same direction [4].

We close this section by noting that it is not quite trivial to have a 3-quark distribution function as simple as the one given above fulfil the constraints imposed upon it. Regarding shapes of the structure functions for $x \gtrsim 0.25$, this success is controlled by the general shape of the leading particle spectrum and the fact that 3 quarks are involved (see Ref. [2] for a qualitative discussion of the meson case, where this number is 2 and our scheme predicts structure functions of quite different shape than for the nucleon). As to the agreement in normalization, it is of course due to the values $^2/_3$, $-^1/_3$ used for the quark charges.

One remark should be added, however, on our factorization assumption (9). It has been made for convenience only, and we believe that it should not be taken seriously in the domain of small $x_1+x_2+x_3$ where one could as well replace $\bar{g}$ by $2(x_1+x_2+x_3)^{-2}$, its mean value on the triangle $x_1+x_2+x_3 = \text{const}$. Except for this reservation, there is a real possibility that the 3-quark distribution in the nucleon is not too different from the function $g(x_1, x_2, x_3)$ given by (8–10) with $n \simeq 13$.

3. *Additional contributions to the structure functions at small x*

As is well known, the nucleon structure functions νW_2 contain small x contributions additional to those of the valence quarks. It has become conventional to attribute them to additional pointlike constituents, usually assumed to form a "sea" of quark-antiquark pairs. Fits to the data then lead to a sea containing many, perhaps infinitely many, $q\bar{q}$ pairs, but carrying in total a small fraction of the nucleon momentum. Another type of mechanism commonly taken to contribute to νW_2 is vector meson dominance (VD), usually in the generalized form (GVD) [5]. It can be made to account for the whole of νW_2[5], or for the part not due to the valence quarks [6].

The present section comments briefly on these contributions in the framework of our approach. The main point is that in our case all contributions additional to those of the valence quarks must be concentrated at small x. Indeed, as explained above, it is a characteristic of our model that the rapid drop of f_u, f_l for $x \to 1$ forces these functions to saturate the data around $x \simeq 0.2 - 0.3$.

We discuss first the contribution of $q\bar{q}$ pairs. Such a contribution is naturally expected to exist , for the simple reason that glue must interact with quarks, which implies that any state of the glue field must contain virtual $q\bar{q}$ pairs. As will now be argued, the fact that these pairs have low x values is related to the strength of the glue field in the nucleon ground-state.

If the glue field is strong, it will be mainly composed of multi-gluon states (we refer here to Fock representation states). In the spirit of the constituent model, each gluon will have a small fraction of the total momentum carried by the glue (which is itself on the average about half of the nucleon momentum). Similarly, whenever a gluon is virtually replaced by a $q\bar{q}$ pair, the momentum fraction of the latter will be equally small. For a n-gluon state, we expect on the average $x \sim 1/4n$ per q or $\bar{q}$ in the sea of $q\bar{q}$ pairs. On the other hand, if the glue field were so weak to be mainly composed of single-gluon states, the same reasoning would give on the average $x \sim 1/4$ per q or $\bar{q}$ of $q\bar{q}$ pairs, which is too large a value to be accommodated by the data.

We now turn to GVD-type contributions to the structure functions of the nucleon. We first note that such contributions are also expected to be present in our model, the main source being inelastic diffraction where the virtual photon materializes into a vector meson state off the nucleon (which may itself be excited, but the latter case of double diffraction dissociation has by factorization a smaller cross section than the photon materialization). The question is again why such processes are concentrated at small x values. For the diffractive process

$$\gamma_{\text{virtual}} + \text{nucleon} \to \text{vector meson} + \text{nucleon}$$

the minimum momentum transfer squared is

$$-t_{\min} \simeq M^2 x^2 (1-x)^{-1},$$

with M the nucleon mass. The requirement of small x therefore corresponds to the condition that the GVD mechanism is limited to the range

$$(-t_{\min})^{1/2} \ll M, \tag{11}$$

which is reasonable for diffractive processes. We note that a similar limitation on GVD has been proposed in Ref. [6] on other grounds.

It would be interesting to estimate the size of $q\bar{q}$ pair and GVD contributions to νW_2. We unfortunately have no reliable way to do this. On the question of their separation, one could remark that $q\bar{q}$ pair contributions should have Bjorken scaling (to the same approximate degree as the valence quark contributions), but that there is no a priori reason for diffractive vector meson production to have the scaling property. Also deep inelastic neutrino reactions may help to disentangle the two classes of contributions.

4. *Further remarks*

In this closing section we comment briefly on two additional questions: the consequences for the quark-glue model of hadron-hadron collisions if quarks carry a colour quantum number, and the extension of the model to hadron-nucleus reactions. The problem of inelastic diffraction in the quark-glue model is treated in a separate publication in collaboration with Fiałkowski [7].

If one considers only the ordinary quantum numbers (Q, B, S, I, G parity, broken SU(3) symmetry), one of course expects the glue to be neutral, and so will be the virtual $q\bar{q}$ pairs coupled to it. There may be additional quantum numbers, however, such as charm or colour. Charm would appear through virtual $c\bar{c}$ pairs in the glue, the heavy mass of the charmed quark c tending to make them less abundant than ordinary $q\bar{q}$ pairs. As to colour, we note the following point which is specific to our quark-glue model of hadron-hadron collisions. The model requires that the glue be essentially in a colour singlet state, with the same property for the valence quarks. This appears clearly in non-diffractive hadron-hadron collisions, where the valence quarks are assumed to fly through and to give rise to the leading particles, which are of course colour singlets.

We come now to the question of hadron-nucleus reactions. This has become an important aspect of high energy hadrodynamics, because many features of multiparticle production in nuclei have been experimentally found to contradict theoretical expectations derived from simple cascade models. It appears that the particle production process can better be understood by assuming that it develops with a considerable degree of coherence in the course of the propagation of the energetic hadron through the nucleus, and not as a cascade-like succession of individual hadron-hadron collisions. A variety of models exist, but there is no consensus yet on the correct description of the process.

One model developed by Kalinkin, Shmonin and others [8] is of particular interest for our approach. It is reviewed in Ref. [9] which also gives a brief summary of the most relevant experimental facts (we refer to Gottfried [10] and Zalewski [11] for reviews of the whole subject). The general ideas underlying the model of Kalinkin et al. go back to earlier work, e.g. by Miesowicz and Feinberg [12]. The main assumptions are:

(*i*) The energetic "leading particle" originating from the first collision of the incident hadron has a negligible amount of inelastic interaction with downstream nucleons in the target nucleus.

(*ii*) A hadronic system called "cluster" is formed in the first collision. While propagating through the nucleus and colliding with successive nucleons, it increases its effective mass and its radius. After leaving the nucleus it disintegrates, mostly into pions.

The work of Kalinkin et al. is based on specific and rather oversimplified equations for the cluster propagation and decay. Compatibility with the main data is found at the crude level which still characterizes all work on hadron-nucleus collisions.

What interests us here is the fact that the assumptions (*i*) and (*ii*) agree with the qualitative predictions of the quark-glue model applied to hadron-nucleus collisions. In the model the valence quarks of the incident hadron can be assumed to fly through the whole nucleus with their original fraction of incident momentum. By time dilation, they will dress up again with glue only after leaving the nucleus. This corresponds to assumption (*i*). The glue of the incident hadron, on the other hand, gets in strong interaction with the glue of successive target nucleons. As a result, a glue droplet or "cluster" of increasing internal excitation energy will form and propagate through the nucleus. After leaving the nucleus it will decay into normal hadrons. This corresponds to assumption (*ii*). Our approach thus gives an interpretation in terms of quarks and glue for the "leading particle" and the "cluster" of Kalinkin et al. Of course, their specific equations for cluster propagation and decay must be replaced in our model by the a priori unknown equations describing the propagation and decay of the glue droplet. The natural procedure in our case will be to learn from the data about the unknown dynamics of the glue field.

We end with a brief summary. We have given an example of joint distribution function $g(x_1, x_2, x_3)$ for the valence quarks of the nucleon, which combines the following properties:

(*i*) it reproduces the deep inelastic structure function νW_2 of the proton for $x \gtrsim 0.2$ and of the neutron for $x \gtrsim 0.3$.

(*ii*) it gives a realistic leading particle spectrum for non-diffractive pp collisions.

For the small x region, we have argued that the concentration of $q\bar{q}$ pairs at $x \lesssim 0.2$ is related to the fact that the glue field in the nucleon ground-state is dominated by multi-gluon components. As to the contribution of vector meson induced processes, it must be restricted to small x, corresponding to diffractive collisions with momentum transfers small compared to the nucleon mass.

In case colour exists, our model implies that in the nucleon ground-state the glue field and the set of valence quarks are each dominantly in colour singlet states. Finally, we have considered hadron-nucleus collisions and noted that the qualitative predictions of the quark-glue model agree with the basic assumptions of an existing model for hadron--nucleus collisions.

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