The structure of a finite hadronic state in deep inelastic scattering

L. V. Gribov, Yu. L. Dokshitzer, S. I. Troyan, and V. A. Khoze
B. P. Konstantinov Institute of Nuclear Physics, Academy of Sciences of the USSR

(Submitted 12 March 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **45**, No. 9, 405–407 (10 May 1987)

The QCD structure of a finite hadronic state in deep inelastic scattering is discussed. Special attention is focused on the physics of the chromodynamic coherence.

It is known that the study of deep inelastic lepton-hadron scattering (DIS) has played a key role in the development of quantum chromodynamics as the present theory of strong interactions (see e.g., Ref. 1). The interest in DIS QCD physics, however, has recently diminished considerably. In particular, the structure of the final states[1] has only been recently analyzed theoretically in a systematic way and the role of chromodynamic coherence has only been recently understood. At the same time, experimental attention regarding this matter is increasing, especially in view of the new possibilities provided by the next-generation colliders (HERA, LHC, SSC).

In this letter we summarize the results of the QCD analysis of the final-particle distributions in DIS and we focus attention on the role of coherent phenomena in the evolution of the parton system in the spacelike momentum range (see Ref. 4 for a detailed discussion of this subject; see also Ref. 5).

The underlying feature of deep inelastic *eN* scattering is the absorption of a virtual photon by a quark-parton in a field cloud of a nucleon, whose parton wave function is controlled by a perturbative QCD and can be described in terms of the decay of the original dressed particle (a valence quark, for example) into quarks q and gluons g with gradually increasing $k_\perp$ (virtualities).

The DIS process with a momentum transfer, $-q^2 \gg \Lambda^2$, and a fixed Bjorken variable x isolates those parton fluctuations where there is a quark-parton k with a fraction of the momentum $x = k/p$ (p is the target momentum) at a corresponding level of virtuality $k_\perp^2 \lesssim -q^2$. A part of these configurations specifies the cross section of the process—the structural functions of the deep inelastic scattering.

The structure of the final state is determined by two phenomena: the decay of the parton fluctuation which is set up long before the interaction and whose coherence is destroyed by the "exclusion" of the virtual q (target fragmentation) and by the evolution of the knocked-out quark (current fragmentation).

The Breit reference frame is the most natural one for the description of the DIS process ($q_0 = 0.2\,x\mathbf{p} = -\mathbf{q}$), where the target and current fragmentation productions are clearly divided kinematically.

From the viewpoint of the color transfer, this process takes on the form of the dispersion of the 3 and $\overline{3}$ color states (the knocked-out q and "excited" nucleon as a

0021-3640/87/090515-04$01.00

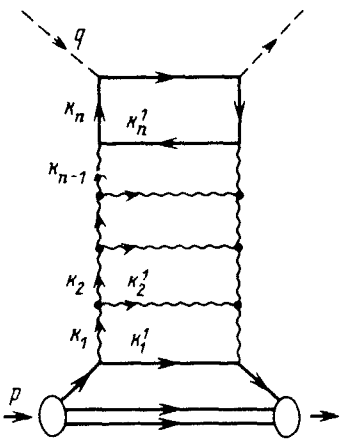

FIG. 1. A representative ladder diagram for deep inelastic scattering cross section for small values of x.

whole). In the current fragmentation the bremsstrahlung that accompanies the emission of q leads to the formation of a jet which is identical to the q jet in e^+e^- annihilation at an energy $w=\sqrt{-q^2}$. In particular, a "bulging" plateau, which is caused by the coherence of the soft gluon radiation, such as the one in Ref. 6, appears in the energy spectrum of the products.

The situation is much more complicated in the target fragmentation region. Its internal color structure is seen most clearly at $x\ll 1$, where the DIS is determined by multistepped ladders of the type shown in Fig. 1, and the source of the sea quarks are the bremsstrahlung pairs q and $\bar{q}$ of nearly the same rapidity in the color octet state (the gluon exchange in the t channel). We wish to emphasize that the underlying feature of the random radiation which accompanies the development of the spacelike fluctuation is the angular order, as in the case of the timelike cascade.[4,5] Here the shape of the resulting energy distribution ω of the particles h, which is attributable to the cascade multiplication of partons, is markedly different from the current fragmentation. A complete answer to this distribution is provided by the sum of the three contributions, I, II, III, two of which correspond to the region $\omega\leqslant q$. The first contribution, which is linked with the upper quark cell in Fig. 1, is identical to the spectrum in the current fragmentation region:

$$\left(\frac{d\sigma^h}{\sigma dy}\right)_{\rm I}=\frac{C_F}{N_c}\left[\frac{\omega}{q}\,\bar{D}_g^h\left(\frac{\omega}{q},\ \ln\frac{q}{\Lambda}\right)\right],\qquad y=\ln\frac{\omega}{\Lambda}\,, \tag{1}$$

The fragmentation structure function $\bar{D}$ is identical to the annihilation structure function.

The second contribution is a soft collective emission from the "depth of the ladder," which is approximately the same as the emission by the g jet with a vertex angle $\theta_{k'_n}$:

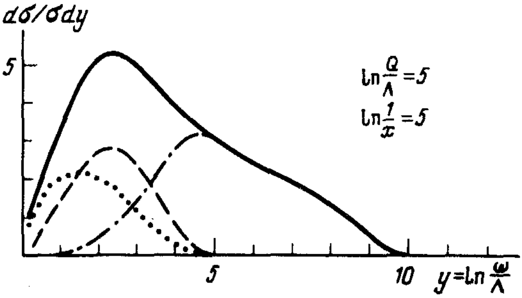

FIG. 2. Contribution of particles to the energy spectrum in the target fragmentation region for $\ln(q/\lambda) = 5$ and $\ln(1/x) = 5$. I—Contribution from the upper quark cell (dotted curve); II—coherent t-channel emission (dashed curve); III—fragmentation of the ladder rungs (dot-dashed curve). Solid curve—resultant spectrum.

$$\left(\frac{d\sigma^h}{\sigma dy}\right)_{\rm II} = \frac{1}{D_p^q(x, q^2, \mu^2)} \int_0^{\ln(q/\Lambda)} d\ln\frac{k_\perp}{\Lambda} \frac{\partial}{\partial \ln k_\perp} D_p^q(x, k_\perp^2, \mu^2) \left[\frac{\omega}{q} \bar{D}_g^h\left(\frac{\omega}{q}, \ln\frac{k_\perp}{\Lambda}\right)\right] . \tag{2}$$

The third contribution combines the fragmentation of the structural ladder rungs and the t-channel radiation of the "relatively soft" gluons l: $q < l < p$

$$\left(\frac{d\sigma^h}{\sigma dy}\right)_{\rm III} = \frac{1}{D_p^q(x, q^2, \mu^2)} \int_q^p \frac{dl}{l} \int^{\xi_q} d\xi_k\, D_p^g\left(\frac{l}{p}, k_\perp^2, \mu^2\right) \frac{\partial^2}{\partial \xi_k^2} D_g^q\left(\frac{q}{l}, q^2, k_\perp^2\right)$$

$$\times \int_\Lambda^{k_\perp} \frac{dl_\perp}{l_\perp} \frac{\alpha_s(l_\perp^2)}{2\pi} \left[\frac{\omega}{l} \bar{D}_g^h\left(\frac{\omega}{l}, \ln\frac{l_\perp}{\Lambda}\right)\right] , \tag{3}$$

where

$$\xi_k = \frac{1}{b} \ln \ln \frac{k_\perp}{\Lambda} \quad \left(d\xi_k = \frac{\alpha_s(k_\perp^2)}{2\pi} d\ln k_\perp\right) .$$

Figure 2 shows the individual contributions. The contributions II and III, which are unimportant as $x \sim 1$, increase with decreasing x. These contributions account for the asymmetry of the spectrum.

The relative strength of the soft t-channel radiation (II), in comparison with I, is determined by the characteristic angle of emission of the sea quark k_n', which increases with increasing number of cells, i.e., with $\ln(l/x)$ [see Eq. (2)].

The angular structure of the principal ladder is also responsible for contribution III. The most energetic particles, $q \ll \omega \lesssim p$, are produced in the lower part of the ladder, where the angles of emission of the partons and hence the vertex angles of the fragmenting "subjects" are small. This circumstance limits the cascade multiplication of particles. As a result, the "plateau" height decreases monotonically with increasing $\ln \omega$.

It is important to note that structural parton fragmentation (III) does not affect the region of the spectrum $\omega < q$. This coherent phenomenon was predicted by Gribov on the basis of general physical considerations, using the old parton model.[7]

Like in the e^+e^- annihilation, the QCD coherence in DIS causes the energy spectrum of particles to harden.

The number of slow particles $[\ln(\omega/m) \lesssim 1]$ should not depend on q^2.

We wish to thank V. N. Gribov, L. N. Lipatov, A. Muller, and V. S. Fadin for useful discussions.

[1)] Some aspects of this problem were discussed in Refs. 2 and 3.

[1] Yu. L. Dokshitzer, D. I. Dyakonov, and S. I. Troyan, Phys. Rep. Ser. C **58**, 269 (1980); G. Altarelli, *ibid.*, **81**, 1 (1982); D. W. Duke and R. G. Roberts, *ibid.*, **120**, 276 (1985).
[2] L. V. Gribov and M. G. Ryskin, Preprint LIYaF-865, 1983.
[3] A. Bassetto, Nucl. Phys. Ser. **B202**, 493 (1982); A. V. Kiselev and V. A. Petrov, Yad. Fiz. **38**, 1304 (1983) [Sov. J. Nucl. Phys. **38**, 792 (1983)]; Preprint IHEP 85-10, Serpukhov, 1985.
[4] L. V. Gribov, Yu. L. Dokshitzer, S. I. Troyan, and V. A. Khoze, Proceedings of the XXII Winter School, Leningrad Institute of Nuclear Physics, Leningrad, 1987.
[5] Yu. L. Dokshitzer, V. A. Khoze, and S. I. Troyan, Preprint LNPI-1218, 1986.
[6] Ya. I. Azimov, Yu. L. Dokshitzer, S. I. Troyan, and V. A. Khoze, in Elementary Particle Physics. Proceedings of the XX Winter School, Leningrad Institute of Nuclear Physics, Leningrad, 1985, Vol. 1, p. 82.
[7] V. N. Gribov, in Proceedings of the VIII Winter School, Leningrad Institute of Nuclear Physics, Leningrad, 1973, Vol. 2, p. 5.

Translated by S. J. Amoretty