Production of hadrons with large transverse momenta in deep inelastic lepton scattering

N. N. Nikolaev

L. D. Landau Institute of Theoretical Physics, USSR Academy of Sciences
(Submitted May 21, 1974)
ZhETF Pis. Red. **20**, 202–206 (August 5, 1974)

Production of hadrons with large transverse momenta in deep inelastic scattering of leptons by hadrons is discussed. It is shown that the transverse momenta in the spectrum should have a minimum at $p_\perp \simeq 1/2\sqrt{Q^2}$. Scaling properties of the spectrum in $z = p_\perp/\sqrt{Q^2}$ as a function of Q^2 and x are predicted.

The present article discussed the production of hadrons with large transverse momenta $p_\perp$ in deep inelastic lepton-hadron scattering. We are interested mainly in the possibility of verifying in these processes the mechanism whereby hadrons with large $p_\perp$ are produced as a result of large-angle parton-parton scattering, followed by fragmentation into final hadrons.

In the Breit system, where the virtual-photon energy is zero, the photon is absorbed by a parton with momentum $xp_z \approx \frac{1}{2}\sqrt{Q^2}$ whose momentum reverses sign, while the remaining partons retain their momenta.[1] Since the transverse momenta of the partons are small and bounded, nor are large momenta produced by interaction with the photons, it is clear that hadrons with large $p_\perp$ can be produced within the framework of the parton model only if the recoil parton is large-angle scattered by one of the remaining partons of the hadron, followed by fragmentation into the final hadrons.

This mechanism of production of large-$p_\perp$ particles has been under detailed discussion in the recent literature, and is successfully used to describe the experimental data on the production of particles with large $p_\perp$ in hadron-hadron collisions (see, e.g.,[2,3] and the reference cited therein). There is, however, one important difference between hadron-hadron and lepton-hadron interactions. Namely, in hadron-hadron interactions we are dealing with the mutual scattering of two partons that come from different hadrons. In lepton-hadron processes, on the other hand, two partons from one and the same hadron should be scattered by each other. The probability of such a process is determined by the two-parton distribution function, which should have a minimum when the parton momenta coincide, owing to repulsion of partons having close rapidities. In the Breit system this should lead to an irregularity of a plateau type in the $p_\perp$ spectrum at an angle $\theta = 90°$, or even to a minimum at $z = p_\perp/\sqrt{Q^2} = 1/2$.

What is important is that the repulsion of the partons at small rapidity differences is a universal property of all the parton models, for otherwise no equilibrium parton density is possible in the limit. Therefore the prediction that the $p_\perp$ spectrum will have a plateau or a minimum at $z = 1/2$ is tantamount to predicting a parton-parton scattering mechanism common to all parton models, so that its experimental confirmation would also be a weighty argument in favor of the parton model.

The most convenient quantity for analysis is the inclusive spectrum $f(Q^2, x, z)$ integrated with respect to ν. If the recoil parton is assumed to be on the mass

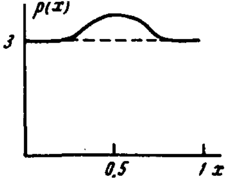

FIG. 1.

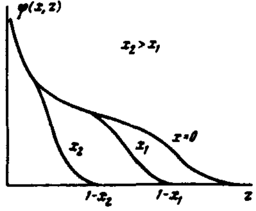

FIG. 2.

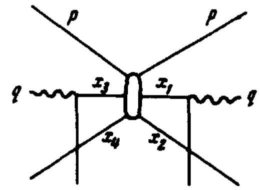

FIG. 3.

shell, then we have for the production of one fast hadron at an angle $\theta = 90°$, within the framework of the described mechanism,

$$f(Q^2, x, z) = \frac{d^3\sigma}{dQ^2 d\Omega dz} \Big/ \frac{d\sigma}{dQ^2} \cong A\, v(x, x_2) F_h(z^2 Q^2) \frac{x(1-z)}{z}. \qquad (1)$$

Here $F_h(z^2Q^2)$ is the probability of the transition of a parton, moving at an angle $\theta = 90°$, into one fast registered hadron h, while $v(x, x_2)$ is the density of partons with momentum px_2, from which a recoil parton with momentum-px is scattered. From the elastic-scattering kinematics we have $x_2 = xz/(1-z)$, and it is accounted-for in (1) that the differential cross section for the scattering of pointlike partons is given by $d\sigma/d\Omega \sim 1/s_{12}$ with $s_{12} \approx Q^2 z/(1-z)$.

The probability $F_h(z^2, Q^2)$ of transition of a parton into one hadron should have the simpler power-law form

$$F_h(z^2Q^2) \cong (z^2Q^2)^{-C_h} \qquad (2)$$

where the exponent C_h should apparently be the same as in the electromagnetic form factor of the hadron h, by virtue of the "parton-hadron" duality.[4]

If $|\ln[x_2/x]| \gtrsim \rho$, where ρ is the radius of the short-range rapidity correlations, then $v(x, x_2)$ does not depend on x, and $v(x, x_2) = u(x_2)$, where $u(x)$ is the single-parton distribution function. At $x \approx x_2$, owing to the parton repulsion at short distances, $v(x, x_2)$ should have a minimum that leads respectively to a minimum in the transverse-momentum spectrum at $z \approx 1/2$. On the other hand if $x + x_2 \to 1$, then $v(x, x_2)$ decreases rapidly: $v(x, x_2) \approx (1 - x - x_2)^{p(x)}$. It is known from experiment for the one-parton density that $u(x) \approx (1-x)^3$ as $x \to 1$. Therefore $p(x) \to 3$ as $x \to 1$. In the opposite limiting case $x \to 0$ there are two possibilities, for in this case the recoil parton can be scattered either by a parton or by a gluon, and $p(x)$ depends on the ratio of their densities as $x \to 1$. In experiment, the only surviving partons as $x \to 1$ are those carrying the nucleon-isospin projection. This can be further generalized and assumed that the gluon density is simultaneously small in comparison with the valence parton density. Then $p(x) \to 3$ as $x \to 0$. To the contrary, if the gluons survive as $x \to 1$, then $p(x) \to 3$. Finally, at $x = 1/2$ it is necessary to take into account the repulsion of the partons, and then $p(1/2) > 3$. The qualitative dependence of $p(x)$ on x is shown in Fig. 1.

Recognizing that at small x we have $u(x) \approx c/x$, we get

$$f(Q^2, x, z) \approx \frac{1}{(Q^2)^{C_h}} \begin{cases} (1-z)^2 z^{-2(1+C_h)}, & xz/1-z \ll 1 \\ (z_{max} - z)^{p(x)} (1-z)^{1-p(x)} z^{-1-2C_h}, & z \to z_{max} \end{cases}. \qquad (3)$$

The function $\phi(x, z) = f(Q^2, x, z)(Q^2)^{C_h}$ should in this case be independent of Q^2. A qualitative plot of $\phi(x, z)$ is shown in Fig. 2. If both x and x_2 are in the rapidity plateau region, i.e., $x,\ x_2 \lesssim a \approx 0.3$,[5] then the spectrum with respect to z should exhibit in addition a scaling behavior in the sense of independence of x, up to $z \approx a/(a+x)$, as can be seen from formula (3) and is shown in Fig. 2.

In the foregoing discussion and in the kinematic relations we have assumed that the recoil parton is on the mass shell. Actually the recoil parton can go off the mass shell. It is easy to verify, however, that allowance for this fact does not change the situation qualitatively, and the only result is that instead of a parton density $v(x, x_2)$, with values of x and x_2 obtained from the scattering kinematics on the mass shell, the inclusive transverse-momentum is proportional to the effective value of $v(x, x_2)$ averaged over a rapidity interval on the order of unity, not larger than the rapidity correlation radius. We note to this end that the discussed inclusive spectrum is determined by the diagram of Fig. 3. The absorption part of the amplitude of the process $3 \to 3$ in this diagram coincides, in accordance with the Kancheli-Mueller theorem[6] with the two-parton distribution function in the case of forward scattering. The requirement that the momentum transfers in the $3 \to 3$ amplitude be finite imposes on the integration region the conditions $(x_1 - x_3)^2 \lesssim x_1 x_3$ and $(x_2 - x_4)^2 \lesssim x_2 x_4$, so that the rapidity region over which $v(x, x_2)$ is effectively averaged turns out to be finite and independent of x. The irregularity in the spectrum should therefore remain, and its position relative to z does not change.

The author is grateful to V.I. Zakharov, V.A. Novikov, and M.V. Terent'ev for valuable critical remarks.

[1] R. P. Feynman, Photon-Hadron Interactions, Benjamin, 1972.
[2] D. Amati, L. Kaneschi, and M. Testa, Phys. Lett. 43B, 186 (1972); E.M. Levin and M.G. Ryskin, Yad. Fiz. 18, 1108 (1973) [Sov. J. Nuc. Phys. 18, 570 (1974)].
[3] R. Blankenbecler, S.J. Brodsky, and J.F. Gunion, Phys. Rev. D 8, 287 (1973); J.D. Bjorken, Phys. Rev. D 8, 4098 (1973).

[4]V.N. Gribov, in: Elementarnye chastitsy, I shkola fiziki ITÉF (Elementary Particles, First Physics School Inst. Theor. and Exptl. Phys.), Atomizdat, 1973.
[5]H. Kendall, Cornell Internat. Conf. on Electron and Photon Interactions, Cornell Univ. Press, 1972.
[6]A.H. Mueller, Phys. Rev. D 2, 2963 (1970); O.V. Kancheli, ZhETF Pis. Red. **11**, 397 (1970) [JETP Lett. **11**, 267 (1970)].