Koba-Nielsen-Olesen scaling and production mechanism in high-energy collisions

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An analysis of the existing data on photoproduction and electroproduction of protons is made. Koba-Nielsen-Olesen (KNO) scaling is observed in both cases. The scaling function of the nondiffractive γp processes turns out to be the same as that for nondiffractive hadron-hadron collisions, but the scaling function for deep-inelastic e^-p collisions is very much different from that for e^-e^+ annihilation processes. Taken together with the observed difference in KNO scaling functions in e^-e^+ annihilation and nondiffractive hadron-hadron processes these empirical facts provide further evidence for the conjecture: The KNO scaling function of a given collision process reflects its reaction mechanism. Arguments for this conjecture are given in terms of a semiclassical picture. It is shown that, in the framework of the proposed picture, explicit expressions for the above-mentioned KNO scaling functions can be derived from rather general assumptions.

I. INTRODUCTION

The recent CERN $p\bar{p}$ collider experiments,[1] in which Koba-Nielsen-Olesen (KNO) scaling[2] has been observed, have initiated considerable interest[3,4] in studying the implications of this remarkable property. A physical picture has been proposed in an earlier paper[4] to understand the KNO scaling in the above-mentioned experiments,[1] and in pp[5] and e^+e^- reactions.[6] It is suggested in particular that the qualitative difference between the KNO scaling function in e^+e^- annihilation and those in nondiffractive hadron-hadron collisions is due to the difference in reaction mechanisms.

In this paper we report on the result of a systematic analysis of high-energy γp and e^-p data[7,8] as well as that of a theoretical study of the possible reaction mechanisms of these and other related processes. We show the following.

(A) KNO scaling is valid also in high-energy γp and e^-p processes. The scaling functions for nondiffractive γp and low-Q^2 (invariant momentum-transfer squared) e^-p processes are the same as for nondiffractive hadron-hadron collisions, but the scaling function for deep-inelastic e^-p collisions is very much different from that for e^-e^+ annihilation processes.

(B) The KNO scaling function for e^-e^+ annihilation,

$$\psi(z)=6z^2\exp(-\alpha z^3),\ \ \alpha^{1/3}=\Gamma(\tfrac{4}{3})\,, \tag{1}$$

and that for nondiffractive hadron-hadron collisions,

$$\psi(z)=16/5(3z)^5\exp(-6z) \tag{2}$$

(here $z=n/\langle n\rangle$, n is the charged multiplicity and $\langle n\rangle$ is its average value), can be obtained from the basic assumptions of the proposed physical picture using statistical methods.

(C) The similarities and differences between observed KNO scaling functions mentioned in (A) can be understood in the framework of the proposed picture.

II. KNO SCALING IN γp AND e^-p PROCESSES

We studied photoproduction and electroproduction of protons at incident energies above the resonance region. We made a systematic analysis of the existing data[7,8] and found that: there is KNO scaling in e^-p as well as in γp processes. (See Figs. 1 and 2.) The KNO scaling function for nondiffractive γp processes and that for e^-p at low momentum transfer are the same as that for nondiffractive hadron-hadron collisions. (See Fig. 1.) The KNO scaling function for deep-inelastic e^-p collisions is very much different from that for e^+e^- annihilation processes. (See Fig. 2.)

The similarity between the KNO scaling function in nondiffractive γp (and low-momentum-transfer e^-p) and that in nondiffractive hadron-hadron processes is not very surprising. In fact, it shows nothing else but the well-known fact[9] that real (or almost real) photons at high energies behave like hadrons.

But does the difference in KNO scaling functions in e^-e^+ and deep-inelastic e^-p processes indicate that the reaction mechanisms of these two kinds of processes are qualitatively different from each other?

Before we try to answer this question, let us first examine in more detail the relationship between KNO scaling functions and reaction mechanisms in e^-e^+ annihilation and in nondiffractive hadron-hadron collisions.

III. e^-e^+ ANNIHILATION: FORMATION AND BREAKUP OF ELONGATED BAG

The KNO scaling function in e^-e^+ annihilation processes is shown in Fig. 3. It is sharply peaked at $n/\langle n\rangle\approx 1$ (n is the multiplicity of the charged hadrons

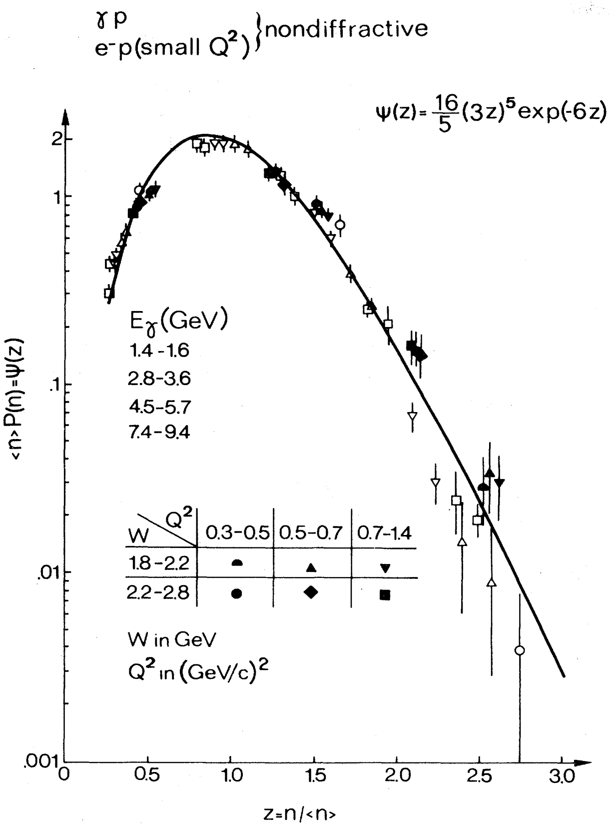

FIG. 1. The scaled multiplicity distribution for nondiffractive γp and low-momentum-transfer e^-p reactions. The experimental data are taken from Refs. 7 and 8, respectively. The curve is obtained from Eq. (2).

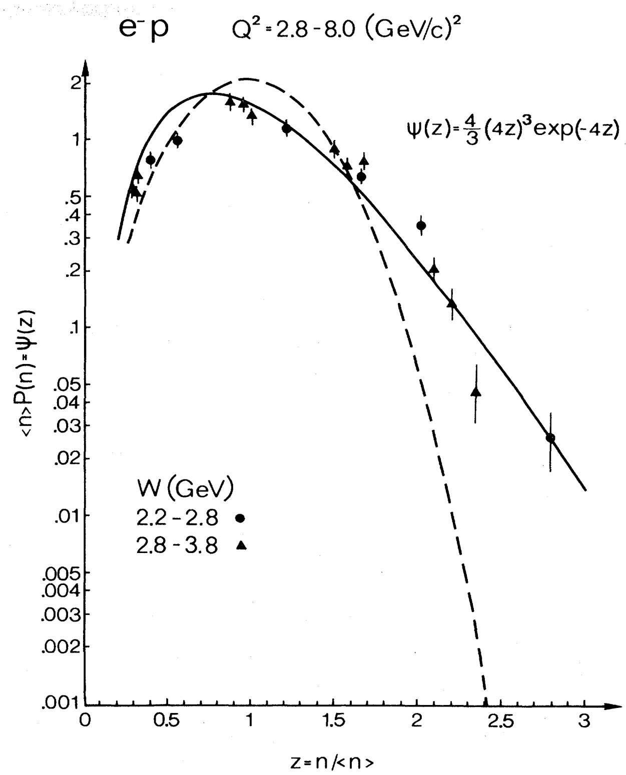

FIG. 2. The scaled multiplicity distribution for e^-p reactions at large momentum transfer. The experimental data are taken from Ref. 8. The dashed curve is the scaled function for e^-e^+ annihilation processes, shown in Fig. 3. The solid curve is the scaled function given in Eq. (24).

and $\langle n \rangle$ is its mean value) and can be approximated by a Gaussian.[4,10] It can be qualitatively understood[4] as follows: In e^-e^+ annihilation processes, the electron and the positron can be considered as pointlike particles. Hadronization takes place when the colliding e^- and e^+ hit each other so *violently* that *the entire amount* of the initial energy and momentum is deposited into a single system which subsequently breaks up into pieces.

It is clear that, without further specifications, this picture would be too general and too crude to account for all the characteristic features of the e^-e^+ annihilation processes. In fact, the observed two-jet structure[11] and the central rapidity (along the jet axis) plateau[12] suggests that in such a collision event the compound system formed after the violent collision should have the form of a long tube which eventually breaks up. (See Fig. 4.)

A number of models[13] have been proposed in the literature to account for the above-mentioned jet and plateau structures. The most natural and most successful ones among them seem to be those based on the Schwinger mechanism.[14] We recall that Schwinger[14] observed that the quantum vacuum of a gauge field theory may be so polarizable that the charge can be completely screened. The vector meson of the gauge theory then acquire a mass. It has been pointed out by Casher *et al.*[15] that this mechanism can be used to understand why isolated quarks are

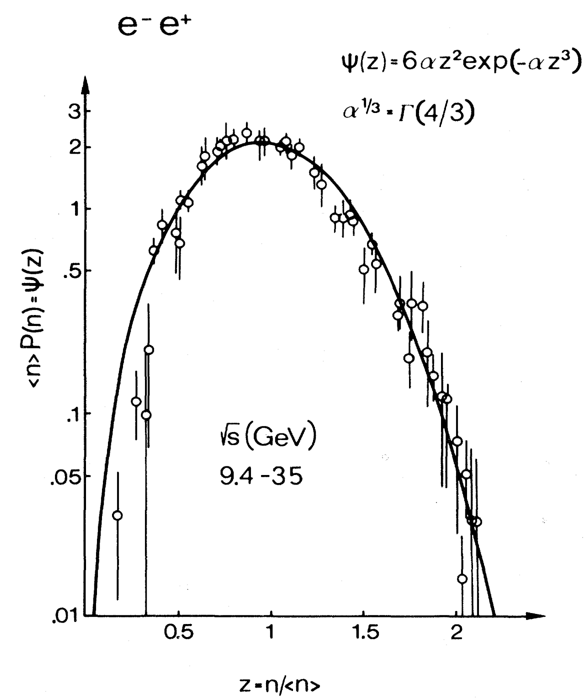

FIG. 3. The scaled multiplicity distribution for e^-e^+ annihilation processes. The experimental data are taken from Ref. 6. The curve is the scaling function given by Eq. (1).

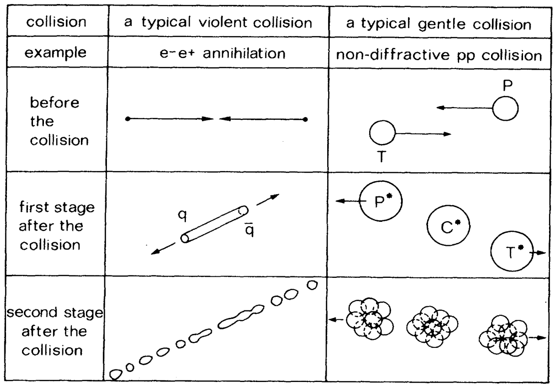

FIG. 4. Two qualitatively different types of high-energy collisions are illustrated; and one characteristic example in each case is given.

not seen in e^-e^+ annihilation processes, where the decay of the virtual photon into a quark-antiquark ($q\bar{q}$) pair is generally accepted to be true. In fact, it is envisaged that as q and $\bar{q}$ of the original $q\bar{q}$ pair move apart (at almost the velocity of light) a color-electric field is developed, and a number of polarized pairs (secondary $q\bar{q}$ pairs) are formed between them. Now, since the gluon exchanges allow q ($\bar{q}$) of arbitrarily high subenergy to interact with finite probability, an "inside-outside" cascade[16] takes place and as a consequence only color-singlet hadrons are produced. Quantitative comparisons between experiments[11,12] and the Lund model,[17] which is a semiclassical model that incorporates all the relevant features of the Schwinger model,[14] have been made.[18] The agreement seems to be very impressive.

Is it possible to understand the observed KNO scaling behavior in e^-e^+ annihilation processes in models based on the Schwinger mechanism? We now show that this question—which does not seem to have been asked before—can be answered in the affirmative.

In order to study multiplicity distributions in this framework, we need to know the relationship between the observed multiplicity of charged hadrons and the properties of the elongated bag. The following points are of particular importance in establishing this relationship:

(α) Since the number of sub-bags at the final stage of a given event is nothing else but the total multiplicity of hadrons in that event, it seems plausible to assume that the total multiplicity of charged hadrons (n) is proportional to the final length (l) of the elongated bag in every event,

$$n=(\bar{\gamma}/l_0)l\ . \tag{3}$$

Here, l_0 is the average length of the elongated hadron-bags in their "rest frames" and $\bar{\gamma}$ is the inverse of the average Lorentz contraction factors of the hadrons along the jet axis. This means, we have assumed that $\bar{\gamma}/l_0$ depends only on the total c.m. energy $\sqrt{s}$, provided that n is not too small compared to $\langle n \rangle$. Obviously, Eq. (3) is in accordance with the following empirical facts[6,19]: (i) The overwhelming part of the produced hadrons are pions of approximately the same transversed momentum with respect to the jet axis; (ii) The multiplicity of charged hadrons is distributed mainly around its average value $\langle n \rangle$ which is rather high at incident energies where KNO scaling has been observed (e.g., $\langle n \rangle \approx 7$ and 14 at $\sqrt{s}=10$ and 30 GeV, respectively).

We note that the final length l is determined by the first breakup of the elongated bag. This is essentially a kinematical effect which can be readily demonstrated in terms of the one-dimensional Lund model[17] as shown in Fig. 5. The generalization from the one-dimensional string to a three-dimensional elongated bag does not influence the arguments used to reach this conclusion. The reason is: In the present model, the existence of a $q\bar{q}$ pair is not a sufficient, but a necessary condition for the breakup.

(β) As the original quark-antiquark pair fly apart, their kinetic energy is converted into volume and surface energies. Secondary $q\bar{q}$ pairs are produced and the elongated bag begins to split when the bag reaches a certain length such that it is energetically more favorable to do so. Note that the collective effect due to color interaction is a substantial part of the bag concept. Hence, it is expected that the probability of bag splitting should depend on the *global* rather than the *local*[20] properties of the entire system. We shall assume, for the sake of simplicity, that the elongated bag is uniform in the longitudinal direction, and that the probability df/dl_1 for a bag of length l to break somewhere (at l_1, say, where $0<l_1<l$) is proportional to l, that is approximately proportional to the total energy U of the elongated bag.[21] This means

$$f(l)=\int_0^l \frac{df}{dl_1}dl_1\ , \tag{4}$$

$$\frac{df}{dl_1}=\lambda l\ , \tag{5}$$

where λ is a constant. It should be mentioned that we do

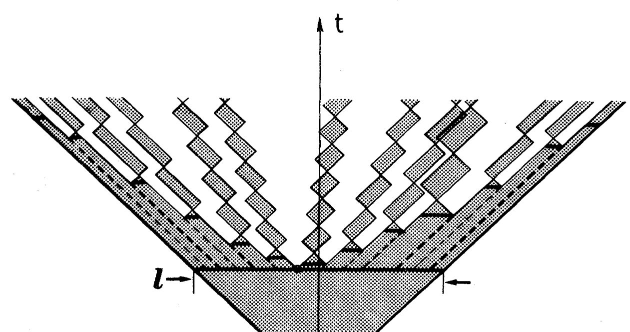

FIG. 5. The one-dimensional Lund model (see Ref. 17) is used to demonstrate that in e^-e^+ annihilation processes the final length of the elongated bag is determined by the first breakup. Here, t and x denote the time and space coordinates, respectively. Note that the generalization from the one-dimensional string to a three-dimensional elongated bag does not influence the arguments used to reach this conclusion.

not know why the above-mentioned l dependence [Eq. (5)] should be *linear*. What we know for the moment is: By assuming a power behavior l^k for df/dl_1, the experimental data require $k=1$.

(γ) Having obtained the probability $f(l)$ for an elongated bag of length l to break up, the density function for the l-distribution $P(l)$ can be calculated in the following way: Consider N events, among which in $N(l)$ of them the bag has reached the length without breaking and dN of them will break up in the interval $(l,l+dl)$, then

$$dN=-f(l)N(l)dl \ . \tag{6}$$

It follows from Eqs. (4), (5), and (6)

$$P(l)=\frac{dN}{dl}=Cl^2\exp(-\lambda l^3/3) \ , \tag{7}$$

where C is a normalization constant. The corresponding density function for multiplicity distribution $P(n)$ is therefore [see Eq. (3)]

$$P(n)=An^2\exp(-Bn^3) \ , \tag{8}$$

The constants A and B are determined by the usual normalization conditions[22]:

$$\int_0^\infty P(n)dn=2 \ , \tag{9}$$

$$\int_0^\infty nP(n)dn=2\langle n\rangle \ . \tag{10}$$

From Eqs. (8), (9), and (10), we have

$$\langle n\rangle P(n)=\psi(n/\langle n\rangle) \ , \tag{11}$$

where $\psi(z)$ is given by Eq. (1). Comparison with experiments[6] is shown in Fig. 3.

The following should be pointed out: (a) The KNO scaling behavior is obtained as a direct consequence of Eqs. (8), (9), and (10). (b) The elongated-bag model, which is obviously consistent with the physical picture discussed in Ref. 4, is more specific and gives a better description (than the Gaussian approximation) of the existing data. (c) There is a discrepancy between model and data for $z \lesssim 0.3$. This is due to the fact that Eq. (3) is only a poor approximation for $n \ll \langle n\rangle$. (d) since the final length is determined by the first breakup of the elongated bag, the existence of intermediate states does not influence the observed multiplicity of charged hadrons.

IV. NONDIFFRACTIVE HADRON-HADRON COLLISIONS: FORMATION AND DECAY OF THREE-FIREBALLS

We now turn to Eq. (2) and show that it can be derived in the framework of the proposed picture under more general conditions than those mentioned previously. We recall that, according to this picture,[4] the dominating part of the high-energy inelastic hadron-hadron collision events are nondiffractive. The reaction mechanism of such processes can be summarized as follows: Both the projectile hadron (P) and the target hadron (T) are spatially extended objects with many degrees of freedom. They go through each other during the interaction and distribute their energies in three distinct kinematical regions in phase space: the projectile fragmentation region $R(P^*)$, the target fragmentation region $R(T^*)$, and the central rapidity region $R(C^*)$. Part of these energies materialize and become hadrons. We denote these parts by E_{P^*}, E_{T^*}, and E_{C^*}, respectively. They are the internal (or excitation) energies of the respective systems. The difference in reaction mechanisms of e^-e^+ annihilations and nondiffractive hadron-hadron collisions is illustrated in Fig. 4.

Let us consider the internal energy E_i of the system i ($i=P^*,T^*,C^*$) in a large number of collision events. Viewed from the rest frame of the system i, both the projectile (P) and the target (T) before the collision are moving with a considerable amount of kinetic energy. The interaction between P and T causes them to convert part of their kinetic energies into internal energies of the systems P^*, T^*, and C^*. Hence, each system i has two energy sources so that E_i can be expressed as

$$E_i=E_{iP}+E_{iT}, \quad i=P^*,T^*,C^* \ , \tag{12}$$

where E_{iP} and E_{iT} are the contributions from the source P and that from the source T, respectively. Note that the two sources are independent of each other, and that among the nine variables in Eq. (12) six of them are completely random. Let $F_P(E_{iP})$ be the probability for the system i to receive the amount E_{iP} from P, and $F_T(E_{iT})$ is that for the system i to receive E_{iT} from T, then the probability for the system i to obtain E_{iP} from P and E_{iT} from T is the product $F_P(E_{iP})F_T(E_{iT})$. Physically, it is very likely that the system i completely forgets its history as soon as the system is formed. This means, the probability for the system i to obtain E_{iP} from P and E_{iT} from T depends only on the sum $E_{iP}+E_{iT}$. That is

$$F(E_i)=F_P(E_{iP})F_T(E_{iT}) \ , \tag{13}$$

where E_i and E_{iP} and E_{iT} are related to one another by Eq. (12). Hence

$$\frac{d}{dE_{iP}}[\ln F_P(E_{iP})]=-\frac{d}{dE_{iP}}[\ln F_T(E_i-E_{iP})] \ , \tag{14}$$

that is

$$F_P(E_{iP})=A_P\exp(-BE_{iP}) \ , \tag{15}$$

$$F_T(E_i-E_{iP})=A_T\exp[-B(E_i-E_{iP})] \ , \tag{16}$$

where A_P, A_T, and B are constants.

In order to obtain the *total* probability $P(E_i)$ for the system i to be in a state characterized by a given energy E_i, without asking the question "How much of E_i is contributed from P and how much of it from T?" we have to integrate over all the possible values of E_{iP} and E_{iT} under the condition given in Eq. (12). That is

$$P(E_i) = \int dE_{iP}dE_{iT}\delta(E_i-E_{iP}-E_{iT})F_P(E_{iP})F_T(E_{iT}) \ . \tag{17}$$

It follows from Eqs. (15), (16), and (17)

$$P(E_i)=CE_i\exp(-BE_i) \ , \tag{18}$$

where the constants B and C are determined by the normalization conditions

$$\int P(E_i)dE_i = 1 \ , \tag{19}$$

$$\int E_i P(E_i)dE_i = \langle E_i \rangle \ . \tag{20}$$

Hence

$$\langle E_i \rangle P(E_i) = 4E_i / \langle E_i \rangle \exp(-2E_i / \langle E_i \rangle) \ , \tag{21}$$

which is Eq. (11) of Ref. 4.

The multiplicity ($n_{\rm ND}$) distribution for nondiffractive hadron-hadron collisions given by Eq. (2) is obtained by taking into account (for details, see Ref. 4)

$$n_i / \langle n_i \rangle = E_i / \langle E_i \rangle \ , \quad i = P^*, \ T^*, \text{ and } C^* \tag{22}$$

and

$$n_{\rm ND} = n_{C^*} + n_{P^*} + n_{T^*} \ . \tag{23}$$

Note that z in Eq. (2) stands for $n_{\rm ND}/\langle n_{\rm ND} \rangle$.

It should be emphasized that the simple relationship, $E_i/n_i = \text{constant}$ ($i = C^*, P^*, T^*$), is an idealization. In reality, fluctuation in n_i for a given E_i is expected. Such effects have been taken into account by assuming that the KNO distribution for e^-e^+ annihilation (which can be approximated by a Gaussian; see Ref. 4) is due to the fluctuation of $n_{ee}/\langle n_{ee} \rangle$ about 1, and that the fluctuations of n_i about $\langle n_i \rangle$ is of the same magnitude. These fluctuations are folded into the distributions obtained from the three-fireball model for hadron-hadron processes (a detailed discussion on this point is given in the preliminary version of our paper; see Ref. 20 of Ref. 4). Comparison between data and results of that calculation shows, however, that the effect is negligible in first-order approximation.

V. A POSSIBLE REACTION MECHANISM FOR DEEP-INELASTIC e^-p PROCESSES

We now come back to the question raised at the end of Sec. II.

According to the conventional picture[23] for deep-inelastic e^-p collisions, one of the colored quarks inside the proton is hit so violently that it tends to fly away from the rest (to which it is bounded by the confining forces). As a consequence quark-diquark jet structure is expected.[23] Hence, it is natural to believe that also in this case elongated bags[15] or strings[17] are formed which hadronize. In fact, compared with the above-mentioned model for e^-e^+ annihilation, the only difference would be that the bags, tubes, or strings end with quark and diquark, instead of quark and antiquark. If this were true, the KNO scaling function for deep-inelastic e^-p processes would be the same as that for e^-e^+ annihilation.

The qualitative difference in KNO scaling functions of e^-e^+ and deep-inelastic e^-p collisions is probably because the virtual photon in e^-p processes behaves differently as that mentioned in the conventional picture.

Once we accept that (a) the virtual photon in deep-inelastic e^-p collisions cannot fragment like a hadron in hadron-hadron collisions because it has an energy deficiency compared with its momentum,[24] and (b) the proton is a spatially extended object with many internal degrees of freedom (possibly a large number of colored gluons and sea quarks in addition to the colored valence quarks) such that various colorless objects can be formed in an excited proton, it seems natural to conjecture that deep-inelastic e^-p processes take place as follows: The virtual photon in such collision processes interacts with a part of the proton gently in the sense that it "picks up" a certain amount of colorless matter in order to fragment.[25]

Note that by picking up a certain amount of colorless matter from the proton, the virtual photon becomes a real physical object. The fragmentation products of this object are nothing else but the "current fragments" observed in lepton-nucleon reactions.[26] This conjecture can be readily tested experimentally. Because, if it is correct, we should see: First, the average multiplicity $\langle n \rangle$ does not depend on Q^2 (the invariant momentum transfer). Second, $\langle n \rangle$ depends on W (the total energy of the hadronic system) in the same way as the average multiplicity in hadron-hadron collisions depends on $\sqrt{s}$ (the total c.m. energy). Third, the rapidity distribution in single-particle inclusive reactions shows a dip in the central rapidity region (near $y_{\rm c.m.}=0$) at sufficiently high incident energies. This is because the center of the current fragments (formed by the virtual photon and the colorless matter it picked up from the photon) and that of the residue target (the rest of the target proton) move away from the central region in opposite directions. Fourth, the KNO scaling function is

$$\psi(z) = 4/3(4z)^3 \exp(-4z). \tag{24}$$

This is because, according to the proposed picture[4] the two fragmenting systems mentioned above act independently, and the KNO scaling function of each system is [See Eq. (21)]

$$\psi(z) = 4z \exp(-2z) \ . \tag{25}$$

That is, the mechanism of e^-p deep-inelastic scattering can be described as the formation and decay of two fireballs. Here we have assumed, by analogy with the nondiffractive hadron-hadron collision, that the average multiplicities of the two fireballs are equal.

The first and the second points are well-known experimental facts.[27] In connection with the third point, we see that the rapidity distribution in neutrino-proton reactions at $W > 8$ GeV clearly shows the expected dip. (See, e.g., Fig. 10 of Ref. 26.) Corresponding data for electron-proton reactions at comparable energies is expected to exhibit the same characteristic feature. Last but not least, Fig. 2 shows that Eq. (24) (the fourth point mentioned above) is indeed in agreement with the data.

The conclusion that there should be two fireballs in the intermediate stage of deep-inelastic e^-p collisions can also be reached without referring to the properties of the virtual photons, provided that such collisions take place as follows: The pointlike electron goes through the spatially extended proton, gives part of its energy and momentum to a colorless subsystem of the proton and separates this subsystem from the rest. While the incident electron is only deflected due to the interaction, the two separated subsystems of the proton become excited and subsequently decay. It should also be pointed out that, if this conjecture is correct, we expect to see only one central fireball in the $e^-e^+ \rightarrow e^-e^+X$ processes at sufficiently large momentum transfer. In that case the corresponding KNO scaling function should be the same as that given in Eq. (25). It would be very interesting to see whether this and other consequences of the proposed reaction mechanism will agree with future experiments.

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[20]See, e.g., Ref. 17.

[21]In first-order approximation the energy of the elongated bag at a given instant is proportional to its length at that moment. This energy can be considered as the total potential energy of the $q\bar{q}$ system. We recall: Hadron-spectroscopy strongly suggests that the interaction inside a hadron can be described by a linear potential (the potential energy is directly proportional to the distance) between q and $\bar{q}$, provided that they can be considered as a static source and sink of color flux. This is, e.g., the case when the quark-antiquark pairs are heavy ($c\bar{c}$, $b\bar{b}$, etc.). Now, in the case of e^-e^+ annihilation processes, since the *primary* q and $\bar{q}$ are *always* on the two ends of the elongated bag while they separate, it is *always* possible to envisage the existence of an instantaneous static source and a corresponding sink in each bag. Hence we can assume the existence of such linear potentials for *all kinds* of *primary* $q\bar{q}$ pairs.

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[23]See, e.g., Hofmann (Ref. 12), p. 71 and papers cited therein.

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[25]This colorless matter is not chargeless. It consists probably of a large number of sea quarks. Note also that the existence of such processes does not necessarily contradict the underlying picture of the quark-parton model which may be true to the impulse approximation.

[26]See, e.g., N. Schmitz, in *Proceedings of the 1979 International Symposium on Lepton and Photon Interactions at High Energies, Fermilab,* edited by T. B. W. Kirk, and H. D. I. Abarbanel (Fermilab, Batavia, Illinois, 1980), p. 259.

[27]See, e.g., Chen *et al.* (the last paper of Ref. 8).