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Z-SCALING AND *A*-DEPENDENCE OF FRACTALITY OF DIRECT PHOTON PRODUCTION IN $p-A$ COLLISIONS

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1 Introduction

A study of the A-dependence of particle production in lA and hA collisions is traditionally connected with phenomena of nuclear matter influence on particle formation. The difference between the cross sections of particle production on free and bound nucleons is normally considered as an indication of new physics phenomena (EMC-effect [1, 2], J/ψ-suppression [3, 4], enhanced A-dependence in hadron production [5]). The A-dependence of cross section is usually presented in the form $\sigma = \sigma_0 \cdot A^{\alpha(x,p_\perp)}$. Here the factor $\alpha(x,p_\perp)$ characterizes the influence of nuclear matter on the mechanism of particle formation.

The A-dependence of hadron production over a high and low transverse momentum range was investigated in [5, 6] and [7, 8, 9], and a nontrivial dependence of α on $x = p/p_{max}$ and $p_\perp$ was found. The analysis of the deep-inelastic lA scattering data [10] shows [11] that the ratio of F_2 structure functions $R^{A/D}(x,A)$ for nucleus and nucleon is independent of transverse momentum Q^2. The ratio parametrized in the form $R^{A/D}(x,A) = x^{a_1}(1+a_2)(1-a_3x)$, is described by the coefficients a_i expressed via a universal function depending on atomic number only.

The A-dependence of cumulative π^+-meson production in pA collisions at $\theta_\pi^{lab} = 180^0$ was studied in [12].[2] The ratio $R^{A/D}(X,A) = A^{-1}\rho_A^\pi/\rho_D^\pi$ as a function of cumulative number X [8] was have shown a strong A-dependence. The ratio was found to be practically constant over the range $X < 1$ and to reveal an exponential growth at $X > 1$. The A-dependence of the ratio $R^{A/D}$ demonstrates an asymptotic behaviour with increasing A. A similar exponential behaviour for the ratio $R^{C/D}(x) = F_2^C/F_2^D$ of deep-inelastic structure functions at $x > 1$ was predicted in [14].

A detailed review of the A-dependence of particle production in hA and AA collisions can be found in [6, 9, 13],[15]-[18] (see also references therein).

One of the methods to study the properties of nuclear matter is to search for the violation of scaling laws established in elementary collisions (pp, $\bar{p}p$, lp etc.). In this paper, we study the A-dependence of z-scaling for direct photon production.

A new scaling, z-scaling, of particle production in pp and $\bar{p}p$ collisions was proposed, and the A-dependence of the scaling function for the process $pA \to \pi^+X$ ($A = H, D, Ti, W$) was studied in [19, 20]. The scaling is based on fundamental principles of nature such as self-similarity, locality, fractality and scale-relativity. The first one reflects the dropping of certain dimensional quantities or parameters out of a physical picture of the interactions. The second principle concludes that the momentum-energy conservation law is locally valid for interacting constituents. The third the fractality principle says that both the structure of interacting particles and their formation mechanism are self-similar over a kinematic range. The forth one, a scale relativity principle, states that the structures of interaction and interacting objects reveal self-similarity and fractality on any scale [23, 24].

It was established [19, 20, 24] that the scaling function $H(z)$ was expressed via two experimental observables, inclusive cross section $Ed^3\sigma/dq^3$ and the multiplicity density of charged particles $dN/d\eta|_{\eta=0} = \rho(s)$. The $H(z)$ was found to be inde-

[2] A-dependence of cumulative $\pi^\pm, K^\pm$ and $\bar{p}$ production on Be, Al, Cu, Ta nuclei and at $\theta_\pi^{lab} \simeq 90^0$ and $\simeq 120^0$ was studied in [13].

pendent of center-of-mass energy $\sqrt{s}$ and the angle of produced particle θ. The symmetry properties of $H(z)$ allow us to connect the scaling functions for different particles $(\pi^{\pm}, K^{\pm})$. The transformation parameter $a^{h/\pi^{+}}$ is interpreted as a relative formation length. The scaling function $H(z)$ describes the probability to form the hadron with formation length z. The universality of $H(z)$ means that the hadronization mechanism of particle production is of a universal nature. It was found [20] that $H_{pW} < H_{pp}$ for π^+-meson production over a high z range. It was concluded that nuclear matter in the hadronic phase intensified the hadronization process and decreased the formation length z. The influence of nuclear matter in the partonic phase on particle formation was assumed to differ from that in the hadronic phase. In the first case, the melting of the hadron "coat" increases the hadronization length. In the second one, the enhancement of "dressing" bare parton leads to decreasing formation length.

Direct photon production is studied in pp and $\bar{p}p$ collisions over a wide kinematic range of colliding energy and transverse momentum at CERN amd Fermilab. It is considered that photons are mainly produced at high energy via two mechanisms, hadron decay (for example, $\pi^0 \to 2\gamma$) and directly (Compton scattering and quark-antiquark annihilation). One of the main advantages of direct photons over the study of jets and single hadrons deriving from jets is t he following: the electromagnetic vertex is understood better than the hadronic one, the observed photons come from elementary interaction itself and only a few diagrams are important. Directly produced photons carry away information on a parton subprocess and, consequently, on the hadron structure. Experimental data on the cross section are widely used to perform a QCD analysis, to determine the gluon structure function and to verify the theory itself [25]. The search for a discrepancy between experimental data and QCD results can give an indication of new physics. A NLO QCD analysis of the data [21] on the cross section of direct photon production in pp and $\bar{p}p$ collisions at $\sqrt{s} = 24$ GeV was successfully performed, and the gluon structure function was determined [21] (see also [26] and references therein). Nevertheless, there is a problem of QCD description of data dealing with the choice of factorization, renormalization and fragmentation scales at different energy $\sqrt{s}$. The principle of minimum sensitivity proposed in [22] does not completely resolve the problem.

Prompt photon production is one among very few signals which can also provide direct information on the partonic phase of interaction in nucleus-nucleus collisions. 'Penetrating probes', photons and dilepton pairs are traditionally considered to be one of the best probes for quark-gluon plasma (QGP) [27]. Direct photons do not feel strong forces, they provide both an undisturbed picture of collision for very short times and a comparison sample for understanding the interaction between quarks and gluons and surrounding nuclear matter.

Direct photon production based on the concept of z-scaling was considered in [28]-[31]. The validity of z-scaling for direct photon production in pp and $\bar{p}p$ collisions over a wide range of colliding energy, transverse momentum and the angle of produced photons was confirmed. A fractal behaviour of the scaling function, $H(z) \sim z^{-\alpha}$, for both processes was found.

In the present paper the A-dependence of the fractal dimension α of the scaling

function $H(z)$ for the process $pA \to \gamma X$ $(A = p, Be)$ is studied. The paper is organized as follows. A general concept of z-scaling is described in Section 2. Analysis of the experimental data and discussion of the obtained results are presented in Section 3. Conclusions are summarized in Section 4.

2 General concept of Z-scaling

Let us consider the inclusive process

$$M_1 + M_2 \to m_1 + X, \tag{1}$$

where M_1 and M_2 are the masses of colliding hadrons and m_1 is the mass of produced inclusive particle. In accordance with Stavinsky's ideas [8], the gross features of the inclusive particle distributions for reaction (1) at high energies can be described in terms of the corresponding kinematic characteristics of the exclusive parton subprocess

$$(x_1M_1) + (x_2M_2) \to m_1 + (x_1M_1 + x_2M_2 + m_2). \tag{2}$$

The parameter m_2 is a minimum mass introduced in connection with internal conservation laws (for isospin, baryon number and strangeness). The x_1 and x_2 are the scale-invariant fractions of the incoming 4-momenta P_1 and P_2 of colliding objects

$$x_1 = \frac{(P_2q) + M_2m_2}{(P_1P_2) - M_1M_2}, \qquad x_2 = \frac{(P_1q) + M_1m_2}{(P_1P_2) - M_1M_2}. \tag{3}$$

The secondary particle carries away momentum q. The centre-of-mass energy of subprocess (1) is defined as

$$\hat{s} = x_1^2 \cdot M_1^2 + x_2^2 \cdot M_2^2 + 2x_1 \cdot x_2 \cdot (P_1P_2) \tag{4}$$

and represents the energy of colliding constituents necessary for inclusive particle production. The cross section of inclusive particle production in hadron-hadron interactions in the framework of the parton model is governed by a minimum energy of colliding constituents $\sigma \sim 1/s_{min}(x_1, x_2)$.

In accordance with the self-similarity principle, we search for the solution

$$\frac{d\sigma}{dz} \equiv \psi(z), \tag{5}$$

where $\psi(z)$ must be a scaling function, and we choose the variable z as a physically meaningful variable which could reflect self-similarity as a general pattern of hadron production. As shown in [19, 24], the choice of z in the form

$$z = \frac{2\sqrt{\hat{s}}}{M \cdot \Omega \cdot \rho(s)}, \tag{6}$$

allows us to obtain a universal spectra description of hadrons $(h = h^{\pm}, \pi^{\pm}, K^{\pm}, p^{-})$ produced in pp and $\bar{p}p$ collisions at high energies over a high transverse momentum range. The coefficient Ω is considered to describe the tension of a string stretched by partons. The dynamic quantity $\rho(s)$ represents the average multiplicity density of charged particles produced in the central region of collisions at a given energy $\sqrt{s}$. The coefficient Ω depending on x_1 and x_2 is introduced to take into account various degrees of "softness" of the subprocesses underlying secondary particle production. The factor, for particle production in the central rapidity range, can be written as

$$\Omega = [(1-\lambda_1)\cdot(1-\lambda_2)]^{\delta} \tag{7}$$

Here, the coefficients λ_1 and λ_2 are expressed via the fractions x_1 and x_2 as follows

$$\lambda_1 = x_1 + \sqrt{x_1\cdot x_2\cdot\frac{(1-x_1)}{(1-x_2)}}, \quad \lambda_2 = x_2 + \sqrt{x_1\cdot x_2\cdot\frac{(1-x_2)}{(1-x_1)}} \tag{8}$$

The invariant differential cross section for the production of inclusive particle m_1 depends on two variables, $q_\perp$ and $q_\parallel$, through $z = z(x_1, x_2)$ and $x_{1,2} = x_{1,2}(q_\perp, q_\parallel)$ in the following way:

$$E\frac{d^3\sigma}{dq^3} = -\frac{1}{s\pi}\left[\frac{d\psi(z)}{dz}\frac{\partial z}{\partial x_1}\frac{\partial z}{\partial x_2} + \psi(z)\frac{\partial^2 z}{\partial x_1\partial x_2}\right]. \tag{9}$$

Using (5) and (9), we can obtain the expression

$$E\frac{d^3\sigma}{dq^3} = -\frac{1}{16\pi\rho(s)^2M^2}\left[\frac{d\psi(z)}{dz}h_1(x_1,x_2) + \frac{\psi(z)}{z}h_2(x_1,x_2)\right]. \tag{10}$$

The functions h_1 and h_2 are proportional to the partial derivatives

$$h_1 = \frac{\partial z}{\partial x_1}\cdot\frac{\partial z}{\partial x_2}, \qquad h_2 = \frac{z\partial^2 z}{\partial x_1\partial x_2}, \tag{11}$$

and $h_1 \simeq h_2$ in a high energy region. Therefore the scaling function $H(z)$ is determined by the equation

$$H(z) \equiv -\frac{1}{16\pi}\left[\frac{d\psi(z)}{dz} + \frac{\psi(z)}{z}\right]. \tag{12}$$

Using (10) and (12), we obtain the relation

$$H(z) = \frac{(M_1+M_2)^2\rho^2(s)}{4h_1}\cdot E\frac{d^3\sigma}{dq^3} \tag{13}$$

relating the inclusive differential cross section and multiplicity density $\rho(s)$ to the scaling function $H(z)$.

The properties of the scaling functions $\psi(z)$ and $H(z)$ under scale transformations of their argument z can be written in the following form:

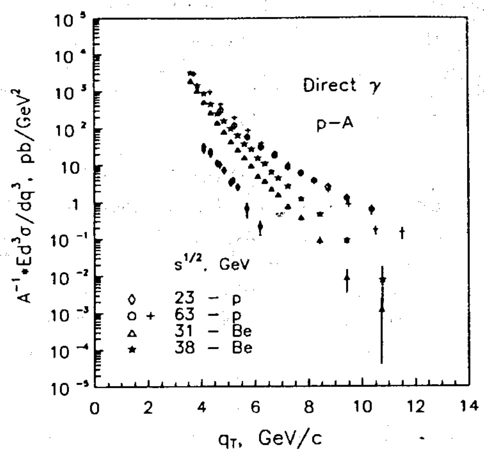
$$z \to a^{-1}z, \qquad H(z) \to a^{-2}H(a^{-1}z). \tag{14}$$

3 A-dependence of fractal dimension

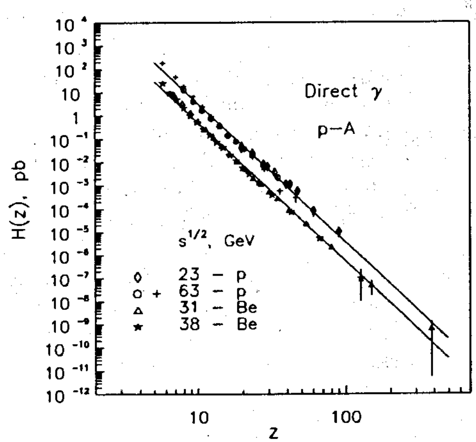
The calculation of $H(z)$ for the $pp \to \gamma X$ and $pBe \to \gamma X$ processes are performed using general expressions (6),(11) and (13) under the condition $m_1 = m_2 = 0$. The fitting functions of the experimental data on the multiplicity density of charged particles are used in the form $\rho(s) = 0.74\cdot s^{0.105}$ [32]-[34] and $\rho^A(s) = 0.67\cdot A^{0.18}\cdot s^{0.105}$ [20]. Recent experimental data [35] are well described by parametrization $\rho^A(s)$.[3]

Figure 1(a) shows the dependence of the invariant cross section $A^{-1}Ed^3\sigma/dq^3$ on the transverse momentum of produced photon $q_\perp$ at different energy $\sqrt{s}$. The experimental data for pp collisions are taken from [36]-[38]. The high accuracy data on the inclusive direct photon cross section for an incident 530 and 800 GeV/c proton beam and a Be target averaged over a center-of mass rapidity range of -0.75 to 0.75 and -1.0 to 0.5 per nucleon are taken from [39]. The statistical errors are shown in Figure 1 only. We would like to note a general tendency of $q_\perp$-presentation of the cross section data: a divergence of the spectra over a high $q_\perp$ range with increasing $\sqrt{s}$. The scaling functions $H(z)$ corresponding to the same data are presented in Figure 1(b). Note some important features of $H(z)$. The first one is that the points corresponding to pp collisions at $\sqrt{s} = 23$ GeV and 63 GeV coincide. The fact reflects the energy scaling of direct photon production in pp collisions. Similar results were obtained for pBe collisions, too. Moreover, the coincidence of the points obtained for different energies and angles gives us evidence of the validity of energy and angular independence of the scaling function $H(z)$ for direct photon production in pBe collisions. The second one is that the scaling function reveals the power behaviour, $H(z) \sim z^{-\alpha}$. This implies that the process of photon formation demonstrates the property of fractality as well as self-similarity. The fractality of photon production means that the underlying parton subprocess reveals the self-similarity property over a kinematic range of $\sqrt{s}, q_\perp, \theta$. The level of virtuality of the underlying process determined by the values of colliding energy and transverse momentum, corresponds to fixed renormalization, factorization and fragmentation scales. Transition from one to another level is governed by the renormalization equation of corresponding field theory (perturbative and nonperturbative QCD). As seen from Figure 1(b), the scaling function for the $pBe \to \gamma X$ process is found to be a linear one on log-log scale. The value of fractal dimension α_{pBe} equals 5.97 and $\alpha_{pBe} \simeq \alpha_{pp}$. The fact means that the nuclear matter changes the probability of photon formation with different length z and not the fractal dimension of the mechanism (photon "dressing"). The nuclear effect can be described by the ratio $R^{A/p}(z,A) = H^A(z)/H^p(z)$ of the scaling functions of nucleus and proton. One can see from Figure 1 that the ratio is practically independent of z and the function $R^{A/p}$ depends on atomic number only. Nevertheless, the experimental verification of the statement should be performed. Taking into account an experimental accuracy, the obtained results give us a confirmation, that the fractal dimension α is independent of A. It should be emphasized that the z-independence of the ratio $R^{A/p}$ can allow us to make predictions of photon spectra in different pA collisions using

[3] The author is grateful to G.P.Škoro for useful discussions on this matter.



a)



b)

Figure 1. (a) Dependence of the inclusive cross section of direct photon production on transverse momentum $q_\perp$ in pp and pBe collisions. The experimental data on cross section: $\diamond$ - WA70 [36], + - R806 [37], $\circ$ - R807 [38], $\triangle, \star$ - E706 [39]. (b) The corresponding scaling function $H(z)$. Solid lines are obtained by fitting the function taken in the form $H(z) = a_1/z^{a_2}$.

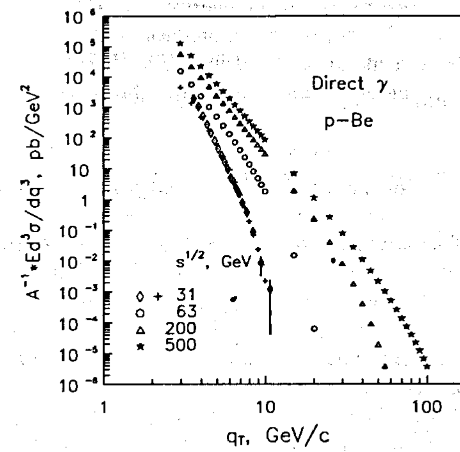


Figure 2. Inclusive cross section of direct photon production in pBe collisions as a function of transverse momentum $q_\perp$ for different cms energies $\sqrt{s} = 31, 63, 200$ and 500 GeV at an angle of $\theta = 90^0$. The experimental data on cross section ($\diamond$ - E706) are taken from [39].

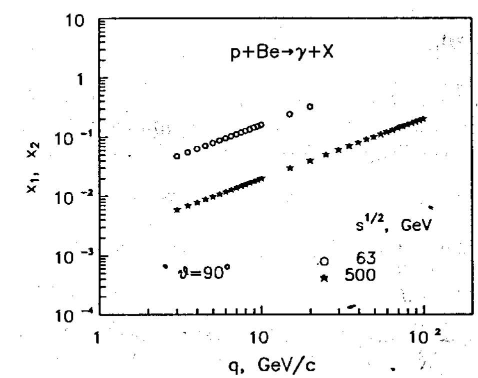


Figure 3. Dependence of the fractions x_1 and x_2 on the momentum q of direct photon produced in the central region at energies $\sqrt{s} = 63$ and 500 GeV.

the expression

$$H^A(z) = R^{A/p}(A) \cdot H^p(z). \tag{15}$$

We use the universality of the scaling function of direct photon production in pBe collisions to predict photon spectra at higher energy $\sqrt{s}$. Figure 2 demonstrates the $A^{-1}Ed^3\sigma/dq^3$ dependence on the transverse momentum of produced photon $q_\perp$ at $\sqrt{s} = 63, 200$ and 500 GeV and at an angle of 90^0. The fractions x_1 and x_2 covering the kinematic range with changing momentum q are shown in Figure 3.

4 Conclusions

The z-scaling of direct photon production in pp and pBe collisions at high energies was considered. The scaling functions $H(z)$ for the processes $pp \to \gamma X$ and $pBe \to \gamma X$ were constructed. The confirmation of the energy and angular independence of $H(z)$ for pBe and pp collisions was obtained. The power behaviour of the scaling function, $H(z) \sim z^{-\alpha}$, for photon production in pBe and pp collisions was established. The fractal dimension α was found to be the same for both processes, $\alpha_{pBe} \simeq \alpha_{pp}$. Based on the obtained results, the conclusion that the fractality of the self-similar process of photon formation is not changed by nuclear matter was drawn. The violation of the fractal dimension α of direct photon production is considered to be a new signature in searching for new physics phenomena in pp and pA collisions at high colliding energies over a transverse momentum range.

The study of the A-dependence of z-scaling and the search for z scaling violation of direct photon production in pA and AA collisions at high energies and high $q_\perp$ are of great interest with commissioning such a colliders of heavy nuclei as RHIC (BNL) and LHC (CERN).

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