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Z-SCALING IN PROTON-NUCLEUS COLLISIONS AT HIGH ENERGIES

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1 Introduction

The search for quark-gluon plasma (QGP) in hadron-nucleus and nucleus-nucleus collisions is the main goal of the future experiments at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven and the Large Hadron Collider (LHC) at CERN [1, 2, 3]. Numerous signatures of the unusual properties of nuclear matter at extreme conditions (high density, temperature, multiplicity, etc.) are proposed to study [4]. For example, there is an enhancement of strange particle production in the final state with respect to the typical level of the normal hadronic collision [5]. The enhancement is explained as the consequence of the chiral symmetry restoration [6]. The observed J/ψ- suppression is related to the color screening effect and the enhancement of "open charm" (D-mesons) production is predicted [7]. The ϕ production rate is expected to be extremely sensitive to changes in the quark mass [8] due to a possible chiral phase transition at high energy densities. Prompt photon production can provide direct information on the early phases of the parton interaction - thermal radiation from QGP and mixed phases [9]. Lepton pair production by hadronization processes has been widely discussed as a possible signature of QGP formation [10]. Lepton final states can relate information from the early and dense phase of the system owing to their minimal final state interaction. The study of the $J/\psi, \psi'$, and Υ production gives information on mechanism of Debye screening and deconfinement [7]. Correlations between identical bosons provide information on the freezeout geometry, the expansion dynamics and on the existence of QGP [11]. General indication of a phase transition is the appearance of the dynamical fluctuations of particle ratio, energy and entropy density as a function of $p_\perp$ and/or rapidity. The fluctuations have been predicted to arise from the process of hadronization of QGP [12].

However, there is no single clearly established signature of the QGP and, therefore, access to many observables simultaneously will be critical for identifying the event in which QGP is formed. It is important to study the observables which are well defined in hadron-hadron collisions and are sensitive to the nature of phase transition from hadron to quark-gluon degrees of freedom. The investigation shall address in depth the space-time evolution of the collision. The invariant inclusive cross sections for the production of charged hadrons, direct photons, Drell-Yan pairs, heavy mesons with beauty and charm, hyperons and jets can be considered as one of the possible experimental observables to study the unusual properties of nuclear matter at extreme conditions. Data on the inclusive processes as a function of incident energy, momentum, angle and type of the produced particles will be accessible experimentally.

In the paper we suggest to use the concept of the z-scaling [13] to the description of inclusive production cross sections in pA interactions at high energies. The scaling was applied for the analysis of the inclusive particle production in pp or $\bar{p}p$ collisions in the energy range $\sqrt{s} > 30$ GeV. The scaling function $H(z)$ is expressed via the invariant inclusive cross section $Ed^3\sigma/dq^3$ and the multiplicity density $dN/d\eta$ of charged particles produced at the c.m.s. pseudorapidity $\eta = 0$. It was found that the $H(z)$ is independent of c.m.s. energy $\sqrt{s}$ and angle θ of the inclusive particle. The symmetry properties of $H(z)$ allow us to connect the inclusive production cross sections for different particles ($\pi^\pm, K^\pm$). The corresponding transformation parameters - a^{h/π^+} have been interpreted as a ratio of their characteristic formation lengths. In this scenario the scaling function $H(z)$ describes the probability to form the hadron with a formation length z. The universality of $H(z)$ means that the hadronization mechanism of particle production is of universal nature. We suggest that the difference between $H(z)$ for pp and $H_A(z)$ for pA collisions can give definite evidence about the character of nuclear medium which influences the production process. We propose that the dependence of $H_A(z)$ on z for hadronic and QGP phases of nuclear matter can be quantitatively distinguished.

The method of constructing the scaling function $H_A(z)$ for the $p + A \to h + X$ process is described in Sec. II. In Sec. III we show that the available experimental data for the pA collisions ($A = d, Ti$, and W) confirm the z-scaling predicted for inclusive particle production in pp or $\bar{p}p$ interactions at high energies. The parameters representing relative formation lengths for $\pi^\pm$- and $K^\pm$ -meson production have been established for pd interactions at $p = 400$ GeV/c. The A-dependence of the scaling function is studied. It is found that the formation length of produced particle decreases due to nuclear matter influence. The prediction for the scaling function $H_{Au}(z)$ for π^+-meson production in pAu collisions at the energy $\sqrt{s} = 200$ GeV/n and for the detection angles $\theta = 15^0, 90^0$, and 165^0 is made. Verification of the z-scaling in pA collisions in high z range at BNL RHIC and CERN LHC allows us to study the transition regime from hadron to QGP phase and hopefully it will help to establish the general features of the constituent interactions in the nuclear medium.

2 Scaling function H(z)

We start with the investigation of the inclusive process

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

where M_1 and M_2 are masses of the colliding nuclei (or hadrons) and m_1 is the mass of the inclusive particle. In accordance with Stavinsky's ideas [14] the gross features of the inclusive particle distributions for the reaction (1) at high energies can be described in terms of the corresponding kinematical characteristics of the exclusive subprocess

$$(x_1 M_1) + (x_2 M_2) \to m_1 + (x_1 M_1 + x_2 M_2 + m_2). \tag{2}$$

The parameter m_2 is 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 the colliding objects. The c.m.s. energy of the subprocess (2) is defined as

$$s_x^{1/2} = \sqrt{(x_1 P_1 + x_2 P_2)^2} \tag{3}$$

and represents the energy of the colliding constituents necessary for the production of the inclusive particle. In accordance with the space-time picture of hadron interactions at the parton level the cross section for the production of the inclusive particle is governed by the minimal energy of colliding partons

$$\sigma \sim 1/s_{min}(x_1, x_2). \tag{4}$$

We find the fractions x_1 and x_2, which correspond to the minimal value of Eq. (3), under the additional constraint

$$\frac{\partial \Delta_q(x_1, x_2)}{\partial x_1} = 0, \quad \frac{\partial \Delta_q(x_1, x_2)}{\partial x_2} = 0, \tag{5}$$

where $\Delta_q(x_1, x_2)$ is given by the equation

$$(x_1 P_1 + x_2 P_2 - q)^2 = (x_1 M_1 + x_2 M_2 + m_2)^2 + \Delta_q(x_1, x_2) \tag{6}$$

and q is the 4-momentum of the secondary particle with mass m_1. So we determine the fractions x_1 and x_2 in the way to minimize the value of Δ_q, simultaneously fulfilling the symmetry requirement of the problem, i.e. $A_1 x_1 = A_2 x_2$ for the inclusive particle detected at 90^0 in the corresponding NN center-of-mass system. This gives

$$x_1 \equiv \frac{\bar{x}_1}{A_1} = \frac{(P_2 q) + M_2 m_2}{(P_1 P_2) - M_1 M_2}, \quad x_2 \equiv \frac{\bar{x}_2}{A_2} = \frac{(P_1 q) + M_1 m_2}{(P_1 P_2) - M_1 M_2}. \tag{7}$$

Here A_1 and A_2 are mass numbers and $\bar{x}_1$ and $\bar{x}_2$ are the fractions of the colliding nuclei expressed in units of the nucleon mass. Note, that x_1 and x_2 are therefore less than 1 for all values of q. The minimal value of Δ_q corresponds to the subprocess (2) with the minimal released energy in the direction opposite to the inclusive particle m_1.

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

$$\frac{d\sigma}{dz} \equiv \psi(z), \tag{8}$$

where $\psi(z)$ has to be a scaling function and choose the variable z as a physically meaningful variable which could reflect the self-similarity (scale invariance) as a general pattern of the hadron production. The invariant differential cross section for the production of the inclusive particle m_1 depends on two variables, say $q_\perp$ and $q_\parallel$, through $z = z(x_1(q_\perp, q_\parallel), x_2(q_\perp, q_\parallel))$ in the following way:

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

This can be shown by partially differentiating using the approximation to the Jacobian of the transformation (7) which at high energies tends to the value $-2q_\perp/(sE)$. If we choose for $z = \sqrt{s_x}/Q$, with a scale Q which in a first approximation does not depend on x_1 and x_2, we get

$$Q^2 E\frac{d^3\sigma}{dq^3}(q_\perp, q_\parallel) = 4\mathcal{H}\left(\frac{s_x^{1/2}}{Q}\right) \tag{10}$$

from the expression (9) in the high energy region. The function $\mathcal{H}(z)$ is determined by the equation

$$\mathcal{H}(z) \equiv -\frac{1}{16\pi}\left(\frac{d\psi(z)}{dz} + \frac{\psi(z)}{z}\right). \tag{11}$$

We specify the variable z in the case of pA interactions in analogy with the z-scaling construction for the elementary pp or $\bar{p}p$ collisions. We determine the scale Q to be proportional to the dynamical quantity - average multiplicity density $dN/d\eta|_{\eta=0}(s)$ produced in pA collisions. The point $\eta = 0$ represents the angle $\theta = 90^0$ in the corresponding NN center-of-mass system. We postulate

$$z = \frac{s_x^{1/2}}{\Delta M \cdot dN(0)/d\eta}, \tag{12}$$

where the coefficient ΔM has the dimension of energy and we determine it as "the reaction energy of the inclusive reaction" or, in other words, as the kinetic energy transmitted from the initial channel to the final channel of the subprocess (2). From the total energy conservation we have

$$\Delta M = M + m - m_1 - (x_1 m + x_2 M + m_2) = T_f^x - (T_i - E_R) \equiv T_f^x - T_i^x, \qquad (13)$$

with M and m being nucleus and proton masses. The T_i, T_f^x, and E_R are the initial kinetic energy, the kinetic energy in the final state of the subprocess (2), and the energy consumed on creation of the associate multiplicity, respectively. Inserting Eq. (12) into Eq. (9), we obtain the expression

$$E\frac{d^3\sigma}{dq^3} = \frac{1}{4\pi[dN(0)/d\eta]^2(M+m)^2}\left(\frac{d\psi(z)}{dz}h_1(x_1,x_2) + \frac{\psi(z)}{z}h_2(x_1,x_2)\right), \qquad (14)$$

where the functions h_1 and h_2 are defined in Appendix. They can be written in a simple approximate form (A7) and (A8) at high energies ($\sqrt{s} > 30$ GeV). In this energy region $h_2 \simeq h_1 \equiv h(x_1,x_2)$. Therefore, according to Eqs. (A7), (14), and (11), we obtain the approximate relation

$$\mathcal{H}_A(z) = \frac{(M+m)^2[dN(0)/d\eta]^2}{4h(x_1,x_2)}\cdot E\frac{d^3\sigma}{dq^3}. \qquad (15)$$

This relation connects the inclusive differential cross section and the multiplicity density with the scaling function $\mathcal{H}_A(z)$. The properties of the functions $\psi(z)$ and $\mathcal{H}(z)$ under scale transformations of their argument z can be written in the following form

$$z = \frac{z'}{a} \qquad (16)$$

$$\psi(z) \to \psi'(z') = \frac{1}{a}\cdot\psi\left(\frac{z'}{a}\right) \qquad (17)$$

$$\mathcal{H}(z) \to \mathcal{H}'(z') = \frac{1}{a^2}\cdot\mathcal{H}\left(\frac{z'}{a}\right). \qquad (18)$$

In order to compare $\mathcal{H}_A(z)$ for pA with $\mathcal{H}(z)$ for pp collisions, we normalize the scaling function as follows

$$H_A(z) \equiv \frac{1}{R_{inel}}\cdot\mathcal{H}_A(z). \qquad (19)$$

The coefficient $R_{inel} = \sigma_{inel}^{pA}/\sigma_{inel}^{pp}$ is the ratio of the corresponding inelastic cross sections [15]. Finally, we exploit the symmetry property (18) and perform the transformation of the scale

$$\bar{z} = A\cdot z, \qquad H_A(z) \to \frac{1}{A^2}\cdot H_A(z). \qquad (20)$$

For H_A as a function of $\bar{z}$ we get

$$H_A(\bar{z}) = \frac{(A-1+\delta-x_1-Ax_2)^4 m^2 (dN(0)/d\eta)^2}{4A^2[(A-1+\delta)^2-(x_1-Ax_2)^2]}\cdot\frac{\sigma_{inel}^{pp}}{\sigma_{inel}^{pA}}\cdot E\frac{d^3\sigma_{pA}}{dq^3}, \qquad (21)$$

where $\delta = 2 - (m_1 + m_2)m^{-1}$. We omit the bar symbol over the letter z in the rest of the paper.

Now we would like to present some qualitative picture, the substantial elements of which are the basic characteristics of the underlying parton subprocess (2) in terms of the scaling proposed. If proton-nucleus or nucleus-nucleus collision is considered as an ensemble of individual nucleon-nucleon collisions, the inclusive cross section (9) for particle production in the $A + A \to h + X$ process can be written as follows

$$E\frac{d^3\sigma}{dq^3} \sim \int\{\prod_{i=1,2} d\alpha_i d^2k_{\perp i}\cdot f_{A_i}^{N_i}(\alpha_i,k_{\perp i})\cdot f_{N_i}^{q_i}(\frac{x_i}{\alpha_i}, q_{\perp i} - \frac{x_i}{\alpha_i}k_{\perp i})\}\cdot\sigma_{q_1q_2}^{q}(s_x)\cdot D_q^h(z). \qquad (22)$$

The invariant cross section (22) is proportional to the structure functions $f_{A_i}^{N_i}$, $f_{N_i}^{q_i}$, and the fragmentation function D_q^h. The functions $f_{A_i}^{N_i}(\alpha,k_\perp)$ and $f_{N_i}^{q_i}(\alpha,k_\perp)$ depend on the light cone variable $\alpha = k_+/p_+$ ($p_\pm = p_0 \pm p_z$) and the transverse momentum $k_\perp$. The f_A^N and f_N^q take into account the nucleon and parton momentum distributions in nucleus and nucleon, respectively. The formula (22) can be extended to the case in which the clusters denoted by index N represent, besides the nucleons, QCD bags, fluctons, strangeletts and so on. The integration over the cluster variables α_i and $k_{\perp i}$ is nontrivial in this case and the concept of parton structure function of nuclei $G(x_i)$ is usually introduced [16]. Presence of nuclear matter affects the fragmentation of secondary partons, as well. The inclusive cross section (22) depends on the function $D_{q,A1,A2}^h(z)$ which reflects the fragmentation process of produced parton q. The fragmentation is influenced by the character of nuclear medium formed in the moment of the collision. As we have mentioned above the cross section of hadron interactions at the parton level to produce the inclusive particle is governed by the minimal energy of colliding partons $\sigma \sim 1/s_{min}(x_1,x_2)$. Therefore, we write the expression (22) in the form

$$E\frac{d^3\sigma}{dq^3} \sim \frac{1}{s_{min}(x_1,x_2)}\cdot G_{A_1}(x_{1min})\cdot G_{A_2}(x_{2min})\cdot D_{q,A1,A2}^h(z), \qquad (23)$$

where x_{1min} and x_{2min} satisfy the condition $s(x_{1min}, x_{2min}) = s_{min}(x_1,x_2)$.

It is easy to show that in the infinite momentum frame of colliding objects the variables x_1 and x_2 defined by the formula (7) coincide with the expressions $x_1 = q_+/p_{1+}$ and $x_2 = q_+/p_{2+}$ which are the well known light-cone variables. Theoretically, the best extreme condition to study the QGP would be in the kinematic regime of full cumulation of both nuclei. The asymptotic regime is given by $x_1 \to A_1$ and/or $x_1 \to A_1$, $x_2 \to A_2$ for pA and/or AA collisions, respectively. Higher stage of the cumulation corresponds to the larger values of the variable z (12).

It is assumed that the fragmentation function $D_{q,A1,A2}^h$ depends on the relative formation length z/z_{max} of the produced particle m_1. Really, the variable z can be interpreted in terms of parton-parton collision with the subsequent formation of a string stretched by the leading quark out of which the inclusive particle is formed. The minimal energy of the colliding constituents $s_{min}^{1/2}$ is just the energy of the string which connects the two objects in the final state of the subprocess (2). The off-shell behaviour of the subprocess corresponds to a scenario in which the string has the maximal possible space-like virtuality. The string evolves further, splits into pieces decreasing so its virtuality. The resultant number of the string pieces is proportional to number or density of the final hadrons measured in experiment. Therefore, we interpret the ratio

$$\sqrt{s_h} \equiv \sqrt{s_x}/(dN(0)/d\eta) \quad (24)$$

as a quantity proportional to the energy of a string piece $\sqrt{s_h}$, which does not split already, but during the hadronization converts into the observed hadron. The process of string splitting is self-similar in the sense that the leading piece of a string forgets the string history and its hadronization does not depend on the number and behaviour of other pieces. The factor ΔM in the definition of z is proportional to the kinetic energy of the two objects in the final state of the subprocess (2) and it can be considered therefore as something which reflects the tension of the string. We write finally

$$\sqrt{s_h} = \Delta M \cdot \lambda, \quad (25)$$

where λ can be regarded as the length of the elementary string peace or more precisely the ratio of the length to its characteristic (e.g., average or maximal) value.

The dimensional properties of the scaling function $\mathcal{H}(z)$ confirm mentioned above. One can see from Eq. (11) that they depend on the dimension of its argument. If we require the argument z to be dimensionless, then $\mathcal{H}(z)$ has the dimension of $[fm^2]$. For dimensionless scaling function $\mathcal{H}(z)$ we find the argument z to have the dimension of $[fm^1]$. From the transformation properties (16), (18), and from (23), it follows then

$$H_A(z) \sim D_A^h(\lambda). \quad (26)$$

So, we interpret the variable z as a quantity proportional to the length of the elementary string, or to the formation length, on which the inclusive hadron is formed from its QCD ancestor. In this picture we interpret the variable z as a hadronization parameter, namely as hadronization length. The scaling function $H(z)$ reflects local properties of the hadronization process.

3 Z-scaling in pA-collisions

Before analyzing the results on z-scaling in pA collisions we would like to remind of the results concerning the function $H(z)$ for charged hadrons produced in $pp(\bar{p}p)$-collisions at $\sqrt{s} = 53 - 1800$ GeV and $\theta = 90^0$. The function $H(z)$ is shown in Figure 1. The experimental data are taken from [17, 18, 19]. The solid line corresponds to the fit of the data. Note that the data on inclusive cross sections at $\sqrt{s} = 630$ GeV cover the kinematic region of transverse momenta of the secondary particles up to $q_\perp = 24$ GeV/c. The result demonstrates the universality, the z-scaling, found in hadron-hadron collisions at high energies. Since the function is well defined for hadron-hadron collisions, it can be used to analyze the hadron-nucleus collisions as well. Study of the z-scaling in pA interactions can give information regarding signals of the quark-gluon plasma creation.

We exploit the experimental data [22] on the inclusive $\pi^\pm$ and $K^\pm$-meson production in $p + d \to h + X$ process at incoming momentum $p = 400$ GeV/c. The dependence of the invariant cross sections on the transverse momentum $q_\perp$ is shown in Fig.2. The data can be expressed in terms of universal function $H_d(z)$ in dependence on the scaling variable z as presented in Fig.3. The scaling functions for all types of secondary particles coincide with each other up to the scaling transformation (19). The scale factors were interpreted as the ratio of characteristic formation lengths $a^{h/\pi^+} = z^h/z^{\pi^+}$ of the individual hadrons.

Results illustrated in Figures 2 and 3 show that the description in terms of z-representation demonstrates clearly scaling behaviour. The function $H(z)$ for the lightest nucleus - hydrogen is universal one. The angular independence of the curve $H_d(z)$ is verified to the extent the kinematic of the experiment [22] covers different angles of secondary particle production. The obtained results confirm z-scaling in pd collisions and reflect fundamental nature of the particle formation mechanism. The ratios of the characteristic (average) formation lengths a^{h/π^+} for the secondary particles produced in the reaction are given in Table 1. One can see that the relative hadronization length depends on the type of the produced particle.

Table 1. Relative formation lengths of hadrons produced in pd-collision at the incident proton momentum $p = 400$ GeV/c

a^{h/π^+}	a^{π^-/π^+}	a^{K^+/π^+}	a^{K^-/π^+}
relative formation length	1.06	1.2	1.25

The dependence of the inclusive cross section $Ed^3\sigma/dq^3$ on the transverse momentum $q_\perp$ for the process $p + Ti \to \pi^+ + X$ at the incident proton momenta $p = 200, 400$ GeV/c is shown in Fig. 4(a). The data are represented in terms of the scaling $H_{Ti}(z)$ as a function of the variable z in Fig. 4(b).

Similar dependencies for the different target - tungsten (A=184) are presented in Figures 5(a) and 5(b). The functions $H_A(z)$ for both nuclei manifest the energy independence in contrast to the behaviour of $Ed^3\sigma/dq^3$ as a function of $q_\perp$. So far the kinematic of the experiment [22] covers different angles of secondary particles, the curves $H_A(z)$ in Figures 4(b) and 5(b) demonstrate their angular independence as well. It is important from our point of view to verify the flavour dependence of $H_A(z)$ for heavy nuclei (Ti, W).

The obtained results give us strong argument to use z-scaling formalism for the analysis of experimental data on inclusive cross sections in pA interactions. We would like to remember that for NN collisions z-scaling in the proposed form is valid for the energy $\sqrt{s} > 30$ GeV [13]. It is reasonable to assume that similar restriction will be valid in the proton-nucleus collisions.

The A-dependence of the scaling functions $H_A(z)$ for different nuclei is presented in Fig. 6. The atomic numbers of the nucleus p, d, Ti and W are 1, 2, 48 and 184, respectively. All the functions coincide with each other in the range $z < 1$. The transverse momenta of the particles produced in this region are relatively small ($q_\perp < 3 - 4$ GeV/c). According to the result we conclude that the hadronization mechanism in this range is the same for both pp and pA collisions. The A-dependence of the scaling functions is manifested in the range $z > 1$. The values of $H_A(z)$ for heavy nuclei Ti, W fall steeper than for the proton p and deuterium d. In the range $z > 1$ the functions $H_A(z)$ decrease with the increasing atomic number A. The result reflects the influence of nuclear matter on particle formation process - the decrease of formation length with growth of the atomic number in this z-region. This corresponds to the idea that the nuclear medium affects mostly the particles whose formation takes place on relatively large scales.

As a result, we have found that the behaviour of $H(z)$ for proton-proton and $H_A(z)$ for proton-nucleus collisions are similar. We assume that the effect of formation length decreasing is due to influence of *hadronic phase* of the nuclear matter. The presence of the nuclear matter in this form intensifies the "dressing" of bare parent parton and accelerates its transformation into the real hadron. On the other hand, if QGP will be created in the instant of the collision, this should result in increase of the formation lengths on which the observed particles are formed. The QGP smelts the "coat" of "dressing" parton and the smelting process slows down the particle formation.

We have used the ratio

$$R^{A/d}(z) = \frac{H_A(z)}{H_d(z)} \tag{27}$$

for the study of A-dependence of the scaling function $H_A(z)$. The dependence of the ratio $R^{A/d}(z)$ on z for nuclei Ti and W is shown in Fig. 7. One can see that the nuclear effect grows with z for both nuclei. We assume, therefore, that study of A-dependence of the hadronization process in the high z-range will be preferable. The values of the $R^{A/d}(z)$ ratio for $Ti(A = 48)$ and $W(A = 183)$ at $z = 3$ differ from each other about the order of magnitude.

In order to construct the scaling function $H_A(z)$ for particle production in pA interactions, it is necessary to know the values of the average multiplicity density $dN/d\eta$ of (charged) secondaries produced in pA collisions at $\eta = 0$ as a function of the energy $\sqrt{s}$. The strong sensitivity of the z-scaling in hadron-hadron collision on the energy dependence of $dN/d\eta|_{\eta=0}(s)$ was found in [13]. At present there are no experimental data on $dN/d\eta|_{\eta=0}(s)$ for pA collisions at high enough energies ($\sqrt{s} > 30$ GeV). Therefore, we have used the Monte Carlo code HIJING [23, 24] to determine the energy dependence of the multiplicity densities of charged particles for different nuclei (Al, Ti, W, Au). The atomic numbers of the nuclei change from 27 to 197. The results of the calculations of $dN/d\eta|_{\eta=0}(s)$ as a function of $\sqrt{s}$ for pA and pp interactions are shown in Figure 8. The densities of charged particles $dN/d\eta|_{\eta=0}(s)$ were averaged over the impact parameters b $(0 < b < 10)$ in pA collisions and have been parameterized in the form:

$$dN/d\eta|_{\eta=0}(s) \simeq 0.67 \cdot A^{0.18} \cdot s^{0.105}. \tag{28}$$

The fit $dN/d\eta|_{\eta=0}(s) = 0.74 s^{0.105}$ for pp or $\bar{p}p$ collisions has been used in [20, 21]. The comparison of the multiplicity densities for pA and pp collisions shows that the energy dependence for both cases is determined by the Pomeron trajectory with $\Delta = \alpha(0) - 1 \simeq 0.105$. Therefore, the systematic investigation of s-dependence of multiplicity density $dN/d\eta|_{\eta=0}(s)$ both for pp, pA, and AA collisions allow us to study the A-dependence of mechanism due to single and multiple Pomeron exchanges. It is very important from our point of view to perform the direct measurements of the multiplicity densities of charged particles produced in pA collisions. The results allow us to verify the Monte Carlo code used as well.

To study z-scaling in pA interactions, we applied HIJING code to simulate pAu collisions at $\sqrt{s} = 200$ GeV/n. The dependence of the scaling function $H_{Au}(z)$ on z for π^+-mesons detected at the angles $\theta = 15^0, 90^0$, and 165^0 is shown in Figure 9. We found that the function $H_{Au}(z)$ is independent of the angle θ, similar as for pp case [13]. It means that in the kinematic range the code describes the proton-nucleus collision system as an ensemble of individual nucleon-nucleon collisions. We would like to emphasize that the simulation results have been obtained in the relatively low $z-$range (the transverse momentum $q_\perp$ changes from few hundreds MeV/c up to 1 GeV/c). It is reasonable to expect that the universality of z-scaling will manifest itself at high energies for secondary momenta larger then, say, $q_\perp > 0.4$ GeV/c. The violation of the scaling according to the presence of nuclear matter is of our interest at high transverse momenta (e.g. $q_\perp > 5$ GeV/c). The transition to parton phase of nuclear matter in pA collision corresponds to the joining of partons from different nucleons of nucleus known as a cumulative process [14, 25, 26]. Such processes can reveal themselves more prominent in the high momentum tail of the spectrum what corresponds to the large values of z. The comparison of the obtained results with future experimental data especially in this region is desirable.

Finally, we present the simulation results of the pseudorapidity distribution of the multiplicity density of charged particles $dN/d\eta$ for the pAu collisions at c.m.s. energy $\sqrt{s} = 200$ GeV/n in Fig. 10. The arrows correspond to the angles $\theta = 15^0, 90^0$, and 165^0 of the detected particles ($\eta = -\ln(tg(\theta/2))$ is the pseudorapidity in the corresponding NN c.m.s.). The distribution $dN/d\eta$ as a function of η has an asymmetric shape. The nucleus and proton fragmentation regions are clearly distinguished for $\eta < 0$ and for $\eta > 0$, respectively.

4 Results and discussion

We would like to describe the qualitative picture of the scenario proposed for various types of secondary particle production. Generally it is based on the scheme suggested in [13] for charged particle production in $pp/\bar{p}p$ collisions. We have shown that there is new scaling in inclusive particle production at high energies. The scaling function $H(z)$ is universal function of the variable z. The functions for different types of the produced particles have the same form. They are connected by symmetry transformation with parameters a^{h/π^+}. The factors a^{h/π^+} $(h = \pi^-, K^\pm)$ can be interpreted as ratio of characteristic (e.g. average or maximal) formation lengths for various hadrons. The knowledge of the relative formation length a^{h/π^+} of the observed particle allows us to restore the corresponding scaling function.

The value of the variable z depends also on the factor ΔM, which we interpret as a quantity proportional to the tension of the formed string. Let us look nearer to this aspect of our construction. Particles are produced to two kinematical regions: one characterized with high transverse momenta $q_\perp$ which at high energies correspond to low $x_{1,2} < 0.1$ and another one with extremely high longitudinal momenta $q_\parallel$ which gives $x_1(x_2) \to 1$, and $x_1 + x_2 \simeq 1$. The first region is the central region of secondary particle production and the second one is the fragmentation region of one of the incoming objects. The dependence of x_1 and x_2 on the secondary particle momenta q is illustrated in Figure 11(a-c). Figures 11(a,b) and 11(c) show clear difference between x_1 and x_2 in the fragmentation region of the incoming proton M_1 (a) or nucleus M_2 (b) and the central region (c). The kinematic range $0 < \tilde{x}_1, \tilde{x}_2 < 1$ is not forbidden for free nucleon-nucleon interaction. It is assumed that nucleon-nucleus and nucleus-nucleus collisions with secondary production merely with such kinematics are ordinary nucleon-nucleon interactions modified by nuclear matter in its hadronic phase. On the other hand, the kinematic regions $\tilde{x}_2 > 1$ and $x_1 > 1, \tilde{x}_2 > 1$ accessible in pA and/or AA collisions are of special interest for searching the parton phase of nuclear matter. The features of particle production in presence of QGP should be manifested most prominent just here.

The string tension in the central region is higher than in the fragmentation one. It corresponds to our ideas about the hadronization process in which the produced bare quark dresses itself dragging out some matter (sea $q\bar{q}$ pairs, gluons) from the vacuum forming so a string. The string connects the leading quark of the hadron m_1 with the virtual object with the effective mass $(x_1 M_1 + x_2 M_2 + m_2)$. The momentum of this object compensates the high momentum of the inclusive particle m_1. The quark dressing in the central region is more intensive than that in the fragmentation region. In our opinion it can be connected with the substantially lower relative velocities of the leading quark to the vacuum in the central region than those in the fragmentation one. For the slowly moving quark it is more easy to obtain an additional mass. Such a quark is strongly decelerated with the string which has the high tension. Consequently, the hadron generated from this quark is formed on smaller formation length.

In presented scenario, we focus our study to the regime of local parton interactions of incident hadrons and nuclei at high energies and for secondary particle momenta $q >$ 0.4 GeV/c. In this regime parton distribution functions of incoming objects are separated and, therefore, the scaling function $H(z)$ describes the fragmentation process of produced partons into the observable hadrons. The nuclear matter influences the fragmentation and can intensify the process of dressing of bare quark due to high density of the matter. There are two sources to obtain the mass for construction of hadron. One is the QCD vacuum of quark-antiquark pairs and gluons, an other - the nuclear field of the nuclei. The latter is due to meson (π, ρ, ω) fields. It is assumed that the dragging out of the mass from the nuclear field is more easy than from vacuum. Therefore the hadronization length in the hadronic phase of the nuclear matter should decrease. As mentioned above, the hadronization of a bare parton with the absence the QGP phase in the pA collision should be more intensive than in the elementary pp collision. The process of dragging out some matter from vacuum or nuclear field in the hadronic phase is not dynamically balanced. The number of partons forming the "coat" of leading quark is more larger than number of partons destroying it. Therefore the resultant balance between incoming and outgoing partons should enhanced the hadronization process. The consequence of this is the decrease of the hadronization length. Our result on decreasing of the hadronization length for π^+-meson production in the pA collision in comparison with the pp collision supports partially this statement.

We consider that the influence of nuclear medium for particle production in pA collisions with the formation of the parton (QGP) phase will be qualitatively different. The space-time evolution of the hadronization will be more complicated here. The dynamical balance between number of incoming and outgoing partons forming the mass of hadron will be conserved. Therefore the melt of the hadron "coat" will increase the hadronization length. As a result the enhance of the scaling function $H_A(z)$ for the pA collisions in comparison with the pp collisions may be observed. Such an increase can be considered as a signal of QGP formation in production of particles with high transverse momenta $q_\perp$. To verify the statement the measurement of particle production in the high $q_\perp$ kinematic range in the pA collisions at high energies is necessary.

5 Conclusions

The inclusive particle production in pA collisions at high energies as well as the new scaling, z-scaling, are considered. The scaling function $H_A(z)$ is expressed via two observables - the invariant inclusive cross section $Ed^3\sigma/dq^3$ for the process $p + A \to h + X$ and the multiplicity density $dN/d\eta(s)$ of particle production at pseudorapidity $\eta = 0$ in the corresponding nucleon-nucleon center-of-mass system. Results of analysis based on available experimental data give us arguments that the z-scaling is valid for pA and pp collisions as well. The scaling function $H_A(z)$ for the chosen nucleus (d, Ti, W) is independent of energy $\sqrt{s}$ and angle θ in the considered kinematic region of particle production.

The A-dependence of scaling function $H_A(z)$ is investigated. It is found that the nuclear matter intensifies the hadronization process decreasing the hadronization length. The obtained results give the strong arguments that the z-scaling can be used to study transition regime from hadron to quark-gluon matter in both hadron-nucleus and nucleus-nucleus collisions. We assume that the effect of quark-gluon plasma is the increase of produced particle hadronization length. It is proposed to study the effect in the kinematic ranges $\bar{x}_2 > 1$ and $\bar{x}_1, \bar{x}_2 > 1$ for the pA and AA collisions, respectively. The observed A-dependence of the z-scaling function $H_A(z)$ in the case of hadron-nucleus collisions we interpret in the way that the available energy is not sufficient to create quark-gluon plasma in the considered experiments [22].

We conclude that the z-scaling in pA and AA collisions reflects the general properties of parton-parton interaction in the nuclear matter and can be effective tool to search the signal of the formation and to study the space-time evolution of quark-gluon plasma. The experimental verification of the hypothesis on enhancement of the function $H(z)$ for particle production in high $p_\perp$ range in pA and AA in comparison with pp interactions at high energy $(\sqrt{s_{nn}} > 30\ GeV)$ will be possible in future experiments planed at RHIC (BNL) and LHC (CERN).

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Appendix

In the Appendix we present the results of calculation of the functions h_1 and h_2. Starting from the approximate expression (9) for the invariant cross section $Ed^3\sigma/dq^3$, we define the functions h_1 and h_2 as

$$h_1(x_1, x_2) = 4(dN(0)/d\eta)^2 (M_1 + M_2)^2 s^{-1} \frac{\partial z}{\partial x_1} \frac{\partial z}{\partial x_2} \qquad (A1)$$

$$h_2(x_1, x_2) = 4(dN(0)/d\eta)^2 (M_1 + M_2)^2 s^{-1} z \frac{\partial^2 z}{\partial x_1 \partial x_2}. \qquad (A2)$$

The equation (9) we rewrite in the form

$$E\frac{d^3\sigma}{dq^3} = -\frac{1}{4\pi(M_1+M_2)^2 \cdot (dN(0)/d\eta)^2} \cdot \Big(\frac{d\psi(z)}{dz} \cdot h_1(x_1, x_2) + \frac{\psi(z)}{z} \cdot h_2(x_1, x_2)\Big). \quad (A3)$$

If the scaling variable z is determined by

$$z = \sqrt{s_x}/(\Delta M \cdot dN(0)/d\eta), \ \ \Delta M = M_1 + M_2 - m_1 - m_2 - x_1 M_1 - x_2 M_2, \qquad (A4)$$

the direct calculation of h_1 and h_2 for $M_1 = M_2 = M$ gives the result

$$h_1 = \{sx_1x_2[\delta^2 - (x_1 - x_2)^2] + 2M^2(x_1 - x_2)^2[\delta(\delta - x_1 - x_2) + 4x_1x_2]$$

$$-4M^4s^{-1}(x_1 - x_2)^2[\delta(\delta - 2x_1 - 2x_2) + 4x_1x_2]\} \cdot F^{-1} \qquad (A5)$$

$$h_2 = \{sx_1x_2[\delta^2 - (x_1 - x_2)^2 + 4x_1x_2] + 2M^2\{(\delta - x_1 - x_2)[(x_1^2 + x_2^2)(x_1 + x_2) - 2x_1x_2\delta]$$

$$+8x_1x_2(x_1 - x_2)^2\} + 8M^4s^{-1}(x_1 - x_2)^4\} \cdot F^{-1}, \qquad (A6)$$

where $F = [x_1x_2s + (x_1 - x_2)^2M^2](\delta - x_1 - x_2)^4/4$ and $\delta = 2 - (m_1 + m_2)/M$, $s = (P_1 + P_2)^2$. In the case of different masses of the incoming objects $M_1 \neq M_2$ these expressions become too clumsy and we present them therefore in an approximate form here. This can be obtained by writing for z the expression (A4) with $\sqrt{s_x} \sim \sqrt{x_1x_2s}$. Consequently, we get the relations

$$h_1 = \frac{\Delta^2 - x_{eff}^2 + 4x_1x_2M_1M_2/(M_1 + M_2)^2}{(\Delta - x_{eff})^4} \qquad (A7)$$

$$h_2 = \frac{\Delta^2 - x_{eff}^2 + 8x_1x_2M_1M_2/(M_1 + M_2)^2}{(\Delta - x_{eff})^4}, \qquad (A8)$$

where $\Delta = 1 - (m_1 + m_2)/(M_1 + M_2)$ and $x_{eff} = (x_1M_1 + x_2M_2)/(M_1 + M_2)$.

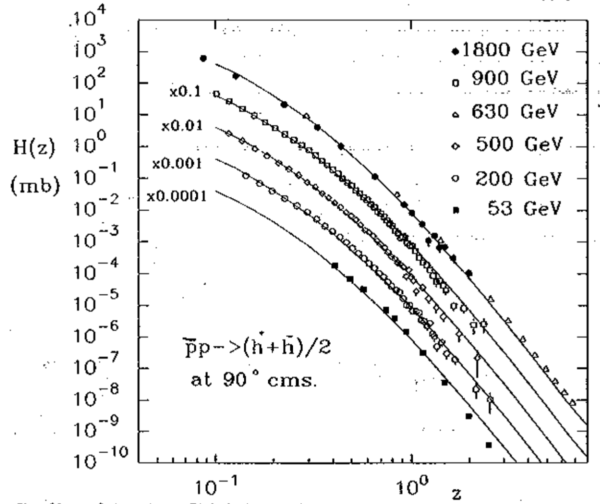


Figure 1. Scaling function $H(z)$ for charged particle production. Experimental data on inclusive differential cross sections for charged hadrons produced in pp or $\bar{p}p$ interactions at $\theta = 90^0$ and $\sqrt{s} = 53 - 1800$ GeV are taken from Refs. [17, 18, 19]. The lines represent fit to the data.

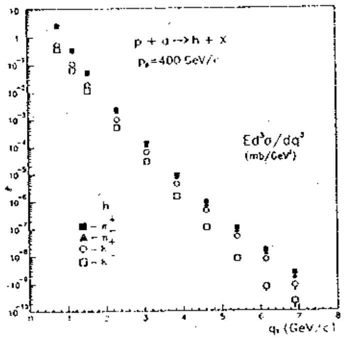


Figure 2. Experimental data [22] on inclusive differential cross sections for $\pi^\pm$ - and $K^\pm$ -meson production in pd interactions at $p_p = 400$ GeV/c as a function of transverse momentum.

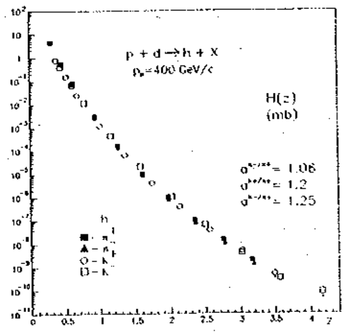
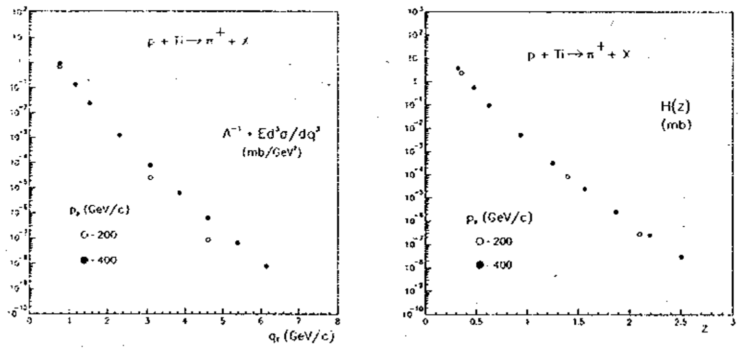
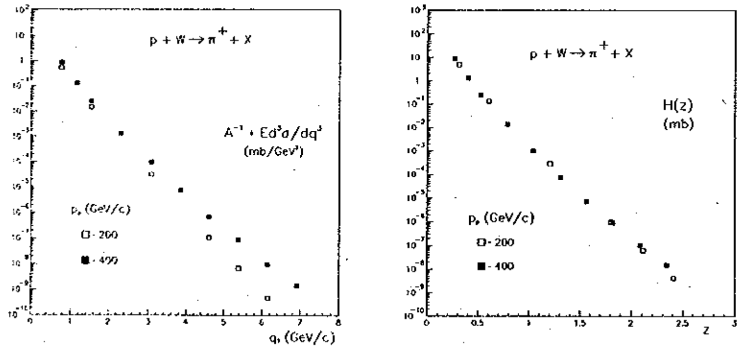


Figure 3. Scaling function $H_d(z)$ for $\pi^\pm$ - and $K^\pm$ -meson production in pd interactions at $p_p = 400$ GeV/c. Experimental data are taken from Ref. [22]. The scale factors a represent relative formation lengths of the produced mesons.



a) b)

Figure 4. (a) Inclusive differential cross section for π^+-meson production in pTi interactions at $p_p = 200$ and 400 GeV/c as a function of transverse momentum. (b) The corresponding scaling function $H_{Ti}(z)$. Data are from Ref. [22].



a) b)

Figure 5. (a) Inclusive differential cross section for π^+-meson production in pW interactions at $p_p = 200$ and 400 GeV/c as a function of transverse momentum. (b) The corresponding scaling function $H_W(z)$. Experimental data are from Ref. [22].

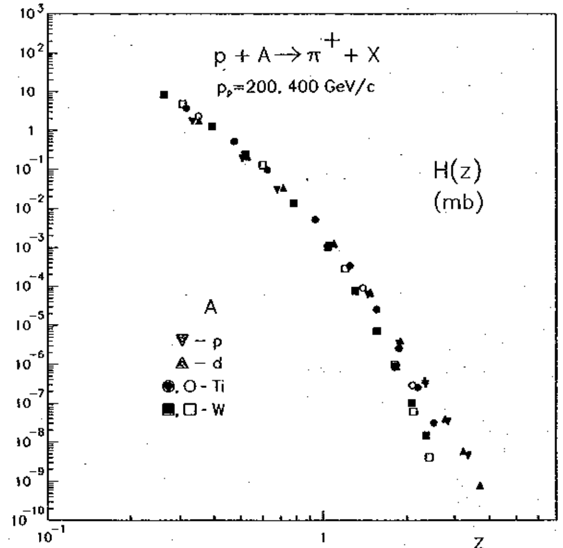


Figure 6. Scaling functions $H_A(z)$ for π^+-meson production in the pA interactions at $p_p = 200$ and 400 GeV/c. Experimental data on inclusive differential cross sections are taken from Ref. [22].

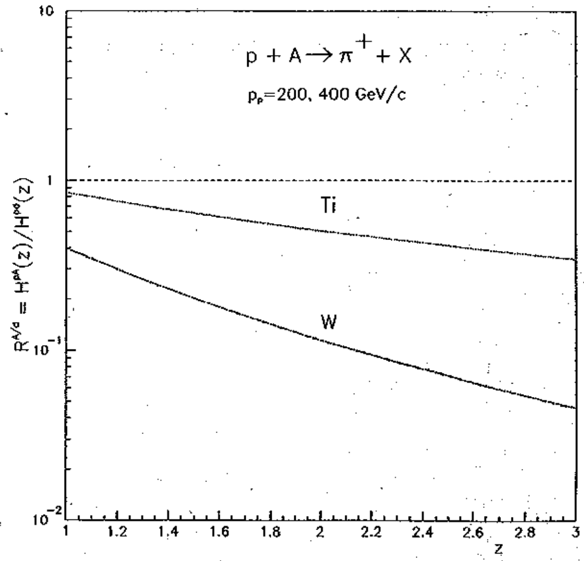


Figure 7. Ratio of the scaling functions $R^{A/d} = H^{pA}(z)/H^{pd}(z)$ as a function of the variable z for different nuclei - Ti, W.

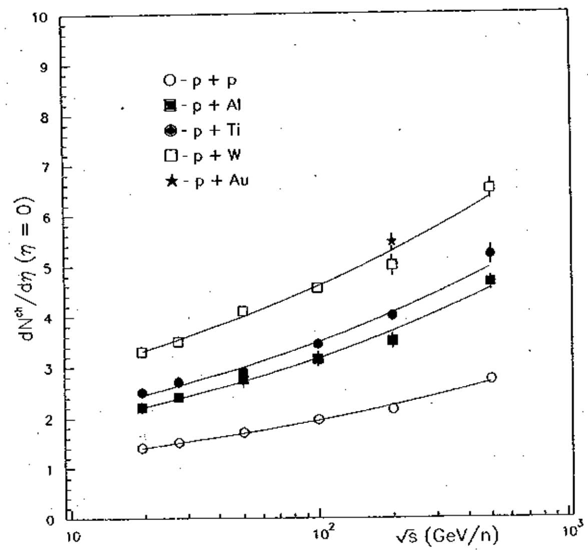
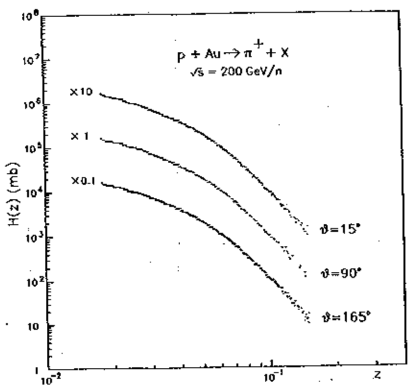


Figure 8. The average multiplicity densities $dN/d\eta|_{\eta=0}(s)$ of charged particles produced in pA interactions at $\eta = 0$ in the corresponding NN center-of-mass system as functions of NN c.m.s. energy $\sqrt{s}$. The Monte Carlo results are represented by points and the lines show the fits given in the text.

Figure 9. Simulation results of scaling function $H_{Au}(z)$ for π^+-meson production in pAu interactions at $\sqrt{s} = 200$ GeV/n and for $\theta = 15^0, 90^0$, and 165^0.



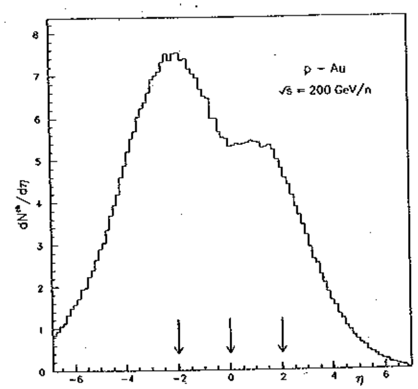
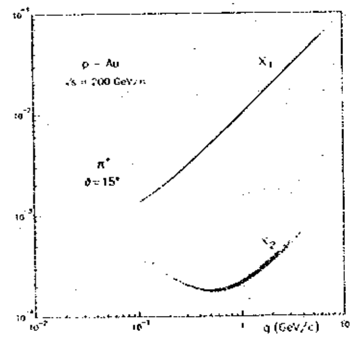
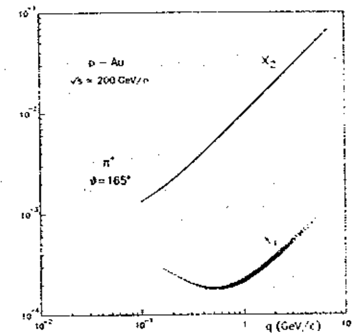


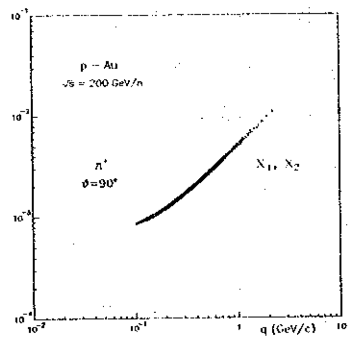
Figure 10. Result of Monte Carlo simulation of the pseudorapidity distribution $dN/d\eta$ of charged particles produced in pAu collisions at c.m.s. energy $\sqrt{s} = 200$ GeV/n. The particle density is averaged over the impact parameter range $0 < b < 10$ fm. Corresponding η-values of the angles $\theta = 15^0, 90^0$, and 165^0 are denoted by arrows.



a)



b)



c)

Figure 11. Dependence of x_1 and x_2 on the secondary particle momentum q in the beam fragmentation (a), target fragmentation (b) and central (c) regions.

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